SOLUTE REDISTRIBUTION AS INFLUENCED BY SOIL PROPERTIES IN RELATION TO LANDSCAPE MORPHOLOGY IN A GLACIAL TILL LANDSCAPE IN MANITOBA

BY

DAVID ALLEN WHETTER

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Soil Science
University of Manitoba
Winnipeg, Manitoba

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

Of

MASTER OF SCIENCE

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ABSTRACT

Whetter, David Allen. M.Sc., The University of Manitoba, June, 2004. Solute Redistribution as Influenced by Soil Properties in Relation to Landscape Morphology in a Glacial Till Landscape in Manitoba. Major Professors; Paul R. Bullock and Lesley G. Fuller.

Solute redistribution was examined as influenced by soil properties in relation to landscape morphology to determine if systematic relationships occur in a glacial till soil-landscape near Miniota, Manitoba. The study examined: 1. Long-term solute redistribution across a representative soil-landscape, and 2. Short-term vertical and lateral movement of a soluble bromide (Br^-) tracer at 3 representative soil-landscape complexes.

Generally speaking, soil properties indicative of progressive development were found to decrease with relative elevation (*RE*) and increase with convergent landscape character and measures of accumulation of water flows. Less variability in soil properties were found among landscape positions than between them.

Soil sampling conducted along a catena indicated topographic variables and static soil properties were poor predictors of solute redistribution within the top 120 cm. A horizon depth (Ahor), solum depth (solum), depth to CO_3 (CO_3), organic carbon (OrgC), *RE*, catchment area (*CA*) and topographic index (*TI*) were strongly correlated to SO_4^{2-} and NO_3^- below 120 cm. Large NO_3^- accumulations were found below 120 cm at Crest and Mid-slope positions relative to Lower-Depressional positions, where profiles were impacted by near-surface water tables. While static soil properties of Ahor, solum, CO_3,

and OrgC increased from UPPER to MID to LOWER landscape element complexes (LECs), associated patterns of solute redistribution parameters were not as obvious, particularly within 120 cm or at lower slope positions.

Detailed sampling of Br^- tracer plots (applied November 1999) was conducted in May and October 2000. High bromide recovery rates within 60 cm ($\%Br_{60}$) were found following the spring recharge period. In October, more Br^- was recovered in the top 30 cm ($\%Br_{30}$) at Midslope plots relative to positions, demonstrating that vertical redistribution was not as important at that position of the landscape, while low $\%Br_{60}$ at the Depression plots indicated that most of the applied bromide had leached below that depth. The Depression plots had the lowest %Br in May and October. CO_3, Ahor, solum and PDI, were negatively correlated to %Br and $\%Br_{60}$, indicating increased soil profile development resulted in more redistribution and lower recovery rates. Solute redistribution was more important during spring runoff than over the growing season at Crest and Midslope plots, while both hydrologic seasons were important at the Depression plots. Soil profiles and Br^- redistribution patterns were found to be the least anisotropic at Crest plots, with high vertical relative to lateral redistribution (Vf/Lf). Vertical redistribution was found to be least important at the Midslope plots, where slope gradient (G) values were the highest. Relatively low Vf/Lf values were found where vertical curvature (Kv) was high, while relatively high Vf/Lf occurred where accumulation curvature (Ka) was high. CO_3, Ahor, solum and PDI were significantly higher at Accumulation relative to Dissipation or Transit zones of flow. However, this concept did not appear to influence bromide redistribution parameters over the course of the study.

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To my best friend and wife, Michelle, I can't thank you enough. Your constant encouragement (and help in the field) has been greatly appreciated.

FOREWARD

This thesis has been prepared in the manuscript format in accordance with the guidelines of the Department of Soil Science. The Canadian Journal of Soil Science referencing style has been used throughout the thesis. Two manuscripts will be submitted for publication to the Canadian Journal of Soil Science, and will be entitled: 1. Long-term solute redistribution in relation to landscape morphology and soil distribution in a variable glacial till landscape in Manitoba, and 2. Short-term vertical and lateral bromide redistribution as influenced by soil properties in relation to landscape morphology in a glacial till landscape in Manitoba.

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1. INTRODUCTION

Recharge of aquifers and entry of water into shallow groundwater sources occurs through the unsaturated zone (i.e. vadose zone) of agricultural soils. The processes influencing the movement of water and associated solutes through the vadose zone have important agronomic, environmental and economic implications. These processes are complex in nature, but are of importance for understanding how soluble nutrients move through agricultural field soils. The vertical and lateral movement of soluble nutrients within the soil profile influences the availability of nutrients required for crop growth, and the entry of nutrients into groundwater and surface water systems, both of which have associated costs. Much research has been conducted measuring and modeling these processes in controlled laboratory environments, however, the complexity of these processes in natural environments requires complementary detailed field investigations to be conducted.

The movement of soluble nutrients is determined, in part, by soil profile characteristics. Spatial and temporal variability of soil properties with depth in the profile and across landscape positions result in diverse patterns of water and solute distribution over the landscape (Bathke et al. 1992; Afyuni et al. 1994). The purpose of this study was to examine the redistribution of soluble materials as influenced by soil properties in relation to landscape morphology in a glacial till landscape under conservation tillage in Manitoba. The study consisted of an examination of long-term solute redistribution across the landscape as well as the vertical and lateral movement of a soluble tracer over the

short-term. Specifically, the study was to examine the spatial and temporal variability of soil properties and soil hydrologic processes across the landscape, to determine if the distribution of soils in relation to landscape features resulted in recognizable, systematic patterns of solute redistribution.

2. LITERATURE REVIEW

2.1 The Soil-Landscape System

The relationship between soil properties and surface form of the landscape has long been recognized. Dokuchaev noted the importance of relief in soil forming factor in 1898 (Jenny 1961). Jenny (1941) described the soil as an open system and conceptualized that the soil was a function of five state factors: climate, organisms, relief, parent material and time. He revised this concept in 1961, and stated the soil system consisted of three state factors: the initial state of the system, environmental flux potentials, consisting of climatic, biotic and other factors, and time (Jenny 1961). In 1959, in contrast to Jenny's state factors, Simonson theorized that soil development was the result of processes of additions, removals, transfers and transformations acting on a soil profile (Hugget 1975). Milne introduced the catena concept in 1936, and theorized that the catena is a functional unit of soil formation (Hugget 1975). The catena, or soil toposequence, concept recognizes the interrelationship between soils developed in different positions on a slope. In 1948, Morison advanced this concept and hypothesized that a soil catena contains an eluvial, colluvial and illuvial complex (Hugget 1975). Morison's concept, analogous to Simonson's processes acting on a soil profile, was applied to the landscape. According to Morison, the eluvial area of the landscape loses material to the colluvial area, which in turns loses material to the illuvial area at the bottom of the slope.

One objective of the analysis of a catena is the identification of soil-slope associations: the association of a distinct soil with a particular landform configuration (Pennock and Acton 1989). To achieve this end, attempts have been made to segment the landscape into units which capture areas of similar soil properties and function. Attempts have been made to define landscape elements on qualitative and quantitative bases. Pennock and Acton (1989) note that the use of landform element classification and an understanding of the evolution of slope morphology through time allow a researcher to identify both distinct soil-slope association and the dominant processes responsible for their development. An understanding of the development and distribution of soils throughout a landscape can aid in explaining the variability of processes acting across that landscape.

2.2 Scale Dependence and Variability of Soil-Landscape Properties and Processes

Spatial and temporal variability in soil properties, with depth in the soil profile and across landscape positions, result in diverse patterns of water and solute distribution over the landscape (Bathke et al. 1992). When examining spatially and temporally variable soil-landscape properties and associated processes, it is important to understand both the spatial and temporal scales upon which they are dependent. Soil properties and processes should be examined at scales applicable to those at which conclusions are trying to be drawn.

Many researchers agree that spatial, and possibly temporal, variability of soil properties can be divided into deterministic and stochastic components (Wilding and Drees 1983;

Stolt et al. 1993; Seyfried and Wilcox 1995; Nielsen et al. 1996). Deterministic, or systematic, variability within the soil environment is often the result of recognizable differences in ecosystem characteristics, such as lithology, topography, hydrology, or vegetation (Stolt et al. 1993; Seyfried and Wilcox 1995;). Stochastic, or random, variability is attributed to unrecognizable differences in these parameters, as well as differences due to sampling and laboratory error (Wilding and Drees 1983). Seyfried and Wilcox (1995) state that, in reality, spatial variability is rarely entirely deterministic or stochastic. Within any deterministic trend, there is invariably a stochastic component, and vice versa. The total variability of a given parameter, therefore, is a composite of the deterministic and stochastic components.

Many efforts have been made in soil-landscape studies to separate systematic variability from random variability. Once separated from random variability, it is possible to determine sources of systematic variability and estimate the contribution of each source to overall variability. An understanding of the systematic variability of soils across a landscape, or over time, will allow for the next step, which is to apply knowledge of the variability of soil properties to soil-landscape processes.

2.2.1 Spatial Variability of Soil Properties

Spatial variability is universal to all soils and can have many possible sources (Stolt et al. 1993). Soil variability in the field is complex, and not easily understood. There are many factors and processes acting on soils across a landscape over time which lead to this variability. Much research has been conducted to determine the nature and causes of soil variability.

The purpose of many field studies is to quantify processes for natural, field soils (Nielsen et al. 1996). The scale of many of these studies is the pedon scale (often termed 'point-scale' in soil studies). The pedon represents the basic hierarchical unit of soil classification within which soil variability is described in vertical and horizontal dimensions. These studies recognize the fact that individual soil types have unique ranges of soil properties, which, in theory, influence processes in a recognizable manner. For studies of soil hydrology, Nielsen et al. (1996) state that random variation of soil properties influencing hydrologic processes is best determined at the pedon scale, where it should be statistically well defined. An understanding of the random variability of soil physical properties at the pedon scale affords researchers the ability to examine and quantify the systematic variability of soil properties due to heterogeneity of such factors as landscape, parent material and microclimate. Random variation of soil properties within a pedon must be understood prior to determining the systematic variability component of properties at smaller scales.

Attempts are often made to extend results from pedon scale studies to the smaller, more practically important and applicable scales of a higher soil mapping unit, landscape, catchment, or field. Prior to extending results from the pedon to smaller scales, Nielsen et al. (1996) note that it is advisable to differentiate between two categories within the catchment scale: 1. the pedotop scale; 2. the higher mapping unit scale. These categories both have inherent variability of soil physical properties, but differ in respect to the nature of that variability. Within the pedotop scale (i.e. a hierarchical unit of soil classification characterized by its position in the landscape, area and associated pedon), variability is

primarily stochastic in nature, whereas within the higher scale, it is both stochastic and deterministic.

Knowledge of the degree of parent material uniformity is essential for studies examining those processes related to pedogenesis, due to its profound effect on those processes. In a study in the Piedmont physiographic region in Virginia, Stolt et al. (1993) examined the spatial variability of select soil properties at different scales. They examined soil particle size distribution and elemental composition, and found parent material and regional climate (i.e. site) explained more of the variability than did landscape position. Residual parent materials (i.e. C horizon) varied only slightly due to landscape position, suggesting that there was little effect of landscape position on parent material. It was found that C horizons were more variable than eluvial A or illuvial B horizons within a given pedon, indicating that surface and near surface horizons have undergone substantial change and ordering due to pedogenesis, and therefore show less variability than C horizons within a pedon. However, mean coefficients of variation for several variables were >30%, indicating considerable lateral variability even within horizons of the same pedon.

Stolt et al. (1993) note that although much research has focused on examining parent material uniformity and soil variability, research evaluating soil variability within sampling units, such as horizons, has been limited. For example, they note that one cause of systematic variability in soil profiles is illuviation resulting in redistribution of clay particles between horizons. Neglecting to evaluate variability of properties and processes such as these within basic sampling units essentially ignores the variable nature of these processes.

Soil properties are inherently variable at many spatial scales. It is important to understand the nature of spatial variability of specific soil properties and related processes being examined. Sources of the different components of spatial variability must be accounted for at the scale applicable to the study in order to determine recognizable patterns in the landscape, if present.

2.2.2 Spatial Variability of Hydrologic Processes

Hydrologic processes occurring within the soil-landscape are influenced by the variable nature of soil properties across the landscape and the surface form of the landscape, as well as many other factors. The variable nature of hydrologic processes can, in turn, have a profound effect on the water input received at a given location of the landscape.

In one study, Seyfried and Wilcox (1995) found the variability of different hydrologic processes resulted in a highly spatially variable distribution of water input, ranging from 0 to more than 750 mm over a small watershed (i.e. 0.26 km^2). They concluded that this variability was strongly deterministic, in that it was predictable and mappable on an event or yearly basis.

Studies examining hydrologic processes have demonstrated that both deterministic and stochastic variability can have an impact on hydrologic response (Seyfried and Wilcox 1995). Seyfried and Wilcox (1995) demonstrate, however, that, in natural systems, different sources of variability in a watershed can be described as either stochastic or deterministic depending on the scale. The spatial scale over which the deterministic component largely controlled hydrologic response is termed the deterministic length

scale. Within the deterministic length scale, the hydrologic response is dependent on arrangement of ecosystem properties specific to that site, including such things as soil properties, topography, vegetation, groundwater hydrology, etc. When studying responses within the deterministic length scale, site-specific examination of parameters is required because hydrologic response is sensitive to the distribution of site-specific characteristics. Seyfried and Wilcox (1995) found that all hydrologic responses they examined displayed a high degree of spatial variability which had a large deterministic component.

Soil water content is a dynamic soil property, in that it is variable in the soil environment in both space and time. The spatial and temporal variability of soil water content in the soil environment is often used as an indicator of soil hydrologic processes. Water content distributions vary on different spatial and temporal scales. Nielsen et al. (1996) state that an understanding of soil water content distributions over space and time can enhance research in soil genesis and pedology that relates to, among other things, the identification of scales of observation most useful for different soil and landscape processes. In other words, an understanding of deterministic patterns of soil water content distributions can lend valuable insight into hydrologic and pedologic processes occurring at the scale over which these patterns are recognized.

Results from many studies have indicated considerable spatial variability of infiltration rates (Warrick and Nielsen 1980; Jury et al. 1987; Seyfried and Wilcox 1995). Seyfried and Wilcox (1995) found local groundwater recharge to be deterministic, and related to, among other factors, topography, soil depths and permeability of underlying materials. They undertook a study to examine the influence of scale on the nature of spatial variability of various hydrologic processes occurring in the field. They examined the

influence of the presence of a particular shrub species on surface runoff and infiltration, and found that at large scales (i.e. 0.1-0.3 m) infiltration rates exhibited considerable spatial variability, however were uniform with respect to shrub influences, because sample areas were either all shrub or all shrub interspaces. At intermediate scales (i.e. 0.3-8 m), the location of shrubs and other shrub characteristics strongly influenced the processes of surface runoff and infiltration, and the variability induced by the shrubs was nonrandom, or deterministic. At smaller scales, the impact of individual shrubs and their location decreased because the "sample size" effectively increased to a point that shrub-induced variability became stochastic. This study illustrates the scale dependent nature of the variability of hydrologic processes in the soil environment.

Other hydrologic processes influence the amount, rate and timing of water infiltration and movement in the soil environment, and are variable in nature. These processes include snowfall and snow redistribution, snowmelt dynamics and soil freezing.

Not all snow remains where it falls, and not all melt water infiltrates where snow melts. Snow redistribution and snowmelt dynamics are two important processes that influence the amount of water entering soil and shallow groundwater systems during spring melt. Wind transport of snow has profound effects on the hydrology of many areas (Tabler et al. 1990; Seelig and Richardson 1994; Seyfried and Wilcox 1995). The effective precipitation at any given point in the landscape may be higher than the areal average snowfall where deposition occurs, or lower where loss, due to blowing and/or sublimation, occurs. Significant redistribution of snow can occur during windy winter conditions, and is largely determined by such factors as prevailing wind conditions,

topography and vegetation (Rawls and Jackson 1979; Seelig and Richardson 1994; Seyfried and Wilcox 1995).

Sublimation, the change in state from solid directly to gas, is a spatially and temporally variable process, which can result in significant losses of snow and a concomitant reduction in effective precipitation. Sublimation is affected by many conditions, including weather and topography. Slope aspect has a significant effect on snow loss from sublimation (Seyfried and Wilcox 1995), resulting in the highest rates of sublimation and snow loss on slopes facing the sun. The redistribution of snow also influences the timing of runoff, because snow concentrated in drifts melts more slowly than uniformly distributed snow due to the smaller surface area / volume ratio (Seyfried and Wilcox 1995). Snow redistribution and snow melt dynamics determine, to a large extent, infiltration, groundwater recharge, and surface runoff. The spatially variable nature of these processes is largely controlled by topography (Seyfried and Wilcox 1995).

Soil freezing affects soil water movement, and, in particular, infiltration of spring runoff. The influence of frozen soil on infiltration is largely dependent on soil type and soil water content at freezing, in that drier soils will have less pores filled and therefore will have less effect on infiltration when compared to wetter soils with pores clogged. Soil freezing is often overlooked in hydrologic studies because its effects typically occur over short time periods and are the result of complex interactions of processes, but its impact on runoff can be dramatic (Seelig and Richardson 1994; Seyfried and Wilcox 1995). Seyfried and Wilcox (1995) note that the spatial distribution of frozen soil is largely deterministic, and can be described by accounting for such factors as air temperature,

snow depth and topography. Assessing the effects of frozen soil on runoff in a quantitative manner is a complex endeavour.

2.3 Soil Properties at the Landscape Scale

Soil properties can be highly variable on both spatial and temporal scales. Some of this variability is determined by landscape morphology. Malo et al. (1974) noted that soil properties follow systematic patterns of distribution on the landscape. Properties such as organic matter content, bulk density, texture, pH and moisture all vary with landscape position and time.

Topography was one of Jenny's soil forming factors (Jenny 1941). The primary role of topography in soil profile development is through influencing surface water redistribution, and therefore controlling the amount of water, a driving force of pedogenesis, entering a soil profile. Water redistribution due to topography also plays a key role in erosional and sedimentological processes. Hall (1983) has argued that limiting the catena to a hydrologic sequence ignores the erosional and sedimentological processes that are constantly occurring on most landscapes. Pennock and Acton (1989) found hydrological processes dominant in shoulder and divergent footslope elements, while sedimentological processes were dominant in convergent footslopes and backslopes.

The interrelation between landscape morphology and pedogenic processes in soil development has generated much research interest. Soil properties are examined, and their distribution related to landscape position and topographic variables. Malo et al. (1974) caution that soils present on a hillslope represent a continuum and not separate

entities, and, consequently, soil properties act as continuous variables on the landscape rather than as discrete values. This is an important concept; one that explains the variable nature of soil properties within a discrete "landscape position". The catena, or toposequence, concept recognizes that variability of soil properties represent a continuum across a landscape.

Despite the presence of general relationships between landscape morphology and soil distributions, Pennock et al. (1987) found considerable variability in soil properties within a given landscape position in hummocky terrain in Saskatchewan. They concluded that although hydrological controls were the dominant influence in this landscape, other processes, including sedimentation and erosion, could not be ignored.

2.3.1 Static Soil Properties

Soil properties are variable on temporal scales, and individual properties can differ in respect to the time scale upon which they are dependent. Static soil properties have a relatively long deterministic time scale. In other words, they are relatively stable over short time periods (i.e. 1-2 years). These properties are the result of pedogenic processes acting over a long time period. Dynamic properties are those that are variable over relatively short time frames. Examples of static soil properties include organic matter, bulk density and texture, while dynamic properties include water content and soluble salts. Understanding the nature of the distribution of soil properties in relation to landscape position, and the temporal scales over which they are dependent, can provide valuable insight into processes acting across a landscape.

Malo et al. (1974) found systematic patterns of static soil properties in a glacial till landscape. They examined the relationships between bulk density, particle size distribution, total carbon and inorganic carbon, and landscape position (i.e. summit, shoulder, backslope, footslope and toeslope). Organic carbon content in the surface (i.e. A horizon) increased logarithmically from the shoulder to the toeslope position, and was attributed to down slope translocation by erosional and sedimentational processes, as well as increasing moisture regimes from shoulder to toeslope. Malo et al. (1974) determined that bulk density was related to geomorphic setting. They found an abrupt decrease in bulk density values at lower landscape positions, and attributed these results to increased organic material and finer textured materials at these positions. They concluded that this relationship was due to erosional, sedimentational and pedogenic processes occurring over the landscape. Malo et al. (1974) also found relationships between measures of particle size distribution and landscape position. The proportion of particles > 2 mm in diameter was highest at the shoulder and lowest at the toeslope, a relationship attributed to erosional processes effectively concentrating coarser textured particles (by removal of finer textured materials) at the upslope positions, and sedimentation and deposition of finer material downslope. They found that pedogenic activity had altered the soil texture throughout the soil profile at the summit and backslope positions, as evidenced by a decrease in the size of clay particles in the solums. At lower landscape positions sedimentation processes dominated, as evidenced by uniform clay size distributions throughout the profiles.

Depth to calcium carbonates and solumn thickness at a given point in the landscape are predominantly controlled by downward penetration of moisture into the soil (Pennock

and de Jong 1990). Pennock et al. (1987) observed that the thickness of A horizons and depth to carbonates of soils associated with landscape elements increased in the sequence shoulders < backslopes < footslopes. They also found these properties increased from divergent to convergent elements. These findings indicate that pedogenic processes of organic matter accumulation and carbonate translocation, which are related to moisture levels and water movement, follow patterns in the landscape. Carbonate dissolution is the result of solution weathering and subsequent removal of the solutes (Pennock and Acton 1989). They note that convergence of water in hollows (i.e. convergent elements) has often been suggested as the cause of increased solution weathering and hence deeper sola in these positions.

St. Arnaud (1979) cautions that depth to carbonates as a measure of long-term average depth of moisture penetration in soils in semi-arid regions does not consider the effects of precipitation of carbonates as a result of lower CO_2 partial pressure below the rooting zone, and concentration effects resulting from leaching and water loss by evapotranspiration. He notes that the nature of the carbonates are important to consider. In depressional areas of medium- to moderately-fine textured glacial till landscape in Saskatchewan, St. Arnaud (1979) found removal of soluble salts to depths considerably below that indicated by Cca horizons. These Cca horizons were dominated by magnesium-free calcite ($CaCO_3$). In upland positions, soluble salt concentrations reached a maximum at depth of 2 to 4 m and then decreased progressively. In these locations, carbonate accumulations had higher magnesium/calcium ratios.

Pennock and Acton (1989) found few distinct soil-slope associations evident when soil morphological properties were compared to the present landform surface at three study

sites in hummocky terrain. Distinct soil-slope associations were more evident when soil morphological properties were compared to the landform elements calculated from the paleo-surface. They found that post-glacial sedimentation had smoothed the glacial land surface, and concluded that the lack of correspondence between soil morphological properties and the present surface landform was likely caused by this change in the land surface. They found increases in thickness of A horizon, thickness of B horizon and depth to carbonate from shoulders to backslopes to footslopes, and thinner horizons in divergent plan curvatures when compared to convergent plan curvatures within each profile group. In both cases, some relationships existed, as did several unexplainable anomalies.

Moore et al. (1993) found A horizons were generally thicker at summit and toeslope positions, and were thinnest at midslope positions which had the steepest slope and convex curvature. Organic matter content was highest in toeslope positions and decreased upslope. pH values were lowest at summit and toeslope, and were highest at midslope positions, and were negatively correlated with A horizon thickness.

Florinsky et al. (2002) found relatively high correlations between solum thickness, organic carbon and depth to calcium carbonates with topographic variables in the study field near Miniota, Manitoba. These soil properties increased in the order: crest < slope < depression. These findings indicate a strong topographic influence on pedogenic and hydrologic processes influencing the thickness of soil horizons.

2.3.2 Dynamic Soil Properties

Dynamic soil properties have a relatively short deterministic temporal scale. In other words, these properties change over short time periods (i.e. < 1 year). These properties are often used as indicators of processes occurring within a soil-landscape, and include soil water content and solute levels.

Soil water movement has a profound influence on pedogenesis and has an important role in soil-crop-water interactions. Soil water content is highly dynamic on short spatial and temporal scales; however an understanding of the distribution of soil water in a landscape over time can provide valuable insight into soil hydrologic processes. Olson and Cassel (1999) note that water content in the top 1 m of soil at field capacity may be a useful indicator of a soils' leaching potential, particularly when considering matrix flow.

Pennock et al. (1987) found a distinct range of dynamic soil morphological properties associated with three-dimensional landscape elements in hummocky terrain in Saskatchewan. They state that soil slope-associations occur because of the influence of hillslope morphology on surface and sub-surface water movement. Pennock et al. (1987) predicted that moisture levels should increase in the profile sequence of shoulders < backslopes < footslopes. Within each of the profile groups, moisture levels were predicted to be higher in convergent elements than divergent elements.

Florinsky et al. (2002) found soil water content correlated well with topographic variables in the study field near Miniota, Manitoba. They demonstrated that water content was negatively correlated to slope gradient, due to less infiltration and greater runoff as slope gradient increases. Soil water was negatively correlated to horizontal and vertical slope

curvatures. This was attributed to increased overland and lateral intrasoil flow when vertical and horizontal curvatures are convex. Soil moisture increased with size of the catchment, or contributing area. An increase in catchment area means more area of land contributes water to a given point. Water content was more strongly correlated with a topographic index composed of catchment area and slope gradient. Florinsky et al. (2002) noted that slope aspect influences soil water content through controlling insolation and evapotranspiration, with south facing slopes in the northern hemisphere being the driest, and north facing slopes the wettest. However, they rarely found significant correlation between aspect and soil water content within plots. Topographic variables as determinants for soil moisture decreased with depth in the soil profile, indicating that topography has less influence on soil moisture with depth.

Kachanoski and De Jong (1988) examined soil water storage in the soil profile along a 720 m transect of a fine-textured, moderately calcareous soil. They measured soil water contents on three dates: June 28, July 12 and October 1. There was no rainfall between June 28 and July 12, therefore that period is representative of evapotranspiration losses. Rainfall occurred between July 12 and October 1, therefore that period is representative of evapotranspiration and precipitation acting to recharge the soil profile. The researchers examined the coherency of relationships between periods of wetting and drying and spatial scale. They found relationships for the drying period were highly significant over all spatial scales, indicating temporal stability. For the wetting (or recharge) period, relationships were significant only at spatial scales larger than 40 m, indicating soil water content following recharge was related to the spatial pattern of the soil surface curvature.

During wetting periods, topography was related to soil water storage, while during drying periods topography had little to do with soil water loss.

2.3.3 Conservation Tillage and Soil Properties

Reduced and zero tillage soil management systems have been adopted by many crop producers in western Canada as a soil conservation strategy to reduce soil erosion, conserve soil moisture and improve soil quality. There are, however, concerns with these management systems in terms of the impact of herbicides and fertilizers on surface and groundwater quality resulting from changes in soil properties (Dick et al. 1989; Andreini and Steenhuis 1990; Gravanosky et al. 1993; Singh et al. 1996; Elliot and Efetha 1999; VandenBygaart et al. 1999).

Past research has shown that tillage affects soil properties, such as structure and organic matter, and influences soil hydrologic function (Elliot and Efetha 1999). Dick et al. (1989) note that increased residue cover associated with zero tillage is thought to decrease surface runoff and increase infiltration. However, they add that near-surface soil bulk density is often greater under zero tillage, which would conceivably decrease water infiltration rates and water movement through the soil. Although bulk densities are often higher under zero tillage, Elliot and Efetha (1999) note that the decreased level of soil disturbance under a reduced tillage system has led to increased organic matter levels and improved soil structure, which have resulted in improved infiltration rates and the soil's ability to transmit water.

When compared to conventional tillage, Elliot and Efetha (1999) found that soil under 11-year zero tillage treatments had more organic C, better structure and greater infiltration capacity. In a study on a silty loam to silty clay soil in a rolling landscape, they found that infiltration rates were significantly higher on the zero tillage plots on all landscape positions examined. Infiltration rate was positively correlated to aggregate stability and negatively correlated to bulk density. Elliot and Efetha (1999) note that improved infiltration in zero tillage soils reduced the potential for surface runoff from rainfall, which would limit surface transport of nutrients and herbicides in runoff water.

Dick et al. (1989) conducted a lysimeter study to measure runoff and leaching in silty loam soil under zero and conventional tillage. Over a 6 year period, they found mean annual sums of runoff plus leachate were 556 and 356 mm for zero and conventional tillage treatments, respectively. There was two times more runoff under the conventional tillage treatment, and much higher leachate collected under the zero tillage treatment. Dick et al. (1989) found that zero tillage management not only increases the total amount of water that infiltrates the soil, but also the amount of water that is transmitted through the soil. They concluded that higher infiltration rates and rapid conduction of water through the zero tillage soil were the result of increased surface residues and greater macroporosity.

Findings of Singh et al. (1996) support the conclusion that increased surface residues increase infiltration. They examined infiltration rates under different tillage and residue treatments, and found infiltration followed the trend: zero tillage + straw > conventional tillage + straw > conventional tillage - straw.

Vandenbygaart et al. (1999) found a reduction in total pore volume and in total number of pores in a soil profile under zero tillage. However, they also found an increase in macropores >100 μm in diameter and biopores (i.e. created by earthworm burrows, root channels, etc.) >500 μm in diameter. Shipitalo and Protz (1987) found a reduction in total porosity and macroporosity in the Ap horizon following the adoption of zero tillage. However, they noted that increased zoological activity, including burrowing earthworms, improved the bioporosity, which may partially compensate for reduced overall porosity. The continuous nature of the macropore and biopore networks that develop over time in the less disturbed zero tillage soil environment allows rapid preferential flow, which results in the increased rates at which water can be transmitted through the profile.

Chang and Lindwall (1989) did not find significant tillage treatment effects on saturated water content, hydraulic conductivity, bulk density, plant-available water holding capacity and large pore porosity (measured as the difference between water held at saturation and -20 kPa), in a long-term (20 year) study between no till, minimum tillage and conventional tillage. They attributed this to the fact that tillage disturbance did not exceed 90 mm. They also noted the importance of freeze and thaw cycles as a soil disturbance mechanism in the clay loam soil in Alberta. The NT soil was found to have the highest infiltration rate.

Chang and Lindwall (1989) note that in the literature the effects of tillage on the soil physical properties are reported as being related to soil type, type of tillage equipment, tillage depth, soil conditions such as moisture content at the time of tillage, and climatic conditions. They caution that site-specific conditions must be considered during the

interpretation of effects of tillage on soil physical properties, and the processes that they influence.

2.4 Landform Classification and Terrain Modeling

Owing to the long recognized relationship between soil distribution and landscape morphology, there has been much interest in quantifying the landscape, based on a range of topographic variables, and relating quantitative landscape data to soil properties and processes. Taking this a step further, many attempts have been made to model the terrain and develop predictive tools for distribution of soil properties and processes.

Over the past 20 years, quantitative topographical information has been used through digital terrain models (i.e. DTM's) (Florinsky et al. 2002), which are composed of unique topographical variables. Topographic variables include elevation (E), gradient (G), aspect (A), vertical curvature (k_v), horizontal curvature (k_h), mean curvature (H), accumulation curvature (k_a), specific catchment area (CA), topographic index (TI) and stream power index (SI) (Florinsky et al. 2002). Pennock et al. (1987) noted that the correlation between topographic variables and soil properties has been determined primarily using regression analysis. They stated that although the models developed have explained a degree of the variability inherent to soil distributions, they generally have not provided distinctive landform elements which can be recognized in the field, limiting their practical importance.

Landscape classifications based on profile curvature (i.e. normal to slope) have been widely used by pedologists (Hall 1983; Pennock et al. 1987). An example of a commonly

used model is Ruhe's (1960) classification summits, shoulders, backslopes, footslopes and toeslopes. However, Pennock et al. (1987) noted that two-dimensional models are not valid where significant plan curvature exists. Plan curvature (i.e. orthogonal to slope) greatly influences geomorphic, pedologic and hydrologic processes, and hence soil distributions (Figure 2.1). Aandahl (1948) recognized the influence of plan and profile curvature on soil properties.

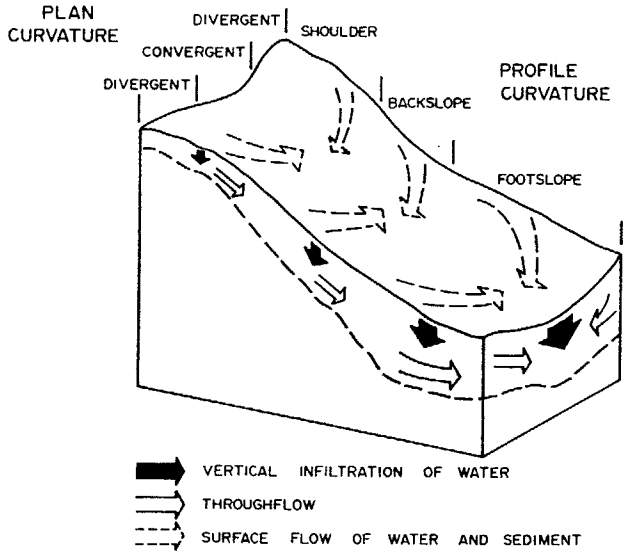


Figure 2.1 Summary diagram of probable water movement associated with different landform elements in a hillslope system (Pennock et al. 1987).

Zaslavsky and Rogowski (1969) postulated that infiltration streamlines governing water movement into the soil should diverge on convex hillslope elements (in both plan and profile curvature) and converge on concave elements. They suggest that the higher moisture contents in convergent landscape elements should lead to more pronounced profile development at these points. Anderson and Burt (1978) found that throughflow following rainfall was strongly convergent into concave landsurface elements, leading to soil saturation and discharge of water into adjacent streams. Speight (1980) has argued

that plan curvature is only an indicator variable for two more hydrologically significant variables: catchment area (the area upslope from a point which can contribute runoff to the point) and dispersal area (area of terrain downslope from a point to which water from the point can drain). If, however, morphological criteria alone are used for the classification, the plan curvature can act as an indicator variable for catchment and dispersal areas because both catchment and dispersal areas vary depending on the plan curvature (Speight 1980; Pennock et al. 1987).

Pennock et al. (1987) used five parameters to describe landscape morphology: 1. elevation of a point in m; 2. gradient (maximum rate of change of elevation at the grid point) in degrees; 3. aspect (azimuthal bearing of the gradient) in degrees; 4. profile curvature (rate of change of gradient) in degrees/m; and 5. plan curvature (rate of change of aspect along a contour line) in degrees/m. They also calculated global catchment areas, which measure the total catchment contributing runoff to a specific location allowing for spill-over of water from depressions, and, local catchment areas, which measure the total catchment contributing runoff to a specific location without spill-over (for areas with a low degree of drainage integration). Pennock et al. (1987) classified a hummocky landscape to distinguish combinations of gradient, plan curvature and profile curvature which define distinct landform elements (i.e. zones of the hillslope with a defined range of surface morphological attributes. They used Ruhe's (1960) hillslope concept of summit, shoulder, backslope, footslope and toeslope, with further sub-divisions based on plan curvature. They sub-divided shoulder, backslope and footslope elements into divergent (convex plan curvature) and convergent (concave plan curvature) elements.

Although the landform classification system developed by Pennock et al. (1987) has been one of the most widely accepted and applied on the Canadian prairies, MacMillan et al. (1998) noted problems with the system, including fragmented spatial patterns of landform elements, confusion in differentiating some upper and lower elements, and required adjustments for different types of landforms. MacMillan and Pettapiece (1997a, 1997b; MacMillan et al. 2000) developed a more practical classification system for partitioning soil-landscapes in the Canadian prairies into landform elements, based on the one developed by Pennock et al. (1987). They developed a system of 15 landform elements, which were grouped into: a. Upper, generally convex, water-shedding slopes; b. Lower, generally concave or level, water-receiving slopes; and c. Mid-slope, generally water-neutral slopes. These three classes exhibited most of the significant variability in soil properties, including organic carbon, pH, bulk density and available nutrients (MacMillan et al. 1998).

Manning et al. (2001a) applied the concept of LEC (MacMillan and Pettapiece 1997a; MacMillan et al. 2000) to a glacial till landscape near Hamiota, Manitoba, and found they were useful in capturing topographic and pedogenic variability in the soil-landscape. They found the thickness of the A horizon, solum thickness and depth to carbonates increased moving from the upper to the lower, and coincided with the extent of convergent character in the landscape. Organic carbon was also found to increase with convergent character, with a relative rank of upper < mid < lower. This relationship was attributed to carbon cycling, as well as erosional and depositional influences. In terms of topographic variables, they found the three pedogenic variables were generally inversely related to relative elevation, slope gradient, plan curvature and profile curvature, and

positively related to global catchment and local catchment. The researchers concluded that the concept of LEC warrant further investigation as a means of capturing systematic variability within the landscape.

Florinsky et al. (2002) noted that there are problems associated with correctly identifying topographic features when subjective criteria are used for terrain segmentation. The commonly used geomorphic concepts such as crest and depression are not rigorously, quantitatively defined. This has led Florinsky et al. (2002) to suggest the use of the concept of dissipation, transit and accumulation zones, which correspond to areas of the landscape corresponding to relative dissipation, transit and accumulation of water flows, respectively. These quantitative terms are analogous to the qualitative landscape descriptors of crest, slope and depression, respectively. Accumulation zones are those where flow convergence and deceleration of flows occur concurrently. Dissipation zones are defined as areas of the landscape where flow divergence and acceleration of flows occur concurrently. Transit zones are those where neither combination of convergence and deceleration, or divergence and acceleration occur.

At the study site near Miniota, Manitoba, Florinsky et al. (2002) found the concept of accumulation, transit and dissipation zones to be a good predictor of soil properties, including solum thickness and soil moisture. Soil properties increased in variability from dissipation to transit to accumulation zones. This was attributed to the fact that dissipation zones across the landscape receive the most uniform amounts of water input, from precipitation only. Water input is much more variable at accumulation zones across the landscape, because they receive precipitation as well as water contribution from overland and throughflow from areas of varying size. As a result of this pattern in variability,

prediction of solum thickness was most accurate for dissipation zones and least accurate for accumulation zones. The model worked well at predicting soil moisture at a depth of 0.3 m, however its accuracy decreased with depth. This is supported by a decrease in the correlation between topographic variables and depth of soil moisture also found by Florinsky et al. (2002).

2.5 The Soil-Landscape and Hydrology

The influence of the soil-landscape on hydrologic processes has important agronomic and environmental implications. Infiltration and redistribution of water and associated soluble materials are important processes that affect the availability of nutrients and water to plants (Bathke and Cassel 1991; Bathke et al. 1992), as well as entry of soluble materials into surface and subsurface waters.

Soil water redistribution across a landscape depends on the condition and variability of both surface and subsurface features (Bathke and Cassel 1991). Changes in surface slope and slope patterns, landscape position, soil properties, and vegetation type and quality all act to partition water flows through the landscape.

Research linking geomorphology and soil science, in terms of hydrology, have tended to emphasize soil-water physics rather than pedogenesis (Burt and Trudgill 1984). Considering the vital role of water movement in soil profile development, and the deterministic relationship between landscape morphology and soil profile development, a logical link between the two sciences is in exploring the influence of soil profile development, in relation to landscape morphology, on soil water movement.

2.5.1 The Influence of Landscape Morphology on Water Redistribution

Not all surface water infiltrates where it falls. This is an important consideration for soil water studies. Jenny (1941) described the surface topography as one of the major soil forming factors. Its primary function, in this respect, is to redistribute water throughout the landscape. Landscape morphology, or surface form, acts to re-distribute surface water, which influences soil development in a systematic nature along a toposequence.

The soil toposequence, or catena, is a familiar concept in pedology which recognizes the interrelationship between soils developed in different positions on a slope sequence (McCaig 1984), resulting in recognizable soil-slope associations: the association of distinct soil types with a particular hillslope configuration (Pennock and Acton 1989). Pennock and Acton (1989) note that these soil-slope associations occur throughout the landscape because of the influence of landscape morphology on surface and sub-surface water movement.

The relationship between soil distributions and landscape morphology exists, and the catena concept has been well developed. The influence of soil properties on hydrologic processes has been well researched. However, as McCaig (1984) notes, while the importance of soil factors in determining both the occurrence and nature of the predominant processes of hillslope drainage and runoff generation has been widely commented upon, relatively little progress has been made toward linking the results of these processes to observations with the toposequence concept. A limited amount of research has examined the relationship between landscape morphology, pedology and water movement.

Bathke and Cassel (1991) note that changes in surface slope, slope patterns and landscape position influence the partitioning of water flow into vertical and lateral components. These vertical and lateral components act to "shape" the soil by removing materials from certain locations in the landscape and the soil profile and depositing them at other locations in the landscape and soil profile.

Research on the influence of the landscape is often conducted through examination of hydrologic variables at different landscape positions. The topographic position of the soil on a slope and its relation to zones of soil moisture storage and supply can have a great effect on the moisture regime of soils (McCaig 1984). At any point along a slope, a soil's moisture regime is determined by inputs from upslope drainage and infiltration, and losses through leaching and downslope drainage. The nature of the land surface is often complex, and its effect on the moisture regime of a soil is determined by the combination of various topographic parameters, including slope gradient, aspect and surface curvatures. Sinai et al. (1981) found a strong linear correlation between soil surface curvature and moisture content. Relating slope position to soil water regime is difficult in complex landscapes due to the confounding influence of the three-dimensional landscape surface curvature.

Manning et al. (2001b) found soil moisture variability was expressed at a scale more consistent with landscape element complexes (LEC), as described by MacMillan and Pettapiece (1997), than with soil series. They found soil moisture in the top 120 cm of an undulating glacial till landscape in Manitoba followed the general trend of lower < mid < upper over a two-year study, although only the lower LEC emerged as statistically distinct. They caution, however, that one must not neglect to consider genetic soil

character when examining soil hydrologic processes. Of interest, the researchers found the largest differences in soil moisture among LEC and soil series occurred during early season sampling and decreased over the growing season to harvest. They attributed the relatively large early season differences to the influence of the landscape on snow redistribution and runoff following snowmelt, which resulted in an accumulation of water in convergent areas of the landscape. Manning et al. (2001b) suggested that lateral movement of water during the growing season was attenuated by the growing crop.

Groundwater recharge in much of the Northern Great Plains is depression-focused (Lissey 1971; Schuh et al. 1993; Seelig and Richardson 1994). Low annual precipitation and high potential evapotranspiration characteristically allow only limited groundwater recharge from major portions of the landscape. Infiltration to groundwater is minimal at upland positions, primarily due to frozen soil minimizing spring infiltration and lack of snow accumulation. Water redistribution throughout the landscape through surface and sub-surface water flow and snow deposition essentially focuses water inputs to small, closed depressional areas. In recharge environments, this water will flow vertically downward into the groundwater system. Although often limited in areal extent and proportion of the landbase, these depressions serve an important hydrologic function, in that the majority of water entry into groundwater systems in these environments occurs there.

In a study conducted in a low relief (i.e. 0.4 %), coarse-loamy glacial till landscape in North Dakota, Schuh et al. (1993) concluded that conditions most conducive to recharge are those of single or sequences of large precipitation events leading to runoff and large concentrations of water in depressional areas, which can then accumulate sufficient

quantities of water to wet the soil profile beneath the zone of crop removal. They concluded that spatial variability of infiltration and drainage below the rooting zone were attributed to differences in relative surface elevation and surface redistribution of water following storms, rather than to variability of soil hydraulic properties. Schuh et al. (1993) found large sensitivity of site-specific recharge to small differences in relative surface elevation.

2.5.2 The Influence of Soil Properties on Water Movement

Soil properties have a profound influence on subsurface water movement. Soil profile development is a strong determinant of hydrologic processes in the subsurface environment. The hydraulic function of a soil profile is influenced by a variety of factors, including stratigraphy of parent materials (Richardson et al. 1992; Steinward and Fenton 1995), and soil profile morphology (Richardson et al. 1992; Thompson et al. 1998), which in turn is a function of hydrologic processes.

Steinward and Fenton (1995) note that stratigraphy of glacial till and post-glacial sediments can have a profound effect on water movement through the landscape, which is a major factor governing pedogenesis. Soil profile development leads to spatially variable soil hydraulic properties both within a soil profile, as well as across the landscape, due to changes in soil profile characteristics (Bathke et al. 1992; Olson and Cassel 1999). Soil properties such as soil texture and structure, antecedent soil water content distributions, and infiltration rates control the efficiency of leaching and movement of water and associated solutes (Anderson and Buoma 1977; Germann et al. 1984; Bathke et al. 1992). Anderson and Bouma (1977) found differences in flow rates and dispersion which were

closely associated with differences in soil structure for similar textures, suggesting that morphological characteristics can be used as diagnostic tools to indicate physical behaviour.

2.5.2.1 Anisotropy

Soil properties influence the partitioning of water flows into vertical and lateral components. This partitioning of flows is termed anisotropy. A soil is said to be anisotropic when the vertical and lateral flow components are not equal. The anisotropic nature of a soil determines, to a great extent, whether water flow paths will favour vertical downward movement or lateral (i.e. throughflow) movement. Soil anisotropy is important in that it influences the direction of infiltration and subsurface flow.

Anisotropy is generally caused when there is a decrease in hydraulic conductivity with depth in the profile. Decreased hydraulic conductivity is often associated with increased bulk density and decreased porosity (particularly macroporosity) (Zaslavsky and Sinai 1981; Bathke and Cassel 1991), but can also occur due to soil texture and structure. Changes in the ratio of vertical and lateral flow generally occur at physical discontinuity boundaries, such as those existing at the soil surface and pedogenic horizon boundaries (Zaslavsky and Rogowski 1969; Burt and Trudgill 1984; Bathke and Cassel 1991; Bathke et al. 1992). Burt and Trudgill (1984) note that, at a boundary of a physical discontinuity above an impeding layer, build-up of a saturated zone can occur, which is of particular importance since hydraulic conductivity is maximal when soil is saturated.

The direction of unsaturated flow in the soil is highly variable, depending on the degree of anisotropy, as well as the surface slope and its changes (Zaslavsky and Rogowski

1969). Bathke and Cassel (1991) note that, for any sloping landscape, water moving through the soil would have a lateral component by virtue of the slope of the soil surface itself. Zaslavsky and Rogowski (1969) suggest that in any given soil profile, with soil layers parallel to the slope, the combined hydraulic conductivity normal to layers is always less than that parallel to the layers. The practical importance of this is that any sloping and/or layered soil profile is inherently anisotropic in nature.

Zaslavsky and Rogowski (1969) theorize that anisotropy is a major influence in the development of soil profiles. They considered the hypothetical case of a sloped soil that is initially uniform with no profile differentiation. Infiltration of rain, evenly distributed over the entire slope, is initially uniform, isotropic and vertical. As soon as profile development begins, horizonation occurs, and anisotropy appears. The horizonation of the soil profile further accentuates the lateral deflection of vertical water movement (Zaslavsky and Rogowsky 1969; Zaslavsky and Sinai 1981; Bathke and Cassel 1991). Through anisotropy, infiltrated water will begin to flow laterally down slope, redistributing water throughout the landscape. As the slope of the soil surface and anisotropy increase, flow lines approach parallel to the soil surface. Zaslavsky and Rogowski (1969) note that once profile differentiation is initiated, streamlines will tend to diverge on convex landform elements and converge at concave elements.

Anisotropy is not limited to two dimensions. It occurs in three dimensions, and results in three different hydraulic conductivities in three directions Zaslavsky and Rogowski (1969). Water accumulation, as well as soil profile development, is more pronounced where streamlines converge than where they diverge. In other words, areas of divergent flows contribute water to areas of convergent flows.

Bathke and Cassel (1991) undertook a study to examine soil anisotropy as influenced by landscape position in well-drained, clayey soil in a piedmont environment in North Carolina. They examined four landscape positions: interfluve, shoulder, linear slope, and footslope. They found, in general, that soil properties of macroporosity (i.e. total porosity minus the water-filled porosity at the soil water pressure of -6.9 kPa, which represents pore sizes > 40 μ) and coarse-fraction content decreased, while bulk density, and plant available water content increased with profile depth. Clay content was greatest in the B horizons, and then decreased with depth. The researchers used the ratio between vertical hydraulic conductivity (Kv) and lateral hydraulic conductivity (Kh) as a measure of directional water flow in various soil horizons. Ratios of Kv/Kh < 1 favour horizontal flow, while ratios of Kv/Kh > 1 favour vertical flow. Results indicated a preference for horizontal flow at the interfluve and linear landscape positions. The shoulder had strong lateral components in the surface A horizon, while vertical conductivity was favoured in the B and C horizons. The footslope had primarily vertical flow components, which would have developed historically due to vertical gravity drainage with little influence of a sloping surface to promote lateral flow (Bathke and Cassel 1991). They found the lowest Kv/Kh ratio at the transition between A and B horizons at the interfluve landscape position, which was linked to the abrupt change in soil physical properties. As water percolating vertically through the soil encounters these zones of abrupt physical changes, direction of flow is deflected to the horizontal direction. Flow continues downslope along these horizontal planes of flow until it encounters zones dominated by vertical flow paths (Bathke and Cassel 1991). Bathke and Cassel (1991) found macroporosity most strongly correlated with K (both Kv and Kh) values. They note that macroporosity, along with bulk density, K and plant available water are composite properties, in that they are a

result of many individual components of the soil matrix, including sand, clay and coarse fraction contents. Further, Bathke and Cassel (1991) concluded that macroporosity integrated the effects of individual soil components of the soil matrix and aggregated properties to predict the behavioural aspect of the soil, namely hydraulic conductivity. They hypothesized that differences between Kh and Kv were probably due to the pattern in which individual macropores, associated with root channels and structural cracks, were connected in the macropore network. Structural cracking and fissures typically develop, and are relatively undisturbed, in the B horizon. Dominance of vertical cracks should indicate a dominant vertical flux. They concluded that the combination of landscape and soil morphology in this toposequence resulted in dissipation and lateral water flows at the interfluve, shoulder and linear slope positions, and accumulation and vertical water flows at the footslope.

Jabro and Fritton (1990) found that soil hydraulic conductivity measured using the percolation test hole method, decreased with depth through a silty-loam profile. For modeling purposes, they divided the soil into three layers: 1. the surface Ap silt loam horizon (weak, fine to medium granular structure) and Bt1 silty clay loam horizon (weak, fine to medium sub-angular blocky structure), 2. a Bt2 silty clay loam horizon (moderate medium sub-angular structure), and 3. a Bx gravely clay loam fragipan horizon (weak, very coarse prismatic structure). The researchers measured significantly more lateral water movement than downward vertical movement, due to increased permeability of the upper two layers compared to the less permeable restricting fragipan layer below. They noted abrupt discontinuities in soil hydraulic conductivity values at layer interfaces, and

concluded that the layer of lowest conductivity in a layered flow medium is the layer that controls the process of infiltration in the long run.

2.5.2.2 Hydraulic Conductivity

Vadose zone soil hydraulic properties are highly spatially variable in the soil environment and properly assessing properties, such as hydraulic conductivity, infiltration and soil drainage, is difficult (Nielsen et al. 1996; Russo et al. 1997). Nielsen et al. (1996) state that description of infiltration and drainage in unsaturated soils is generally complicated by uncertainties in estimating the hydraulic conductivity relation $K(\theta)$. They note the sources of uncertainty in estimating the hydraulic conductivity function at a particular location in a field include: 1. simplifying the description of the physical processes that are used indirectly to infer the hydraulic conductivity function; and 2. the measurements used to determine the hydraulic conductivity function. The borehole permeameter technique is a convenient method of measuring in situ saturated hydraulic conductivity in the unsaturated zone (Wu et al. 1993). The Guelph permeameter method is a common and versatile approach for measurement using this technique (Jabro and Fritton 1990; Wu et al. 1993; Russo et al. 1997).

Russo et al. (1997) noted that the properties used to estimate hydraulic conductivity vary considerably on a spatial scale, and this limits the practicality of using direct vadose zone measurements. In a study conducted by Russo et al. (1997), 22 of 152 hydraulic conductivity measurements on a finer-textured soil using the Geulph permeameter yielded negative values, and had to be excluded from further analysis. These values were attributed to large-scale heterogeneity, local anisotropy, cracks and biopores, and errors in

measurements; however no trends in these results were determined. Schuh et al. (1993) concluded that Darcian measurement of root-zone drainage as an estimate of recharge would result in a significant overestimation of recharge, where vegetation exists, due to the occurrence of transpiration withdrawal at depth.

In a study conducted examining mechanisms influencing salinity development around prairie sloughs, Stolte et al. (1992) examined a glacial till landscape near Hamiota, Manitoba. The researchers found the subsurface glacial till had a measured saturated permeability of approximately 1 x 10^{-04} m h^{-1}. The 1 m of topsoil had a higher permeability, measured to be approximately 0.02 m h^{-1}, as a result of biopores and desiccation cracks in this layer.

2.5.3 Preferential Flow

Preferential flow is a hydrologic process that can result in significant rapid movement of water through the soil environment. Preferential flow, or as it is alternatively termed macropore, bypass or fracture flow, is attributed to structural pore systems that provide pathways for relatively rapid transport of water and dissolved or suspended constituents through the porous medium (Villholth et al. 1998). A better understanding of the importance of the processes of preferential flow in field soils is needed.

Much research has been conducted on soil water movement in relation to soil properties; however, most research has examined matrix flow alone. Preferential flow is difficult to quantify in field soils and laboratory studies. In undisturbed field soils, the highly variable nature of preferential flow is difficult to measure and quantify, while laboratory studies

pose challenges due to soil disturbance during sampling. McCaig (1984) states that when examining relationships between hydrological processes and soil characteristics it is inappropriate and practically impossible to consider matrix throughflow as a single, isolated process of soil water movement. It is more appropriate to view the matrix and macropore flow mechanisms as an interrelated process (McCaig 1984).

Preferential flow occurs in the macropore component of soil porosity. Flow rates through macropores are much faster than through smaller pores of the soil matrix, which has implications for bulk water and solute flow (Burt and Trudgill 1984). Macropores effectively increase the bulk hydraulic conductivity of a soil layer (Germann and Beven 1981; Burt and Trudgill 1984). McCaig (1984) states that macropores function as pathways for both infiltrating and laterally draining soil water. He also notes that several studies examining movement and leaching of soluble material from clayey soils have concluded that a considerable proportion of the total slope drainage within saturated soils bypasses capillary soil pores leaving areas of near-stagnant water. Interconnected preferential flow paths can lead to significant bypass flow (McCaig, 1984). Villholth et al. (1998) note that these 'express routes', which include worm, root channels and structural fractures, are numerous and ubiquitous in most natural soils and many aquifer materials.

Preferential flow paths transmit water through profiles at rates much higher than through the soil matrix. Burt and Trudgill (1984) note this increase in flow rate effectively increases the scale of hydraulic conductivity, to that applicable to hillslope processes. In other words, water movement via preferential flow paths can be orders of magnitude faster than that through the soil matrix, and can transmit water much greater distances over the same time frame. Burt and Trudgill (1984) also note that the presence of

macropores influence the timing, rate and solute load of hillslope runoff. Hillslope runoff rates increase with macroporosity, however, solute loads do not always follow the same trends.

Germann et al. (1984) found some worm holes, insect burrows, roots (living and dead) were stained to depths of 40 cm, while others were not, after sprinkler-application of 18 cm of dyed water to a silt loam field soil. This demonstrated the importance of connectivity of the macropore network in determining its contribution to overall flow. When bromide profiles were examined, the researchers found infiltration generally occurred through macropores, while some of the macropore flow was partitioned into matrix flow, even within surface soil layers. They hypothesized that the matrix flow may have occurred where macropore channels were disconnected. Germann et al. (1984) suggest that macropore flow is the dominant, and possibly the only, pathway of water and chemical movement into the deeper soil layers in the silt loam soil under the experimental conditions. Generally speaking, they found deeply leached bromide (i.e. > 50 cm) in non-tilled soils to be twice as high as tilled soils.

Villholth et al. (1998) measured significant macropore flow in a silty to sandy loam glacial till soil, as evidenced by rapid responses in the quantity and quality of subsurface effluent at 1.2 m depth following surface application of water and a conservative tracer. There was a relatively small tracer load in the initial macropore flow (i.e. less than 1% of applied tracer), however the similar levels were measured in the macropore flow component at depth over longer time-scales, indicating solute was retained in the macropore flow domain following initial leaching events. They also noted that macropore flow was measured following relatively low and commonly occurring rainfall rates. The

soil matrix significantly influenced the tracer distribution by acting as a source or sink for continuous solute exchange with the macropores (Villholth et al. 1998). Solutes surface applied in granular form are liable to leaching for an extended period of time (Villholth et al. 1998), which is of particular importance to the application of surface applied agricultural chemicals. Rapid, deep leaching of solutes, even in small amounts, over time are of particular importance to contaminants of high biological toxicity. Villholth et al. (1998) noted that applying the Poiseuille equation for gravitational flow in vertical cylindrical tubes appeared to significantly underestimate field-measured macropore flow, indicating it is non-ideal flow.

2.5.4 Shallow Groundwater Flow and the Influence of Water Table on Sub-Surface Hydrology

The interactions between the vadose zone and shallow groundwater systems are important when examining near-surface soil-water processes. Schuh et al. (1993) note that most natural recharge of aquifers occurs through the vadose zone. Vadose zone hydrologic processes, therefore, have a profound influence on shallow groundwater recharge. Alternatively, shallow water tables influence vadose zone hydrologic processes.

Groundwater flow can be a significant component in nutrient cycling in catchments (Hinton et al. 1993). In closed catchments without an integrated drainage network, such as glacial till landscapes of the Great Plains, water and solute transfer between the vadose zone and shallow groundwater are important processes to consider. Of particular importance are the hydrologic regimes of wetland areas. Between recharge and discharge wetlands are transitional wetlands, which are characterized by significant inflow and

outflow of groundwater. Wetlands that have a net inflow of groundwater are called discharge wetlands, while those that have a net outflow of groundwater are called recharge wetlands (Lissey 1971; Hayashi et al. 1998). Prairie discharge wetlands tend to be associated with high-salinity water, while recharge wetlands are associated with low-salinity water (Hayashi et al. 1998). Generally, non-carbonated, non-saline, and leached soils occur in recharge areas, while carbonated and saline soils occur in discharge areas (Miller et al. 1985). Miller et al. (1985) note that it is possible to predict the hydrologic characteristics of a soil from its landscape position, morphology and classification.

Schuh et al. (1993) examined drainage fluxes in the vadose zone as influenced by the water table in a nearly level coarse-loamy glacial till field. They measured net negative drainage fluxes at a depth of 1.06 m following periods of high precipitation, indicative of upward flux of water from capillary rise into the vadose zone. This response was attributed to a rising water table and crop water use in the lower root zone. During periods of low precipitation, drainage fluxes at the same sites were positive, as the water table receded.

Shallow water tables are responsive to water recharge through the vadose zone, and tend to correspond to surface topography. Shallow water tables are generally parallel to the topographic surface in fine-textured landscapes (Richardson et al. 1992; Hinton et al. 1993; Seelig and Richardson 1994; Steinward and Fenton 1995; Thompson et al. 1998). Thompson et al. (1998) note that, although these water tables correspond with surface topography, they tend to be deeper in the upper slope positions, particularly during drier periods.

Low annual precipitation and high potential evaporation precludes groundwater recharge from occurring over much of the landscape in the Great Plains region (Seelig and Richardson 1994). However, in these often complex landscapes, water redistribution may result in certain portions of the landscape contributing significantly to groundwater recharge. In these irregular, glacial till landscapes, redistribution of precipitation as both rain and snow results in an accumulation of water in depressions, often resulting in groundwater recharge in these areas of the landscape (Mills and Zwarich 1986; Seelig and Richardson 1994). Although groundwater recharge does not occur in the majority of these landscapes, depression-focused recharge causes significant recharge in portions of the landscape of limited areal extent.

Groundwater mounds often form in depressional areas in landscapes in the Northern Great Plains during spring melt or heavy rainfall events (Lissey 1971; Mills and Zwarich 1986; Seelig and Richardson 1994), as a result of depression-focused recharge. In a hummocky glacial till landscape in Saskatchewan, infiltration of runoff water in upland depressions was found to be the dominant factor influencing the distribution of soluble salts, and lateral groundwater flow was not a major redistribution process (St. Arnaud 1979; Miller et al. 1985). However, Seelig and Richardson (1994) note that, following recharge events in low-lying depressions, groundwater flows laterally from depressional areas to adjacent positions upslope, facilitating a rise in water tables at these positions. Following spring recharge, summer evapotranspiration is strongly differential among the landform positions and causes the configuration of the water table to change. Greater evaporative loss from the wetland position than from the other positions cause the water table under the upland position to be higher than that of the wetland position in late

summer and fall, resulting in a groundwater depression. When this occurs, Seelig and Richardson (1994) note that lateral subsurface flow is reversed toward the wetland in response to the change in water table configuration, but state that lateral groundwater flow reversals are not always observed in the field.

Much research has examined groundwater flow direction (Whipkey and Kirkby 1978; Richardson et al. 1992; Steinward and Fenton 1995), as influenced by such factors as surface topography and stratigraphy. Richardson et al. (1992) examined water flow in landscapes of various soils, parent materials and climates in the Great Plains, and demonstrated that the overall flow of shallow subsurface water was lateral in all examined landscapes. Whipkey and Kirkby (1978) state that flow is dominantly lateral in finer textured soils, where resistance to vertical movement is greater. In a low-relief undulating glacial till landscape, Steinward and Fenton (1995) found that the predominant groundwater flow was laterally from topographic highs to adjacent swales, and suggested this was largely a result of stratigraphy of the parent material. They found the water table paralleled the surface topography during wet periods, however, did not during periods of low water levels, suggesting that throughflow occurs in parts of some topographic lows but not others. Hinton et al. (1993) note that surface topography is generally assumed to indicate the horizontal direction of local groundwater flow.

Many studies have concluded that most groundwater flow in glacial till occurs in fractured portions of the till, while the deeper, unoxidized, unfractured till is relatively inactive with respect to water movement (Steinward and Fenton 1995). Steinward and Fenton (1995) note that this is attributed to the fact that hyrdaulically interconnected fractures in till effectively result in elevated bulk permeability, which can be one to three

orders of magnitude higher relative to unfractured till. This is an important consideration in terms of the contribution of shallow groundwater flow to overall flow in these systems.

2.5.5 Soil Morphological Indicators of Hydrologic Processes

Soil profile morphology is the result of many, complex pedogenic processes. These include physical, chemical and biological processes. The Soil Classification Working Group (1998) states that soil properties vary with depth, and are determined by climatic factors and organisms, as conditioned by relief, and, hence, water regime, acting on geological materials and producing genetic horizons that differ from parent material. The hydrologic regime, therefore, has a profound influence on soil profile development. It follows that examination of soil profile characteristics can provide insight into the hydrologic conditions under which a given soil profile developed. Through examination of soil properties, pedologists can use soil profile morphology as an indicator of hydrologic processes acting on a particular soil profile. Steinward and Fenton (1995) note that soil morphology is often used as a surrogate for expensive monitoring programs to infer long-term wetness conditions and hydrology in the presence of a shallow water table. Soil profile indicators which have been used to infer hydrologic regime have included mottled colour patterns, matrix colours in the solum, clay content of illuvial horizons (Simonson and Boersma 1972), solum thickness, horizonation, depth to carbonates, and soluble salt concentrations.

Soil profile horizonation often results from water movement through the soil profile. The character, distribution and thickness of soil horizons can be used to make inferences regarding hydrologic regime. For example, the presence of eluvial and illuvial horizons

are indicative of water movement translocating soil material from one portion of the profile to another. Eluvial horizons are indicative of eluviation; the process of removal of soil material in suspension or in solution within the solum by the downward or lateral movement of water (Gregorich et al. 2002). Illuvial horizons are indicative of the process of illuviation; the process of deposition of soil material, including silicate clays, aluminum and iron oxides, and organic matter, removed from one portion of the profile to another (Gregorich et al. 2002). The presence, thickness and strength of these horizons in a profile provide an indication of the nature and importance of the hydrologic regime of that soil.

Chemical composition of the soil can also be used to indicate the nature and intensity of the hydrologic regime. The distribution of solutes and soluble material in the soil profile are often used in this capacity. Nielsen et al. (1996) note that soil water movement plays a dominant role in the transport of solutes over both short and long distances. McCaig (1984) puts this concept into a pedological context and states that well-drained and saturated soils experience completely different physicochemical conditions and these in turn encourage either the mobilization or precipitation of ions within the developing profile. During soil profile development, soluble salts and carbonates, initially present at relatively uniform levels in a given parent material, are often translocated throughout the profile as a result of hydrologic processes. The level of, and depth to, soluble salts and/or carbonates in a soil profile, provide an indication of the direction and intensity of water movement in the profile. McCaig (1984) notes that the solute concentration in slope drainage water is controlled by a number of closely interrelated factors in addition to flow volume and the soil's physicochemical state. The process of chemical removal, by

eluviation, from a soil profile requires two basic soil conditions: 1) chemical ions within the soil must be in a mobile state, and 2) there must be an effective vertical or lateral mechanism for the removal of mobilized ions from the soil (McCaig 1984). McCaig (1984) notes that both the frequency and extent of eluviation within the soil have long been recognized as being closely correlated with slope drainage conditions. During soil profile development, soluble salts, which have higher solubilities than calcium- and magnesium-carbonates, will be translocated prior to carbonates. Matzek (1955) consistently found peak soluble salt concentrations at depths in the profile slightly below that of carbonates for loamy Chernozemic soils in North Dakota. The absence of soluble salts and carbonates in a profile, developed on parent material that initially had them, indicate a stronger leaching environment than if both constituents, or carbonates alone, remain in the profile.

Soil colour is one morphological variable used for describing pedologic processes and is often used as an indicator of water regime. Pickering and Veneman (1984) note that the characteristic brown colours of well-drained soils are indicative of higher Fe content and more uniform distribution when compared with wetter soils whose Fe compounds are more unstable and mobile due to reducing conditions.

Gleying in soils has been used as a criterion of drainage conditions in soil studies and soil classification (McCaig 1984; Soil Classification Working Group 1998). McCaig (1984) notes that it has been suggested that, in general, recognizable gleying occurs at and below soil depths that experience saturation by drainage water for approximately two months of the year. On irregular slopes, gleying will be most strongly developed within hollows,

where saturation occurs owing to the convergence of subsurface flow and surface runoff from up slope. (McCaig 1984).

Soil mottling, or the formation of spots of different colour or shades of colour interspersed with the dominant colour in the soil matrix, can be used as an indicator of hydrologic regime, and its characterization in the soil profile is often used to infer soil drainage conditions. The absence, presence, and the nature of mottles have become a key morphological feature for the inference of soil drainage conditions as it is often impractical to measure the soil moisture regime directly through long-term monitoring (Pickering and Veneman 1984). The degree of mottling developed in a soil horizon is dependent upon the length of time for which saturated conditions exist in that horizon. Occurrence of mottling has often been associated with depth to water table (Guthrie and Hajek 1979; Daniels et al. 1971; Pickering and Veneman 1984). Simonson and Boersma (1972) correlated faint and distinct mottling with the presence of the water table and noted a consistent increase in the size and abundance of Fe and Mn concretions with poorer drainage conditions. Richardson and Hole (1979) found maximum Fe concretions occurred in somewhat poorly drained soils with alternating oxidizing and reducing conditions, but fewer concretions in very poorly drained soils on similar landscapes and parent materials. Schwertmann and Fanning (1976) concluded further that optimal concretion formation occurred in soils with rapid changes in aeration and concordant fluctuations of redox potential. Increasing soil moisture contents limit diffusion of O_2 through the soil, and compounds containing Fe and Mn become reduced (Pickering and Veneman 1984). These reduced compounds are more mobile and can contribute to the formation of mottles or concretions under oxidized conditions of drying cycles.

Studies often use combinations of soil morphological indicators to make inferences on the hydrologic regime within a soil profile and across a landscape. Using colour, Seelig and Richardson (1994) found that the materials of the high-chroma (or strength) zone have a consistent pattern of lower salt content than the materials in the low-chroma zone. Pickering and Veneman (1984) examined soil morphology of a hydro-sequence, and found an evenly distributed brown colour with mottling in the sola of the well drained soils, prominent mottling related to the mostly moist but intermittently saturated conditions of the moderately well drained soils, and gleyed soil colours and low chroma mottles in somewhat and very poorly drained soils. They concluded that soil morphology, in general, appeared to be a good indicator of saturated conditions in the soils examined.

In a study to relate soil colour patterns to water table fluctuations, Steinward and Fenton (1995) found that soil morphology overestimated the length of saturation for moderately well drained to somewhat well drained, poorly drained and very poorly drained soils, compared to well drained soils. Soil horizons with redoximorphic characteristics in well drained soils were saturated for longer periods than horizons in more poorly drained soils that exhibited stronger gleyed morphology.

Soil morphology provides indicators of the hydrologic regime under which soils have developed. These indicators offer an inexpensive tool that can provide insight into the hydrologic processes occurring within a soil profile.

2.6 Soil Water Tracer Studies

Soil water tracer studies allow for better understanding of hydrologic processes occurring in soils. In hydrologic studies, Davis et al. (1980) state that a tracer is matter or energy carried by water which will give information concerning the direction and/or velocity. They note that the first known use of a water tracer was almost 2000 years ago, when Philip, the tetrarch of Trachonitis, used chaff to determine that water from a crater lake flowed down-gradient to a spring at the headwaters of the Jordan River.

A soil water tracer study consists of applying a tracer to the soil, in granular form or as a solution, at known rates, then measuring the tracer as it moves through the soil environment. Laboratory tracer studies are often conducted, and provide valuable information on soil hydraulic properties. However, Afyuni et al. (1994) note that common field observations indicate that significant variability exists in both the depth of solute movement and its concentration. This spatial and temporal variability of processes in natural soil environments, limits the application of laboratory results to field soils. Many researchers have acknowledged that laboratory tracer studies should be augmented with field-scale solute tracer experiments if the intent is to predict solute transport behaviour at the field scale (van Wesenbeeck and Kachanoski 1994).

An effective soil water tracer consists of a soluble material that moves at the same velocity as water, and is not reactive in the soil environment. Bowman (1984a) noted that an effective soil water tracer should: i. not be significantly sorbed or otherwise retarded by the soil of interest; ii. be exotic to the soil environment, or should be present at naturally low concentrations; and iii. be conservative in that it is not significantly

degraded chemically or biologically during the course of the experiment (Bowman 1984a). Bowman (1984a) also noted that other considerations in selecting a tracer includes ease of quantitation in a soil solution matrix, and the potential for adverse environmental impacts, particularly when conducting field studies.

2.6.1 The Bromide Tracer

The bromide ion (Br^-) as been used extensively in field studies as a tracer for water and solute movement through the soil profile. Bowman (1984a) stated that, of the common tracers used in soil water studies, Br^- is the most generally suitable. Bromide has been chosen as a tracer for three reasons: i. its background concentration is low in most soils; ii. it can easily be analyzed; and iii. it is non-reactive in the soil environment (Davis et al. 1980; Kung 1990). It is also a low-cost alternative to many other soil water tracers. Davis et al. (1980) added that Br^- is typically found in natural waters at concentrations less than one percent of chloride (Cl^-).

Although Br^- is generally considered a conservative tracer, its negative charge lends itself to some level of reactivity in the soil environment. There are two main soil processes to consider when examining the reactivity of bromide in the soil: 1. anion adsorption and iron oxide complexation; and 2. anion repulsion. Anion adsorption and iron oxide complexation are processes in which a charged ion is adsorbed on exchange sites or complexes with an iron oxide molecule, resulting in decreased solubility and mobility in the soil environment. Anion repulsion is a process in which an ion is repulsed by the soil exchange. Several researchers have examined and commented on these processes in terms of the utility of Br^- as a soil water tracer (Smith and Davis 1974; Thomas and Phillips

1979; Davis et al. 1980; Hammermeister et al. 1982; Jaynes et al. 1988; Schwertmann and Taylor 1989; Jury et al. 1991; Bathke et al. 1992).

The surface charge of iron oxides (Fe-oxides) in the soil is strongly pH dependent. At high pH (i.e. excess OH^-), Fe-oxides have a negative surface charge, which will be balanced by the adsorption of cations (Schwertmann and Taylor 1989). Conversely, at low pH (i.e. excess H^+), Fe-oxides have a positive surface charge, which will be balanced by the adsorption of anions (Schwertmann and Taylor 1989), such as Br^-.

Bathke et al. (1992) stated that anion sorption could retard Br^- movement. Bellini et al. (1996) reported that anion (NO_3^-) retention increases as pH decreases. They estimated a retardation factor of 1.5 to 2 in a clay loam soil with pH ranging between 5 and 6.

These phenomena have obvious implications for the use of charged ionic species as tracer elements in the soil environment, however they are not a concern in calcareous soils, with pH values > 7.0.

Anions can also move through the soil faster than one would predict on the basis of soil water movement (Smith and Davis 1974), because as anions move through the soil they often associate with only part of the total soil water. Smith and Davis (1974) state that this is due to electrical repulsion preventing the association of the anions with water near negatively charged soil surface. The influence of anion repulsion on tracer movement has been demonstrated in field studies, as solutes often travel faster than indicated by the theoretical solute front because of limited mixing with, or bypassing of, a large fraction of the soil water (Jaynes et al. 1988). Further to this, researchers have noted that bypass flow activity can occur regardless of whether macropore flow paths extend to the soil surface

(Thomas and Phillips 1979; Hammermeister et al. 1982; Bathke et al. 1992). It has been estimated that anion exclusion can account for an increase of 10-15% in anion tracer velocities (James and Rubin 1986; Rice et al. 1986; Bathke et al. 1992).

Brooks et al. (1998) conducted a column displacement experiment to examine the reactive transport of Br^- through columns packed with Fe-coated quartz sand at different pH levels. Bromide transport through the Fe-coated sand at pH 7.8 was more rapid than through the uncoated quartz sand at pH 6.5. The researchers hypothesized this is due to anion exclusion occurring at pH 7.8, due to a net negative surface charge of the ferrihydrite. A linear relationship between the retardation factor and pH was found. The implication of the retardation of Br^- transport through ferrihydrite-coated quartz sand at different pH levels is apparent. Brooks et al. (1998) caution the interpretation of solute movement results when using Br^- as a tracer in environments where pH is not at the zero point charge of the predominant oxide mineralogy, or where variably charged surfaces are present. They conclude that if one assumes the Br^- tracer is non-reactive, there exists the opportunity for many errors when estimating solute transport.

Bathke et al. (1992) conducted a study examining bromide movement at different landscape positions, and related these differences to soil properties and geomorphology. They concluded that, in addition to other soil properties, the combination of lower clay content and Fe levels resulted in deeper Br^- transport at the two headslope positions. They reasoned that this was likely due to less complexation between Br^- and Fe-oxides in the areas of the landscape with lower Fe levels, resulting in lower retardation of Br^- movement.

Bromide is readily analyzed by several methods, including ion selective electrode (Abdalla and Lear 1975; Onken et al. 1975; Orion Research 1982; Bowman 1984a), and high pressure liquid chromatography (Pyen and Erdmann 1983; Stetzenbach and Thompson 1983; Bowman 1984a; Bowman 1984b). However, Bowman (1984a) noted that there are a variety of interferences, such as the presence of other ions, which affect the utility of the first method.

2.6.2 Bromide Tracer Studies

Predicting solute transport in field soils is complex; however, soil properties are somewhat predictable in the landscape (Olson and Cassel 1999). The recognizable systematic variability of soil properties with landscape position is expected to cause differences in anion transport (Afyuni et al. 1994; Olson and Cassel 1999).

Vertical and lateral Br^- transport is highly variable on a landscape, and observable differences can be measured at different landscape positions (Afyuni et al. 1994). Afyuni et al. (1994) found the greatest lateral movement of Br^- tracer at the footslope and linear slope positions, in response to slope and decreases in hydraulic conductivity with depth. The least lateral movement was noted at the interfluve position, where the slope gradient was small and abrupt changes in soil properties in the profile were not present. Some lateral movement did occur at this position, however, indicating that lateral transport process should not be ignored at level or nearly level landscape positions. Greater vertical movement was found at the footslope position than at the linear slope and interfluve positions, as a result of lower clay contents and higher saturated hydraulic conductivities in footslope soil profiles, as well as of contribution of water from upslope positions

In a study on sandy clay loam soil in a Piedmont landscape, Bathke et al. (1992) found that changes in soil hydraulic properties across the landscape affected the shape of the descending Br^- plume. Greatest lateral Br^- movement was found at an upland headslope landscape position, at an abrupt boundary between B horizons. A decrease in macroporosity and increase in clay content was noted at this boundary, resulting in a zone of water accumulation within the soil profile. Saturated throughflow along this boundary of physical discontinuity likely accounted for much of the lateral flow at this position. At a similar headslope position, characterized by a more homogeneous soil profile, lateral flow was not as important (Bathke et al. 1992). Van Wesenbeeck and Kachanoski (1994) found similar results and noted significant lateral movement of Cl tracer along the less permeable Bt horizon separating the B and C horizon. The researchers concluded that where porosity changed minimally and/or more gradually in the soil profile, vertical water and solute movement dominated.

Bruce et al. (1985) found bromide transport through a sandy clay loam soil was faster in drainageway positions than on linear slopes, due to higher hydraulic conductivity and lower clay content in Bt horizons in the drainageway. Olson and Cassel (1999) found a similar relationship with Br^- movement and clay content. They noted that increases in clay content may be expected to retard Br^- leaching due to the following associated soil properties: 1. increased specific surface area of iron- and magnesium-rich soil particles with increased potential anion exchange reactions; 2. increased tortuosity within the soil matrix; and 3. higher soil water contents, and therefore, more water to displace for matrix flow.

accumulating at this position. Although some patterns existed, the researchers observed large spatial variation in Br^- concentration profiles within and among landscape positions, which increased the difficulty of quantifying and modeling solute transport under natural field conditions.

Olson and Cassel (1999) found significantly deeper leaching of Br^- in the footslope than at the linear and shoulder slope positions in a clay loam Piedmont soil. The depth to which 50 % of measured Br^- leached (Q50) was 31, 25 and 28 cm for the footslopes, linear slopes and shoulder slopes, respectively, following 11.5 cm of effective precipitation (precipitation minus evapotranspiration). Following 41.4 cm of effective precipitation, Q50's were 82, 71 and 66 cm for footslopes, linear slopes and shoulder slopes, respectively. They concluded that footslopes were more susceptible to leaching losses than linear and shoulder slopes in this soil-landscape. Sampling depths were 90 and 200 cm following 11.5 and 41.4 cm of effective precipitation, respectively. Mean percent Br^- recoveries were determined to be 78 and 75 % following 11.5 and 41.4 cm of effective precipitation, respectively, indicating that some Br^- may have leached to depths below that sampled (Olson and Cassel 1999). The Br^- that was not accounted for may have been due to deep leaching via rapid, preferential flow. Within-plot variability was found to be almost three times greater than variability among landscape plots or among positions, making determination of landscape effects difficult. Olson and Cassel (1990) concluded that the high within-plot variability was due to inherent variability of soil properties, however, the researchers noted that non-uniformity in application may have contributed.

A study conducted by Schulin et al. (1987) examining field-scale Br^- and Cl solute movement in a stony soil indicated strong variations in flow velocities. Roth et al. (1994) showed that Cl^- tracer applied to soil partitioned into a slow moving pulse and a series of rapid pulses. This irregular movement resulted in some tracer reaching much greater depths than predicted by transport models. This is in agreement with other researchers, who have commented that solute applied uniformly to the soil surface may be partitioned into several different pulses of varying velocity (Roth et al. 1991; Afyuni et al. 1994).

Gupte et al. (1996) noted preferential flow of bromide tracer in a conventionally tilled sandy loam soil, which commenced in the Bt1 horizon. They did not find evidence of preferential flow in A or transitional AB horizons. The zone where preferential flow commenced corresponded to the area of the profile where the cross-sectional area coloured with a dye tracer decreased sharply, indicating reduced matrix flow below this point. It was concluded that preferential flow often occurred in regions of soil and in-filled macropores, rather than open macropores. Bronswijk et al. (1995) found the maximum mean Br^- concentration was located at a depth of 55 cm in a clay soil following only 34 mm of net natural precipitation, and concluded that preferential flow was a significant process in the rapid leaching of the solute in this soil.

2.6.3 Bromide Movement vs. Nitrate Movement in the Soil Environment

Nitrate leaching in agricultural fields is an important concern due to environmental impacts through entry into groundwater, economic losses of valuable fertilizer resources, and agronomic losses associated with reduced crop yields. Nitrate enters agricultural soil systems through inorganic nitrogen fertilizer application, organic manure application and

nitrogen transformations in the soil environment. Nitrate is very soluble in water, and is not influenced by soil colloid interactions (Havlin et al. 1999). Due to its high solubility in water and non-reactivity in the soil environment, nitrate is easily transported by water through the soil profile.

Measuring the movement of nitrate through agricultural soils poses challenges due to the presence of nitrate in the soil environment, transformations of nitrogen compounds in the soil, and economic costs associated with using labeled nitrogen compounds. The use of a soluble tracer, such as bromide, allows researchers to study, more easily, the movement of soil water and soluble materials through agricultural field soils. Results from these studies can then be applied to other applicable soluble materials, such as nitrate. An improved understanding of the movement of water and soluble materials through agricultural soils as influenced by landscape morphology will provide insight into how to better manage soluble nutrients, such as nitrate, on agricultural land.

Results from Br^- tracer studies are often extended to processes of NO_3^- movement in the soil environment, but how well does Br^- mimic nitrate in the soil environment? Bowman (1984a) noted that NO_3^- is subject to an array of chemical and biological transformations, such as denitrification (i.e. gaseous losses) and immobilization (i.e. conversion from inorganic to organic form), in the soil environment under both aerobic and anaerobic conditions, which can affect the performance of a conservative tracer in tracing NO_3^-.

Smith and Davis (1974) found that movement of Br^- was not identical to NO_3^- in a range of surface and subsurface soils. For surface soils, movement was quite similar for silty loam and fine sandy loam soils, however for the other soils NO_3^- tended to lag behind that

of Br^-. It was concluded that the lagging of NO_3^- was due to NO_3^- loss, through immobilization and/or denitrification. In one case, the researchers concluded that NO_3^- production must have occurred, through N mineralization, as the NO_3^- curve preceded that of bromide. For subsoils, Smith and Davis (1974) found essentially identical rates of movement between Br^- and NO_3^- for all soils examined. They concluded that microbial activity influences the utility of Br^- as a tracer for NO_3^- in surface soils, however in subsurface soils its performance is very good.

Bromide is not without biological influences within the soil environment, and can be taken up by plant roots. Bromide is absorbed readily by roots of several crop species, including corn, sorghum, potato, and alfalfa (Magarian et al. 1998). Magarian et al. (1998) note that Br^- uptake has generally been found to be related to that of NO_3^- in corn and sorghum, and can serve as an analog for NO_3^- over a wide concentration range. Plant uptake of Br^- is an important consideration in field tracers studies conducted under crop production.

3. LONG-TERM SOLUTE REDISTRIBUTION IN RELATION TO LANDSCAPE MORPHOLOGY AND SOIL DISTRIBUTION IN A VARIABLE GLACIAL TILL LANDSCAPE

3.1 Introduction

Recharge of aquifers and entry of water and associated soluble materials into shallow groundwater sources occurs through the vadose (i.e. unsaturated) zone. Transport through the vadose zone, therefore, is a primary environmental pathway controlling the fate of a variety of potential groundwater contaminants (Dyck et al. 2003). Although water and solute fluxes below the root zone are small in semi-arid environments, with estimates typically in the range <10 mm yr^{-1} (Dyck et al. 2003), once beyond the reach of crop roots the movement of potential soluble contaminants generally occurs unimpeded to shallow groundwater sources present.

The movement of water and soluble materials is determined, in part, by soil profile attributes. It is well known that these soil properties can be highly variable on both spatial and temporal scales. Spatial and temporal variability of soil properties with depth in the profile and across landscape positions result in diverse patterns of water and solute distribution in the landscape (Bathke et al. 1992; Afyuni et al. 1994). There has been much research conducted to assess the variability of soil properties on both spatial and temporal scales. This research has examined both static soil properties (those that are relatively stable over time), and dynamic soil properties (those that are more variable on a temporal scale).

The relationship between soil distribution and landscape morphology has long been recognized by researchers (Jenny 1941, 1961; Hugget 1975; McCaig 1984). The catena concept, introduced by Milne in 1936 and often referred to as the soil toposequence, is based on the recognition of the interrelationship between soils developed in different positions along a slope (Hugget 1975). Moore et al. (1993) state that, in many landscapes, catenary soil development occurs in response to the way water moves through and over the landscape as subsurface and overland flow, respectively.

Recognizing this, many researchers have examined the relationship between topographic variables and soil properties. The control of topography over soil properties can largely be explained by topographical influence on patterns of water movement and distribution (Pennock et al. 1987). For example, Zaslavsky and Rogowski (1969) state that infiltration streamlines governing water movement into soil diverge on convex slope elements and converge on concave ones. This topographical control is commonly assessed by examination of measures of slope morphology that determine overland and intrasoil flow velocity (gradient - *G*), direction (aspect - *A*), convergence (horizontal curvature - *Kh*) and acceleration (vertical curvature - *Kv*), as well as by relative position in the field (relative elevation - *RE*, catchment area - *CA* and topographic index - *TI*) (Florinsky et al. 2002).

Previous research conducted on the field site of the current study (SE32-14-25W) has demonstrated the relationship between topography and soils in this hummocky, glacial till landscape. Florinsky et al. (2002) found correlation between topographic variables and soil properties. They determined correlations for soil moisture with *Kh*, *Kv*, *CA* and *TI* and positive correlations for solum depth and depth to carbonate with *Kv* and *TI*.

However, the strength of these relationships decreased with depth in the rooting zone and they concluded the decreased topographic control over soil properties with depth resulted in a shallow "effective soil layer" for predictive purposes. As well, they found temporal variability of the dynamic soil properties changed the relationships over time.

Manning (1999) found trends for topographic variables and soil properties by landscape element complexes (LECs), as defined by MacMillan and Pettapiece (1997a,b) and also determined significance in relationships between topographic variables and soil properties. He determined that static soil properties (A horizon depth, solum depth, soil organic carbon and depth to carbonates) and dynamic soil properties (water content and nutrients), within the rooting zone, increased with convergent character, and generally increased from upper to mid to lower slopes. He concluded that the concept of LECs provided a practical means of capturing gross variability in temporally stable soil attributes. In terms of dynamic properties, while LECs captured some systematic variability in moisture and nutrients, the practical significance of differences between LECs were often overshadowed by other factors, including temporal variability, fertilization practices and variation in growing season precipitation. Manning (1999) also noted the importance of variations in pedogenic processes and hydrologic regimes acting within LECs.

The ability to delineate areas of the landscape with similar patterns of water and associated solute redistribution would allow for the development of land management tools and strategies aimed at the scale of these processes, and would better allow land managers to protect sensitive environmental resources. The purpose of this study was to characterize the redistribution of solutes and the magnitude of indicators of pedogenic and

hydrologic processes across a glacial till landscape as it relates to soil profile distributions and landscape morphology. It was intended to examine the processes of long-term solute redistribution acting at the practical scale of recognizable soil-slope associations. To achieve this, patterns of deep solute redistribution were examined at locations along a transect selected to represent soil-slope associations of interest.

3.2 Materials and Methods

3.2.1 Site Description

The study site occurs in the Newdale Plain physiographic sub-section, which is characterized by undulating to hummocky topography on ground moraine with numerous potholes, sloughs and small, intermittent lakes (Podolsky 1988). The dominantly loam to clay loam textured soils were developed on glacial till consisting of a heterogeneous mixture of boulders, cobbles, gravel, sand, silt and clay, derived from shale, limestone and granitic fragments. The complex topography precludes a developed surface drainage network, with variable surface drainage that ranges from excessive runoff on steeper slopes to prolonged inundation in depressional areas (Podolsky 1988). Removal of water from small catchment areas is generally through evapotranspiration and shallow groundwater flow.

Detailed soil information (1:5 000) for the study site indicates it is a typical recharge area in the region, where infiltration and leaching are dominant processes acting on the soil-landscape (Fitzmaurice et al. 1999). Soils of the study site are those of the Newdale Association, and are dominated by the well-drained Orthic Black Chernozem (O.BL) of

the Newdale (NDL) series (Figure 3.1, Fitzmaurice et al. 1999), which occurs in mid to upper slopes. Other soils encountered in the study include the well to rapidly drained Calcareous Black Chernozem (CA.BL) of the Cordova (CVA) series (not indicated in Figure 3.1), located in upper to crest slope positions, the imperfectly drained Gleyed Rego Black Chernozem (GLR.BL) of the Varcoe (VRC) series, located in lower slope positions, the imperfectly drained Gleyed Eluviated Black Chernozem (GLE.BL) of the Angusville (ANL) series, located in lower to mid slope positions, and the poorly drained Orthic Humic Gleysol (OHU.GL) of the Hamiota (HMI) series, located in depressional areas. Soils indicated in Figure 3.1, but not encountered in the study, include the poorly drained Humic Luvic Gleysol (HU.LGL) of the Penrith series and the poorly to very poorly drained Rego Humic Gleysol (R.HGL) of the Drokan series, both of which are found in depressional positions of the landscape. Detailed descriptions of the soil series of the study site are found in Appendix I, while soil profile terminology is defined in Appendx III.

In a previous study, conducted in a similar glacial till landscape near Hamiota, Manitoba, Stolte et al. (1992) found the saturated permeability of the till parent material to be approximately 1×10^{-04} m h^{-1}. They noted the 1 m of topsoil had a higher permeability, measured to be approximately 0.02 m h^{-1}, and attributed the higher rate to biopores and desiccation cracks in this layer.

Climate data from one of the closest Environment Canada weather stations, in Virden, Manitoba, indicate the study site near Miniota, Manitoba has a mean annual temperature of 2.5°C and a mean annual frost free period of 120 days (Fitzmaurice et al. 1999). The

climatic data indicate mean annual precipitation is approximately 460 mm, of which 298 mm occurs during the growing season (i.e. May 1 to September 30).

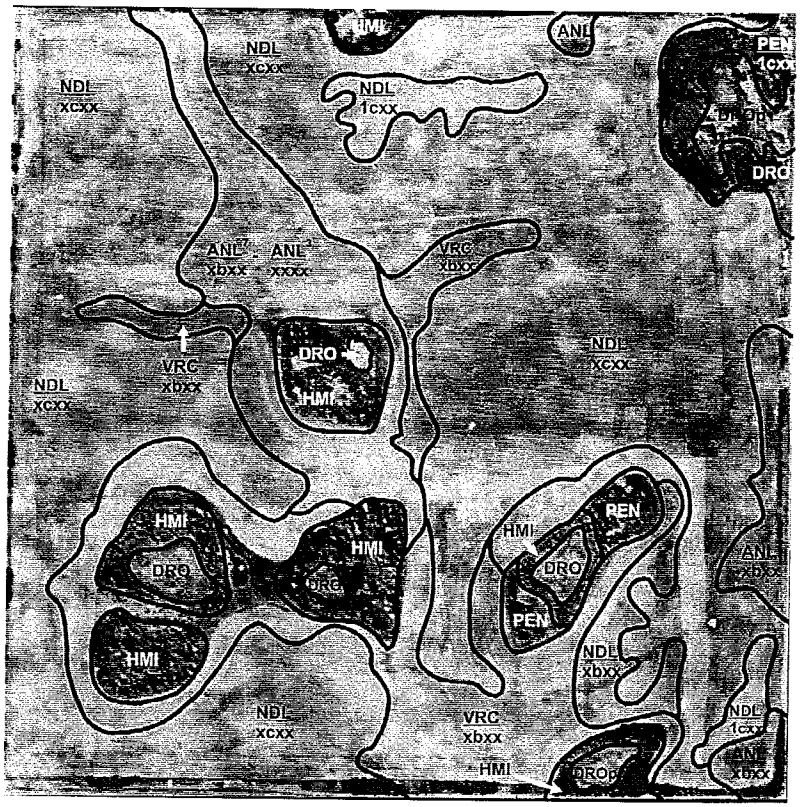


Figure 3.1 Detailed soil series map (1:5 000 scale) of the field site SE32-14-25W.

The study field has been under continuous annual crop production since 1976, and has been under zero tillage management since 1988 (Ron Bell, personal communication).

3.2.2 Transect Establishment and Soil Sampling

A transect was established in the study field to allow for the examination of solute redistribution and other indicators of hydrologic and pedogenic processes occurring along a catena representative of the glacial till landscape. The location of the transect was selected based on an initial qualitative interpretation of the landscape morphology and an examination of existing detailed soil survey information. Following groundtruthing

activities to confirm soil distribution at select qualitative geomorphic positions along the transect, 7 sample locations (i.e. DS1 to DS7) were selected to examine representative soil-slope complexes:

- Calcareous Black (CA.BL) at Crest positions (DS1 & DS6);
- Orthic Black (O.BL) at Mid-slope positions (DS2 & DS5);
- Gleyed Rego Black (GLR.BL) and Gleyed Black (GL.BL) at Lower-toe positions (DS3 & DS7, respectively); and
- Orthic Humic Gleysol (O.HG) at the Depression position (DS4).

Relative sample locations along the transect are shown in Figure 3.2.

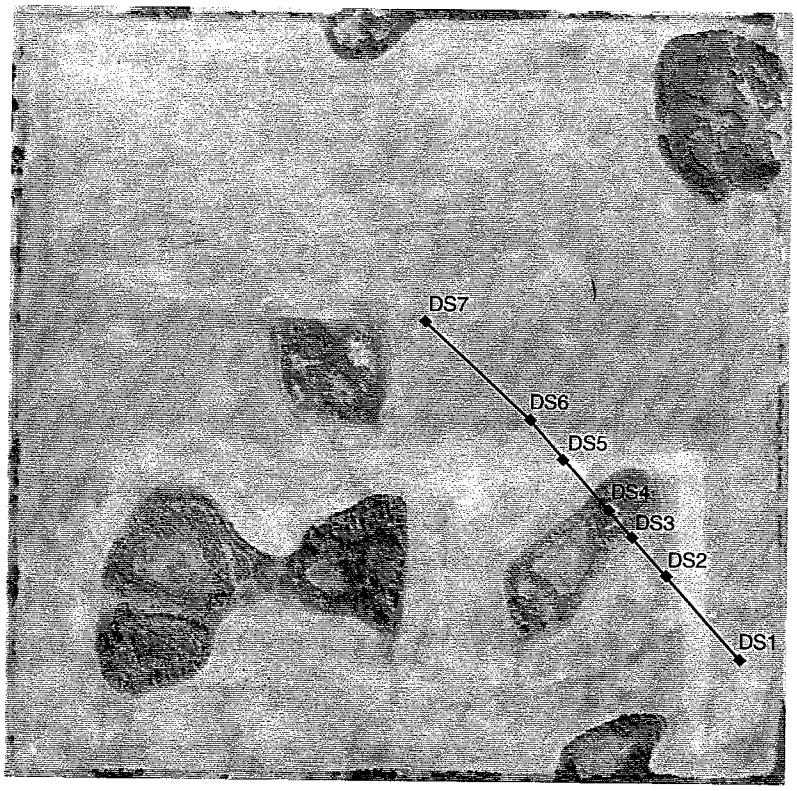


Figure 2.2 Aerial photo of the field site with the transect location and sample positions.

Deep soil samples were extracted using a truck-mounted hydraulic sampling device on December 13, 1999. Bulk soil samples were taken using a 10 cm diameter solid-stem auger. It was attempted to take samples to a depth of 600 cm at all sample locations, however, this depth was not achieved due to the nature of the stony glacial till at depth and limitations of the sampling device. Samples were taken in 30 cm increments to depths ranging from 300 cm to 540 cm (Table 3.1). A total of 7 locations x various depths = 102 soil samples were taken. Samples were sealed in sample bags, placed in a cooler on ice and returned to the laboratory where they were frozen until analyses were conducted.

Table 3.1 Detailed sample location descriptions.

Sample Location	Easting	Northing	Elevation	Depth Sampled	Total No. of Samples
	m			cm	
DS1	367893	5565532	511.7	510	17
DS2	367818	5565617	510.5	510	17
DS3	367784	5565660	508.8	390	13
DS4	367760	5565687	508.2	540	18
DS5	367712	5565740	509.6	300	10
DS6	367678	5565780	511.1	510	17
DS7	367569	5565885	511.7	330	10

Samples were oven-dried at 105°C for 48 hours to determine gravimetric moisture content (Topp 1993), were ground with a mortar and pestle, and were passed through a 2 mm sieve to remove remaining clods and stones. Sub-samples of 10.0 g (+/- 0.1 g) of oven-dried soil were placed into 50 mL plastic centrifuge tubes with 30 mL dH_2O (+/- 0.1 mL), shaken mechanically for 30 min on a flat-bed shaker, vortexed to remove suspended soil from tube sides, and solution-filtered using pre-rinsed Whatman #42 filter paper into 20 mL scintillation vials (United States Environmental Protection Agency (USEPA) 1994; American Public Health Association (APHA) 1998). Vials were capped,

refrigerated and stored until analysis. Samples were analyzed for chloride (Cl^-), nitrate (NO_3^-) and sulfate (SO_4^{2-}) using a Dionex Liquid Chromatography system with a conductivity detector (Eluant: 1.7mM $NaHCO_3$, 1.8mM Na_2CO_3 50mM H_2SO_4; sample loop: 100 µL; flow: 2.0 mL min^{-1}; column: Dionex AG4A and AS4A). Residual nitrate-nitrogen (NO_3^--N) concentrations were determined by multiplying concentrations obtained for each sample by the depth increment over which the sample was considered representative. Detailed analytical results are found in Appendix IV.

Electrical conductivity, as a measure of soluble salts, and 1:2 pH in water values were determined on all bulk soil samples using the fixed-ratio extract method (Hendershot et al. 1993; Janzen 1993).

Intact soil cores were taken at transect sample locations on June 2, 2000, using a Gidding's trailer-mounted hydraulic soil exploration device. An intact core could not be taken at sample location DS4 due to excessive wetness in the depressional area. The cores were taken in 3.7 cm diameter polyethylene sleeves to a maximum depth of 120 cm, sealed and returned to the laboratory for analysis. Detailed soil profile descriptions were conducted on the intact cores in a manner consistent with the guidelines established by the Expert Committee on Soil Survey (1983) and the Soil Classification Working Group (1998). At location DS4, the soil profile description was conducted using a soil pit and hand auger. Bulk soil samples were taken at this position for laboratory examination. Indicators of pedogenic and hydrologic processes include the A horizon depth (the depth of all A horizons), the solum depth (depth of A & B horizons combined), depth to carbonates (indicated by presence of effervescence upon addition of dilute HCl), and the profile development index (PDI) (Fuller, personal communication, AXYS Environmental

Consulting Ltd.). The PDI provides a relative measure of the degree of soil profile development between landscape positions (Manning 1999). The PDI is based on depths of B horizon development relative to solum depth. In calculating the PDI, B horizons are given relative weightings of 0, 1, 2 3 and 4 for no B horizon, Bmk, Bm, Btj and Bt, respectively. The PDI calculation is as follows:

$$PDI = \sum (\text{B horizon depths} \times \text{relative weights}) / (\text{solum depth}) \quad [2.1]$$

Intact soil cores were divided into horizon increments and were oven-dried at 105°C for 48 hours to determine gravimetric moisture content. Bulk density values were measured using the core method, modified from Culley (1993), however, results did not appear to be accurate and were not considered further.

Organic carbon analysis was conducted on Ap/Ah horizon soils from each sample location. Inorganic carbon was removed prior to organic carbon measurement by adding 10 ml of 6M HCl in distilled water to soil and heating the soil slurry on a hot plate for 10 minutes (Tiessen et al. 1983). Samples were rinsed with 240 ml of distilled water to remove inorganic ions present. Soil organic carbon was determined by dry combustion of 0.12 g of oven-dried soil with a LECO 2000 CNS determinator (Nelson and Sommers 1982).

3.2.3 Topographical Survey and Data Analysis

Sample locations along the transect were geo-referenced (UTM coordinates) using a differentially-corrected Trimble Global Positioning System (GPS) (Table 3.1).

A topographic survey was conducted on the study field, by Manning (1999), on a 10 m grid using a kinematic Trimble 4600LS GPS. From the elevation data collected on the irregular grid, a regular digital elevation model (DEM) was generated as described by Florinsky et al. (1995). The surface elevation and contour map for the field site, with sample positions superimposed, is found in Figure 3.3. The DEM was used to generate digital terrain models (DTMs) for various topographic parameters, including relative elevation (*E*), relative relief (*RR*), gradient (*G*), aspect (*A*), specific catchment area (*CA*) and topographic index (*TI*), using algorithms presented by Florinsky et al. (2002), and profile (*Kv*) and plan (*Kh*) curvature, using algorithms described by MacMillan and Pettapiece (1997a,b, 2000) and Eyton (1991). Definitions and interpretations of topographic descriptors are found in Table 3.2. Visual maps were produced for all DTMs using Surfer (Golden Software Inc. 1997) surface mapping software (Figure 3.4). Interpolation was conducted using the Kriging method in Surfer (Golden Software Inc. 1997).

Relative elevation and relative relief provide an indication of the general drainage characteristic of a given location of the landscape. Each of the other topographic variables examined provides a measure of a specific gravity-driven process or mechanism (Florinsky et al. 2002). Slope gradient provides a measure of relative flow velocity while aspect indicates flow direction. Plan (i.e. horizontal) curvature (*Kh*) provides an indication of the convergent or divergent character of the land surface. Convergent character ($Kh < 0$) indicates a focus of surface and intrasoil lateral flows towards a point in the landscape, while divergent character ($Kh > 0$) indicates flow away from a point in the landscape. Generally, convergent character results in more water available for

infiltration into the soil profile, while the opposite holds true for areas of divergent character. Profile (i.e. vertical) curvature (*Kv*) values provide a measure of the relative acceleration/deceleration of surface and intrasoil lateral flows. Flow accelerates when $Kv > 0$ and decelerates when $Kv < 0$. Flow convergence and deceleration at a given point in the landscape result in accumulation of substance flows (Florinsky et al. 2002).

Specific catchment area (*CA*) is a location parameter, and provides a measure of the area of the landscape potentially contributing surface and intrasoil lateral water flow to a given point in the landscape. It can provide a stronger indicator of soil moisture than curvatures, as it takes into account location in the landscape (Florinsky et al. 2002). Florinsky et al. (2002) state the topographic index (*TI*) describes a ratio of specific catchment area to gradient and offers further improvement as a predictor of soil moisture, as it accounts for location (*CA*) and local slope geometry (*G*). It provides an indication of the extent of flow accumulation at a given point in the landscape.

Landform segmentation was conducted using the Landform Description Program from Landmapper Environmental Solutions (MacMillan and Pettapiece 2000) and the landscape was delineated into four discrete segments:

- Upper (UPS) – generally water shedding and in upper landform positions;
- Mid-slope (MID) – generally water neutral and in mid-slope landform positions;
- Lower (LOW) – generally water receiving and in lower landform positions; and
- Depression (DEP) – generally undrained areas with ephemeral or permanent water accumulations.

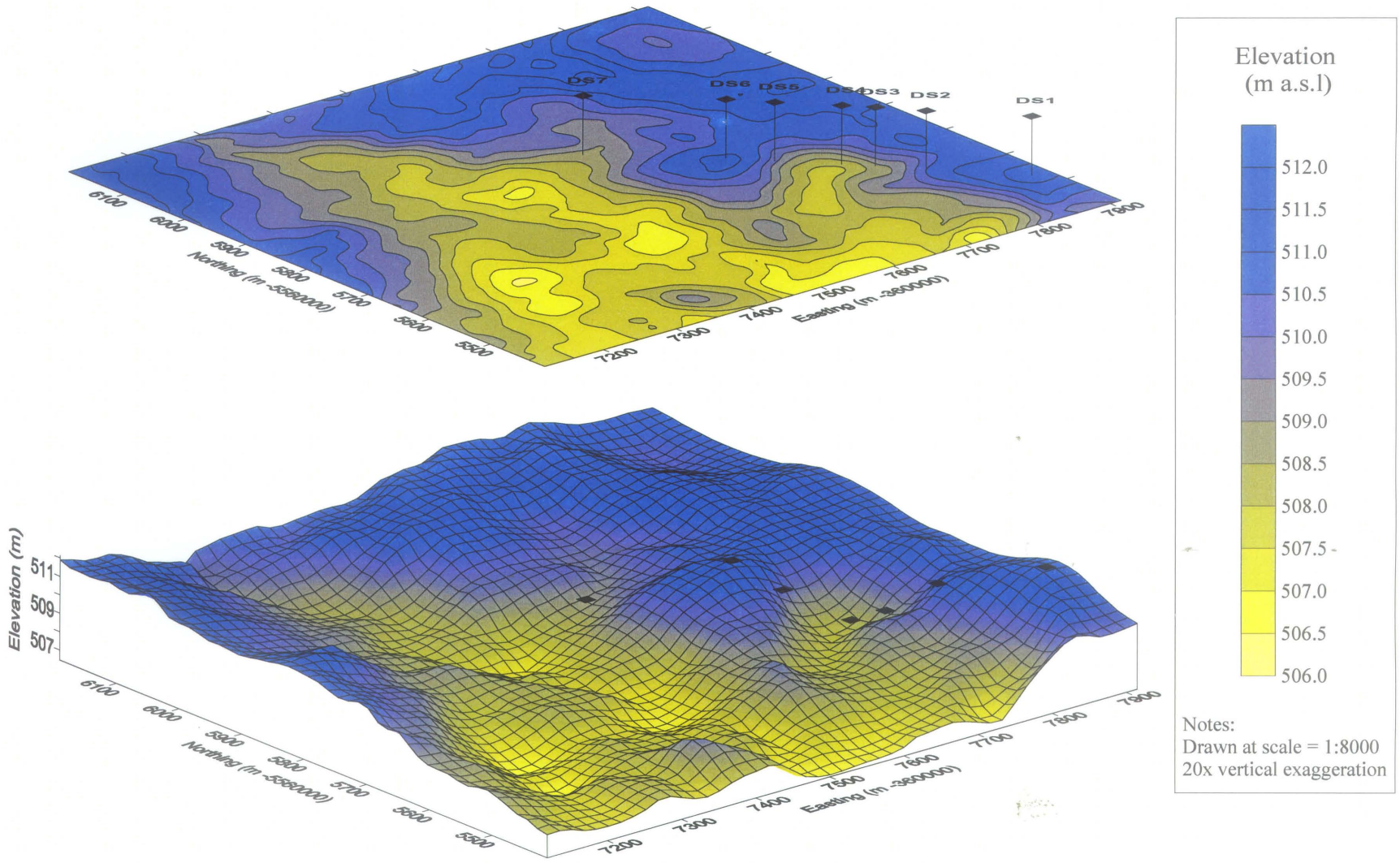


Figure 3.3 Topographic surface and contour map of the field site with sample positions.

Table 3.2 Definitions and interpretations of topographic variables (MacMillan and Pettapiece 1997a,b; Eyton 1991; Florinsky et al. 2002).

Topographic Variable	Definition	Interpretation
E (m)	The relative elevation above the lowest point in the landscape.	Indication of landscape drainage characteristic.
RR (%)	The ratio of the difference in elevation between a given point in the landscape and the lowest point in the landscape to the difference in elevations between the highest and lowest points in the watershed.	Indication of landscape drainage characteristic.
G (°)	The angle between a tangent plane and a horizontal one at a given point in the landscape.	Measure of flow velocity.
A (°)	An angle clockwise from north to a projection of a normal vector to a horizontal plane at a given point in the landscape.	Direction of flow; controls relative insolation and evapotranspiration.
Kv (° $100m^{-1}$)	The rate of change in gradient in degrees per 100 meter.	Measure of acceleration/ deceleration of flows.
Kh (° $100m^{-1}$)	The rate of change of aspect along a contour line in degrees per 100 meter, where aspect is the azimuthal bearing of gradient.	Measure of convergence/ divergence of flows.
CA (m^2m^{-1})	The ratio of an area formed by a contour intercept and upslope flow lines connected with the ends of the contour intercept to the length of the contour intercept.	Measure of the upslope area contributing moisture.
TI	The Napierian logarithm of specific catchment area to gradient ratio.	Extent of flow accumulation.

Using this approach, the study field was found to be dominated by MID (52 %), with significant inclusions of UPS (24 %) and LOW (20 %), and a minor portion classified as DEP (4 %). Landform segments determined using this quantitative approach were not found to be in full agreement with the geomorphic positions determined on a qualitative basis. For instance, no portions of the landscape dissected by the transect were considered Depression (DEP) segments.

3.2.4 Statistical Procedures

The validity of parametric statistical procedures depends on certain assumptions, such as normality of data distribution. When these assumptions are not met, as is often the case in landscape-based studies of soil properties, nonparametric procedures are used. The validity of these procedures does not depend on rigid population assumptions. The nonparametric statistical procedures utilized in this study are based on ranks of observations, rather than absolute values. Kendall's Coefficient of Concordance of rank sums, as described by Daniel (1990), was used to examine the strength of the agreement between sample positions and LECs in terms of indicators of hydrologic processes and solute redistribution parameters. When differences were found between sample positions, a multiple comparison procedure described by Daniel (1990) was used to determine differences between sample positions at an experiment-wise significance level of $\alpha = 0.20$. This experiment-wise significance level is generally acceptable using non-parametric procedures. Kendall's coefficient of concordance and the multiple comparison procedures were calculated by hand.

Spearman rank correlation coefficients were determined to examine the relationship between topographic variables, pedologic attributes, and solute redistribution parameters (Daniel 1990). Spearman rank correlations were determined using JMPIN (SAS Institute Inc. 2000) statistical analysis software at $\alpha = 0.05$.

3.3 Results and Discussion

3.3.1 Landscape Properties

There was a total of 3.5 m of relief between the highest (DS1) and lowest (DS4) sample positions on the transect (Table 3.3; Figure 3.4). Relative relief, considering elevation data collected along the transect only, was found to be highest at DS1 & DS6 and lowest at DS3, DS4 & DS7. General drainage characteristics of the landscape along the transect would occur from areas of high to low relative relief.

Table 3.3 Topographic variables at each sample location.

Sample Location	Relative Elevation[1]	Relative Relief[1]	Gradient	Curvature		Catchment Area	Topographic Index
				Profile	Plan		
	– m –	– % –	– ° –	– ° 100m^{-1} –		– m^{2}m^{-1} –	
DS1	3.5	100.0	2.0	2.6	1.0	14.5	8.7
DS2	2.3	65.2	1.9	7.1	6.0	22.9	9.3
DS3	0.6	17.4	1.6	-2.2	-3.0	145.6	10.6
DS4	0.0	0.0	1.3	-4.2	-5.9	350.6	11.9
DS5	1.5	41.5	2.5	-0.4	2.0	40.2	9.7
DS6	2.9	82.7	0.5	2.9	4.1	14.1	10.2
DS7	0.6	16.4	1.0	-4.8	-4.2	1010.3	11.5

[1] Relative elevation and relief determined using the lowest point sampled along the transect.

Slope gradients were all 2.5 ° or less (Table 3.3; Figure 3.4), and were therefore considered very gently sloping to nearly level. The highest slope gradients were found at DS1, DS2 & DS5, while the lowest gradients were found at DS4, DS6 & DS7. The relatively small slope gradients found along the transect would not suggest rapid surface flow velocities. However, relative flow velocities would be lower at lower-toe positions along the transect relative to mid-slopes. Infiltration rates would be expected to be higher at lower-toe relative to mid-slope positions.

Positive profile (*Kv*) and plan (*Kh*) curvature values were found at DS1, DS2 & DS6, indicating divergent character at these positions in the landscape (Table 3.3; Figure 3.4). Negative *Kv* and *Kh* values were found at DS3, DS4 & DS7, indicating convergent character at these positions along the transect. Slope curvature values are determining local factors of the dynamics of overland and intrasoil water flow (Florinsky et al. 2002). Surface and intrasoil lateral water flows would be expected to diverge and accelerate at positions of the landscape represented by DS1, DS2 & DS6, and converge and decelerate at positions of the landscape represented by DS3, DS4 & DS7. Sample position DS5 was found to have a nearly level (but slightly negative) *Kv* and positive *Kh*. It follows that there would be more water available for hydrologic processes of solute redistribution at DS3, DS4 & DS7, relative to DS1, DS2 & DS6. Florinsky et al. (2002) found soil moisture had higher correlations to *Kv* than *Kh* and concluded that deceleration was the main mechanism determining accumulation in this landscape.

The lowest catchment area (*CA)* values were found at DS1 & DS6, while the highest values were found at DS3, DS4 & DS7 (Table 3.3; Figure 3.4). Based on positive correlations between soil moisture and *CA* found by Florinsky et al. (2002), these would indicate relatively high surface and intrasoil lateral moisture contribution to the lower and depressional positions of the landscape relative to the mid to crest positions. It is interesting to note that although positions DS4 & DS7 were considered depression and lower-toe landscape positions, respectively, on a qualitative basis, DS7 had a much larger associated *CA* value. Sample position DS4 is located on the periphery of the main body of the depressional area, located orthogonal to the transect in a southwest direction (Figure 3.2). The main body of the depression has much higher associated *CA* values. This would

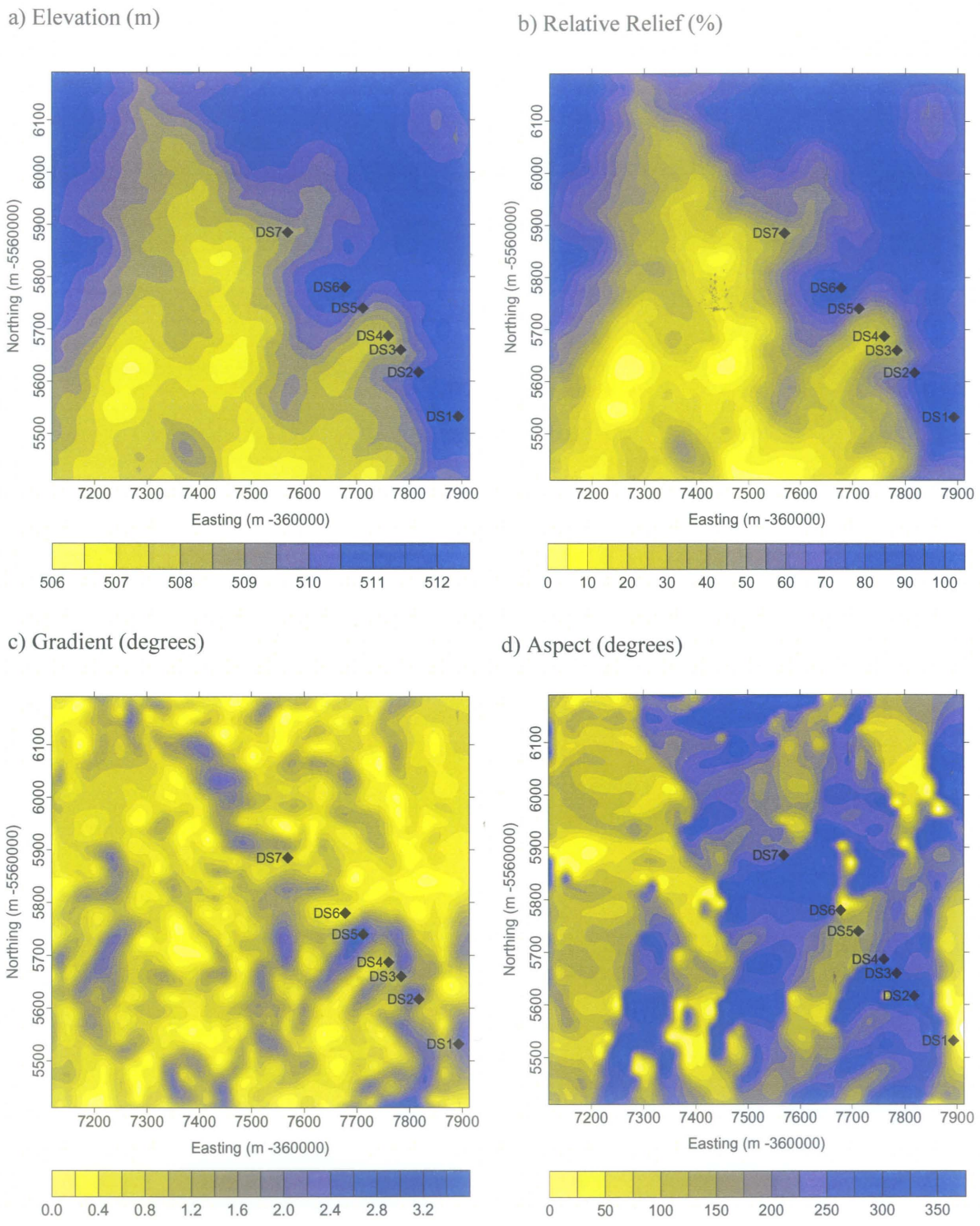
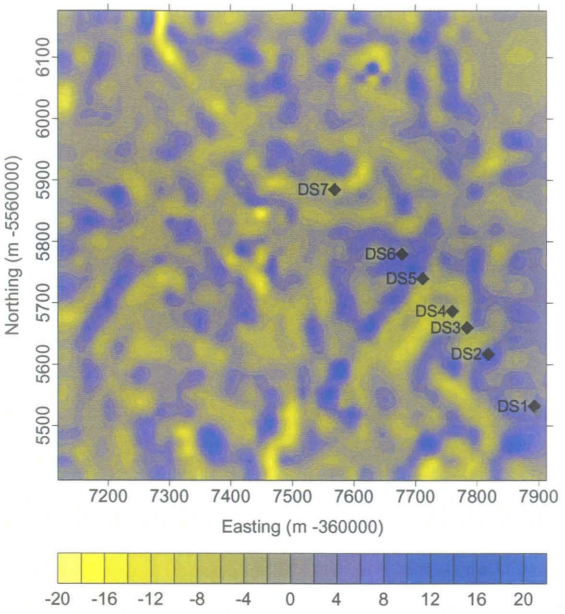
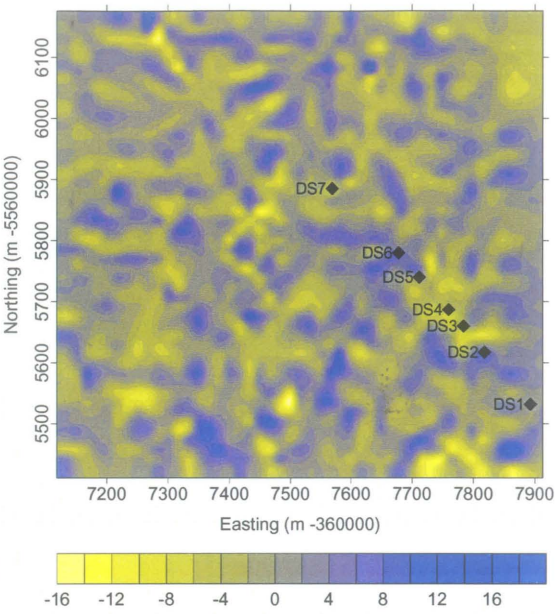


Figure 3.4 Digital terrain models of the field site with sample positions.

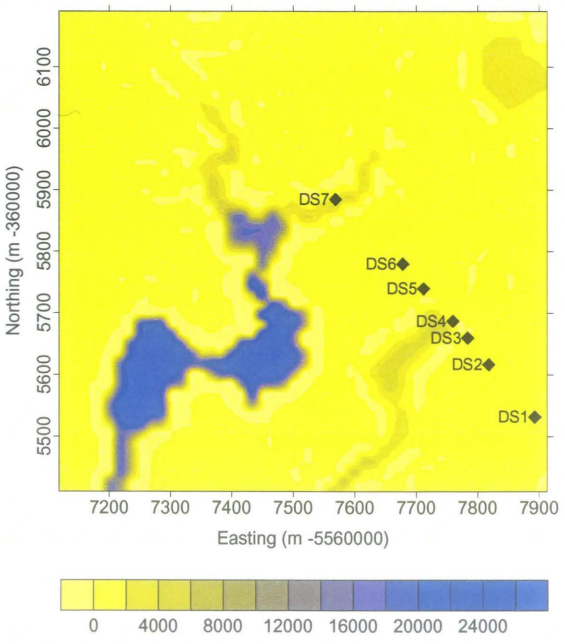
e) Profile Curvature (degrees/100m)



f) Plan Curvature (degrees/100m)



g) Specific Catchment Area (m2/m)



h) Topographic Index

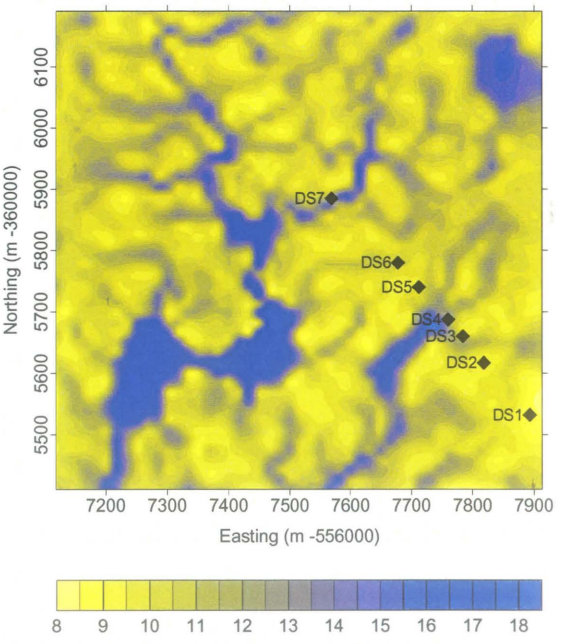


Figure 3.4 continued…

suggest that, although DS4 is an area receiving significant surface and intrasoil water flow from upslope contributing areas, it is acting as a contributing area to the main body of the depression.

The highest topographic index (*TI*) values were found at DS4 & DS7, while the lowest values were found at DS1, DS2 & DS5 (Table 3.3; Figure 3.4). This would indicate a greater extent of flow accumulation at lower to depressional positions relative to mid to crest positions. Florinsky et al. (2002) found higher correlations to *TI* than *CA* for soil moisture values, and concluded that accounting for local slope geometry and landscape location offered further improvement for soil moisture prediction.

3.3.2 Pedologic Attributes

3.3.2.1 Soil Profile Morphology.

A variable degree of soil profile development was found along the transect. Sample positions along the transect were selected based on an initial qualitative interpretation of the landscape morphology in relation to soil distribution. Soil classification at sample positions along the transect was found to be in general agreement with that previously mapped for the field site by Fitzmaurice et al. (1999) (Figure 3.1). However, there were some differences noted due to the nature of the scale of the soil survey. Detailed soil profile descriptions are found in Appendix I.

Crest positions DS1 & DS6 had relatively poor soil development, and were classified as Calcareous Black Chernozems (CA.BL) of the Cordova (CVA) series, with characteristic calcareous B horizons (Bmk) (Table 3.4). These positions had the shallowest depth to carbonate (CO_3) (13 cm) along the transect. Depth to CO_3 is often used as a measure of

the hydrologic regime acting on a soil profile, as it provides an indication of the strength of net downward water flux of water through the soil profile. Divergent areas of the landscape with little upslope contributing areas, such as these crest positions, tend to have shallow depth to CO_3, as little water is available for infiltration and percolation through the soil profile.

Table 3.4 Indicators of pedologic and hydrologic condition at each sample location.

Sample Location	Landscape Position	Soil Subgroup	Soil Series	A Hor Thickness	Solum Thickness	Depth CO_3	PDI	Org C
				cm				- % -
DS1	Crest	CA.BL	CVA	13	18	13	2.00	1.74
DS2	Mid	O.BL	NDL	13	32	26	2.41	1.54
DS3	Lower-Toe	GLR.BL	VRC	31	69	38	0.90	2.54
DS4	Depression	O.HG	HMI	20	40	75	2.50	4.37
DS5	Mid	O.BL	NDL	14	46	46	2.94	2.50
DS6	Crest	CA.BL	CVA	13	19	13	2.00	2.14
DS7	Lower-Toe	GL.BL	ANL	16	48	48	3.10	2.29

Mid-slope positions DS2 & DS5 had relatively good development, and were classified as Orthic Black Chernozems (O.BL) of the Newdale (NDL) series, with well-developed Bm horizons free of carbonates. Depths to CO_3 at DS2 & DS5 were found to be 26 and 46 cm, respectively. This would indicate stronger net downward water movement at DS5, relative to DS2. Topographic indicators support this finding, as DS5 had larger *CA* and *TI* values than DS2 and had a negative Kv value, which would result in more water available for, and conditions more favourable for, infiltration at this position.

Lower-toe slope positions had variable development, with DS3 classified as a Gleyed Rego Black Chernozem (GLR.BL) of the Varcoe (VRC) series, and DS7 a Gleyed Black Chernozem (GL.BL), most closely resembling the Angusville (ANL) series. Sample

position DS7 did not have a distinguishable Ae horizon, however it had a well developed Bt horizon, with visible clay skins on ped faces, indicative of the importance of pervection (i.e. clay translocation) at this landscape position. The Ae may have been lost due to mixing with other surface horizons as a result of tillage disturbance over time. The profile at position DS3 did not have a B horizon. Both of these soil profiles demonstrated impacts from a near-surface water table for a significant portion of the growing season, as evidenced by faint to distinct mottling within 50 cm of the soil surface. The soil profile morphology at the lower-toe positions indicated that regressive development has occurred at DS3, due to the impact of a relatively static near-surface water table preventing strong net downward water movement. Conversely, at DS7, although the water table is high at certain times of the year, the water table dynamics have promoted net downward water movement. Depths to CO_3 at the lower-toe positions DS3 & DS7 were found to be 38 and 48 cm, respectively. Convergent areas of the landscape, such as these, with contributing upslope areas (i.e. where flow accumulation occurs), tend to have relatively high amounts of surface and intrasoil water available for leaching materials through a soil profile. Where subsurface conditions permit (i.e. permeable soil with sufficiently low water table) strong leaching occurs at these portions of the landscape.

The depression position DS4 was classified as an Orthic Humic Gleysol (O.HG) of the Hamiota (HMI) series, and is located in the portion of the landscape, dissected by the transect, most influenced by the water table. The O.HG soil profile is a leached profile, but not highly eluviated, and is characteristic of throughflow areas of the landscape (Fuller, personal communication, AXYS Environmental Consulting Ltd.). However, the greatest depth to CO_3 along the transect was found at DS4 (75 cm), indicating removal of

carbonates from much of the soil profile. This data indicated strong water movement through the profile at this location in the landscape, however the soil profile morphology suggest this flow has been dominantly lateral in nature. This supports the conclusion drawn based on topographic indicators that suggest location DS4 is a contributing area to the main body of the depressional area, located orthogonal to the transect in a southwest direction.

The soil profiles at the crest positions DS1 & DS6 had the smallest A horizon and solum depths (Table 3.4). The crest positions rely on moisture input from precipitation only, and can lose moisture through runoff, and therefore have the lowest moisture contribution in the landscape. In this semi-arid region, moisture is a limiting factor in terms of vegetation growth, and, therefore, crest positions tend to have lower organic matter accumulation relative to other positions in the landscape. Further, erosional processes, including those driven by tillage, water and wind, tend to be relatively high at upper-crest positions, and, therefore, soil and associated organic matter losses are greater at these locations of the landscape. Conversely, higher moisture inputs to lower-depressional positions of the landscape, from direct rainfall input plus run-on from upslope contributing areas, result in higher rates of vegetative growth and organic matter input. Further, these positions receive eroded soil and associated organic material from upslope areas of the landscape. The lower-toe and depressional positions along the transect had the greatest A horizon depths and relatively thick solums. Of the mid-slope positions, DS5 had a greater A horizon depth and solum thickness than DS2, indicating relatively higher organic matter accumulation and translocation at the former position. Organic C tended to be highest at lower-toe to depression positions and lowest at mid to crest positions (Table 3.4).

The profile development index (PDI) values ranged from 0.90 to 3.11. The PDI was found to be relatively low at the crest positions DS1 & DS6 (Table 3.4), with a value of 2.00. Values at the midslope positions DS2 & DS5 were found to be of 2.41 and 2.94, respectively, and indicated a greater degree of profile development at the latter location. The lowest PDI was found at DS3 (0.90). Although DS3 had the greatest solum thickness, the Ah/AC/Ck soil profile at this location scored relatively poorly in terms of PDI due to the lack of a B horizon. This supported the conclusion that regressive development has occurred at this position along the transect. On the other hand, the well developed Ah/Bt/Ck soil profile found at DS7 had a relatively high PDI value (3.10), and indicated strongly progressive development at this location in the landscape. The depression position DS4 had an intermediate PDI value (2.50). Although this location of the landscape has convergent character and a large upslope contributing area, the intermediate PDI value indicated that it is not an area of the landscape with strongly progressive development. From this examination, it appears that the PDI may be of limited utility as a measure of hydrologic processes of solute redistribution. However, in conjunction with other parameters, it may provide an indication of the nature of those processes, in terms of the fate of soluble materials across the landscape.

3.3.2.2 pH

pH values ranged from 6.6 to 8.8 over all samples, with a median value of 8.3. All sample positions had relatively similarly shaped pH depth profiles, however, absolute values and depths of profile inflection points differed between positions. Relatively low pH values were found at the surface at all sample positions (Figure 3.5), as a result of removal of bases via leaching from the upper portion of the soil profile, as well as organic acid

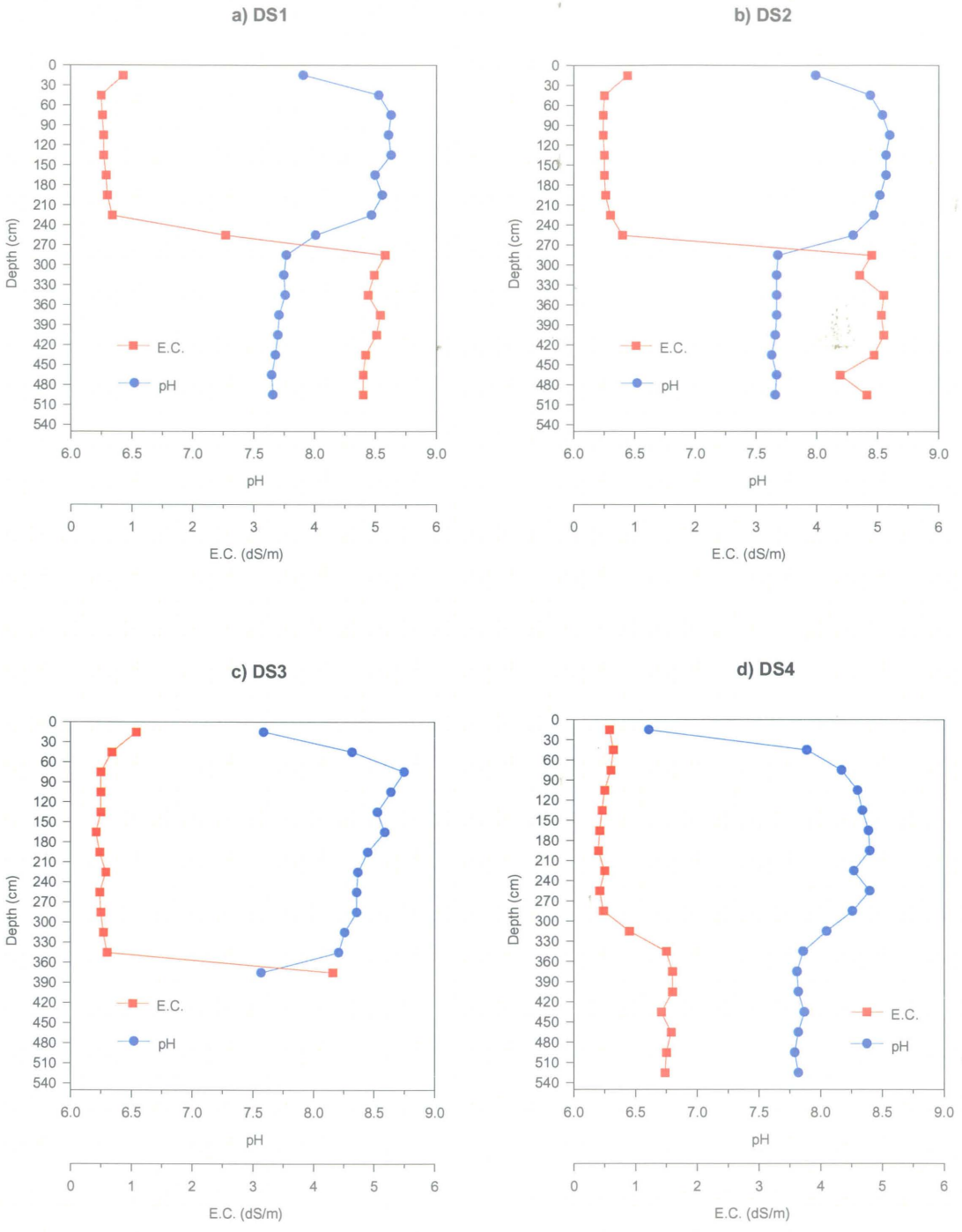


Figure 3.5 pH and electrical conductivity depth profiles at each sample position.

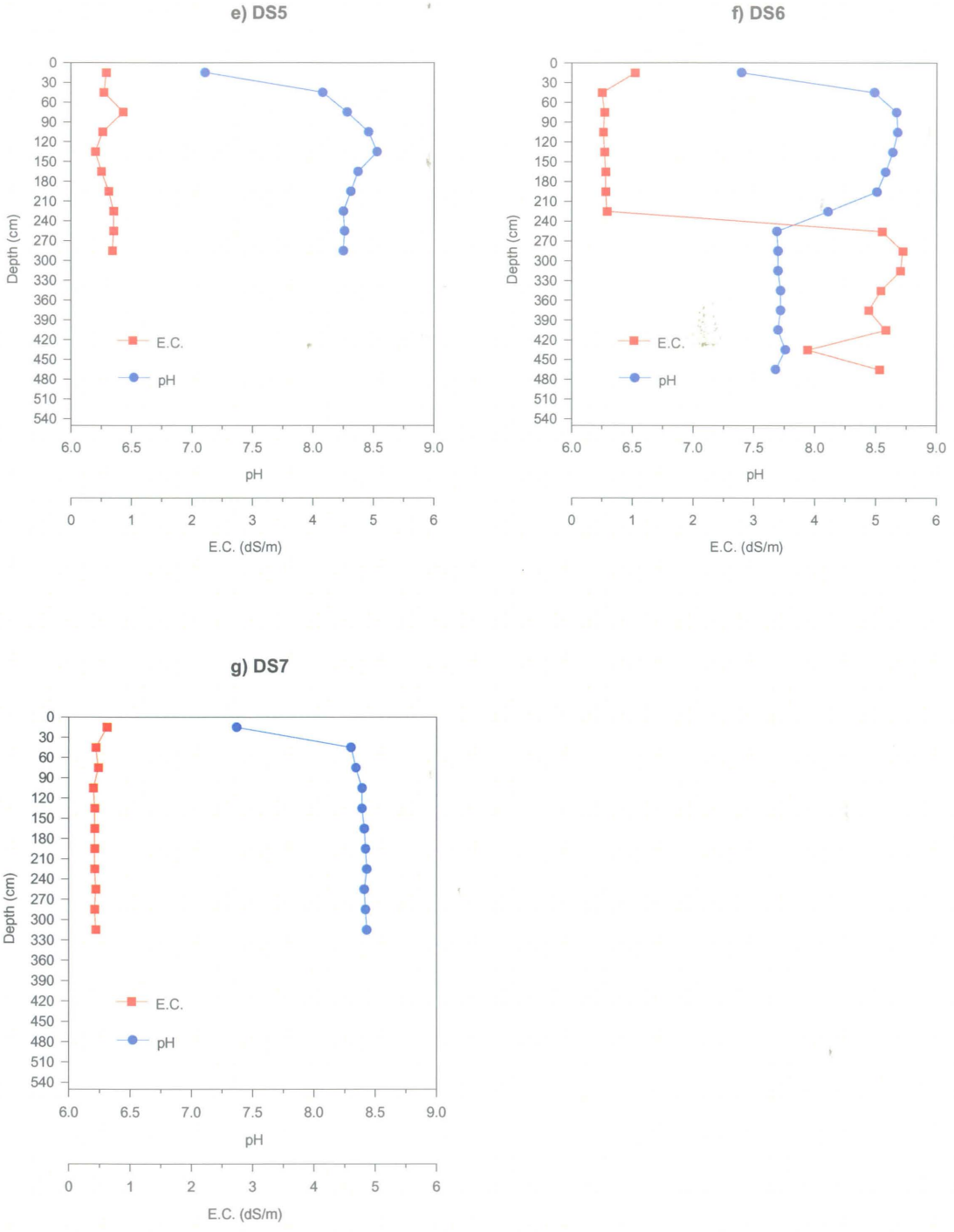


Figure 3.5 continued…

production associated with the A horizon organic matter. Increased pH values were found between 30 and 210 cm, where base removal subsided and profiles reflected genetic properties of the parent material. The pH values tended to drop noticeably below 210 cm, and perhaps indicated the presence of the reduced zone with saturated flow conditions acting to remove bases from the genetic parent material. Soil colour changes were not found to support this conclusion at any positions other than DS4 (Appendix II).

The depression position (DS4) had the lowest pH value at the surface (6.6), reflecting a leached soil surface with relatively high levels of organic acid production, associated with the highest organic C sampled along the transect (Table 3.4). The pH values increased from the surface to 180 cm, and indicated some level of base removal has occurred throughout the entire upper soil profile. Lower-toe position DS7 had a similar pH depth profile to DS4, although no data was acquired below 330 cm.

Crest (DS1 & DS6) and mid-slope (DS2) positions had very similar pH profiles, with relatively low pH values at the soil surface and increased pH values to 210 cm. These data indicated that a combination of some leaching removal of bases and organic acid production has occurred at these positions, however, the depth extent to which this has occurred was relatively small. The relatively low input of water to soil profiles at these positions, as a result of little or no run-on and reliance on direct input from precipitation alone, has precluded the occurrence of deeper base removal in these profiles.

Significant differences in pH rank sum values were found between sample positions for the 0-120 cm and 0-300 cm depth increments (Table 3.5). Using the multiple comparison procecdure, groupings of ranks sums ($\alpha = 0.20$) for the 0-120 cm increment were:

DS4 < DS5 < DS7 < DS2 < DS3 < DS6 < DS1

When the 0-120 cm increment was considered, depression position DS4 was found to have a significantly lower pH than crest positions DS1 & DS6, as well as DS2 & DS3, indicating a stronger leaching regime at this location along the transect.

Groupings of rank sums ($\alpha = 0.20$) for the 0-300 cm increment were:

DS4 < DS5 < DS7 < DS6 < DS2 < DS3 < DS1

When the 0-300 cm depth increment was considered, DS4 was found to have significantly lower pH than DS1, DS2 & DS3.

Table 3.5 Ranks and concordance for pH values.

		Ranks (R) by Sample Position						
Depth (cm)		**DS1**	**DS2**	**DS3**	**DS4**	**DS5**	**DS6**	**DS7**
0-30		6	7	5	1	2	4	3
30-60		7	5	4	1	2	6	3
60-90		5	4	7	1	2	6	3
90-120		5	4	6	1	3	7	2
120-150		6	5	3.5[2]	1	3.5	7	2
150-180		4	5	7	2	1	6	3
180-210		7	6	4	2	1	5	3
210-240		6.5	6.5	4	3	2	1	5
240-270		2	4	5	6	3	1	7
270-300		3	1	6	5	4	2	7
0-120	**Total R[1]**	**23a**	**20a**	**22a**	**4b**	**9ab**	**23a**	**11ab**
	p-value				**<0.005**			
0-300	**Total R**	**51.5a**	**47.5ac**	**51.5a**	**23b**	**23.5bc**	**45ab**	**38ab**
	p-value				**<0.005**			

[1] Rank sum total values followed by the same letter were not found to be significantly at experiment-wise $\alpha = 0.20$.

[2] Ties assigned mean ranks.

3.3.2.3 Electrical Conductivity

The electrical conductivity (EC) values ranged from 0.4 to 5.4 dS/m over all samples. The median EC value was found to be 0.6 dS m^{-1}. Generally speaking, EC values were found to be relatively similar between all sample positions between 0 and 240 cm (Figure 3.5). Slightly elevated EC values were found at the surface of profiles at DS1, DS2, DS4 & DS6, relative to other sample positions, however, all surface soils were found to be non-saline. The low EC values found between 0 and 210 cm at all sample positions indicated that most soluble salts have been leached from these profiles. In other words, with respect to EC, all positions sampled along the transect appear to function as recharge sites, where there has been sufficient water movement through the soil profile to remove most of the soluble salts. There appears to be little effect of landscape position on EC values for these depths, and no significant difference was found between sample positions when the 0-120 cm depth increment was considered (Table 3.6). There were no distinct groupings of rank sums ($\alpha = 0.20$) for the 0-120 cm increment:

DS7 < DS2 < DS4 < DS1 < DS5 < DS6 < DS3

The crest positions (DS1 & DS6) were found to have elevated and relatively uniform EC values between 270 and 510 cm. Midslope position DS2 was found to have a very similar profile to the crest positions, with the elevated EC values beginning slightly deeper in the profile. At these positions, EC values below 270 cm were generally found to be in the range of 5 dS m^{-1}. Unfortunately, no data was acquired at midslope position DS5 below 300 cm. Little water input to the crest positions, as a result of low catchment areas and reliance on water inputs from direct precipitation inputs only, has not permitted removal of soluble salts from deeper in these profiles.

Table 3.6 Ranks and concordance for electrical conductivity values.

Depth (cm)		Ranks (R) by Sample Position						
		DS1	DS2	DS3	DS4	DS5	DS6	DS7
0-30		4	5	7	1.5[2]	1.5	6	3
30-60		3	3	7	6	5	3	1
60-90		4	1.5	3	6	7	5	1.5
90-120		7	2	3.5	3.5	5.5	5.5	1
120-150		6.5	4.5	4.5	3	1	6.5	2
150-180		7	4.5	2	2	4.5	6	2
180-210		6	4	3	1	7	5	2
210-240		6	5	3.5	2	7	3.5	1
240-270		6	5	3	1	4	7	2
270-300		7	5	3	2	4	6	1
0-120	**Total R[1]**	**18**	**11.5**	**20.5**	**17**	**19**	**19.5**	**6.5**
	p-value				**ns**			
0-300	**Total R**	**56.5a**	**39.5ab**	**39.5ab**	**28bc**	**46.5ac**	**53.5a**	**16.5b**
	p-value				**<0.005**			

[1] Rank sum total values followed by the same letter were not found to be significantly at experiment-wise $\alpha = 0.20$.
[2] Ties assigned mean ranks.

Increased EC values were encountered at deeper depths at lower-toe slope positions (DS3 & DS7), although no data was acquired below 330 cm at DS7. The EC profile for DS3 indicated a large increase in EC below 360 cm (no data obtained below 390 cm). These data indicated a stronger leaching environment at the lower-toe slope positions, relative to the mid-slope to crest positions, along the transect.

The depression position (DS4) was found to have slightly elevated EC values below 300 cm, however these values became relatively uniform between 330 and 540 cm, at approximately 1.5 dS m^{-1}, much lower than at similar depths at other slope positions along the transect. These data support the conclusion that this site is a strong throughflow location of the landscape, where soluble salts are being removed from the deeper profile. The relatively high catchment area and convergent character at this position in the landscape results in the contribution of water from upslope areas of the landscape (i.e.

run-on), in addition to direct rainfall inputs. This has resulted in more water movement through the soil and greater removal of soluble salts at this location in the landscape relative to others along the transect.

When greater depths were examined, significant differences in EC rank sum values in the 0-300 cm depth increment were found between sample positions (Table 3.6). Although DS4 & DS7 had the lowest EC values in the 0-300 cm increment and DS1, DS6 & DS5 had the highest, only DS7 was found to be significantly lower than DS1, DS6 & DS5, based on the multiple comparison procedure. Groupings of rank sums ($\alpha = 0.20$) for the 0-300 cm increment were:

DS7 < DS4 < DS2 < DS3 < DS5 < DS6 < DS1

These results indicate that there has been relatively less removal of soluble salts at depth at crest positions DS1 & DS6, relative to lower slope positions DS4 & DS7.

3.3.3 Solute Redistribution Parameters

3.3.3.1 Soil Water Content

The gravimetric soil water content was variable and ranged from 7.4 to 63.6 % and was found to have a median of 18.1 %. Generally speaking, water content was variable between sample positions in the top 180 cm of the soil profile, while it was relatively similar below 180 cm (Figure 3.6). This suggests a landscape effect on the soil water content in the upper portion of the soil profile, while this effect was not apparent at deeper depths.

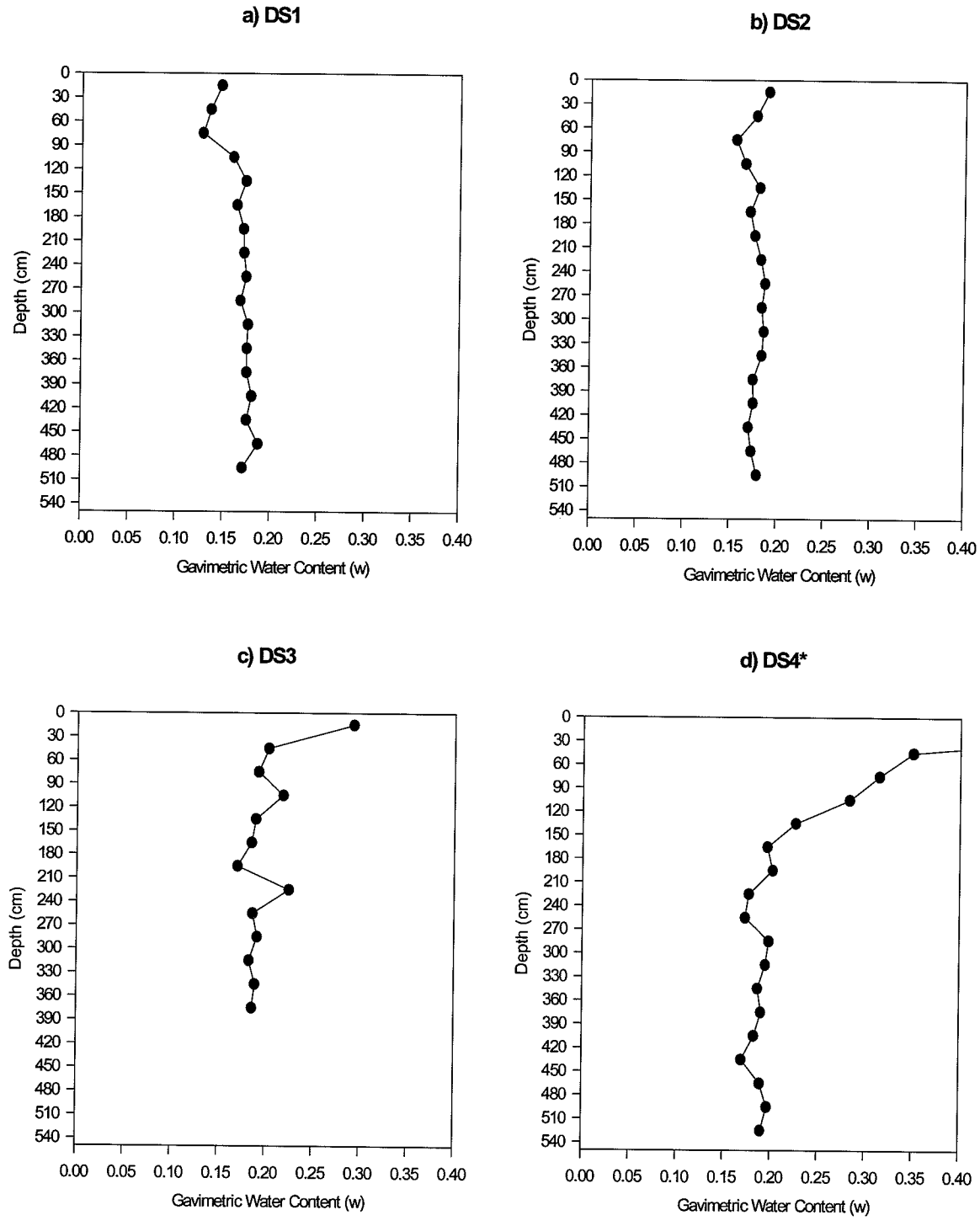


Figure 3.6 Soil water content depth profile at each sample position.

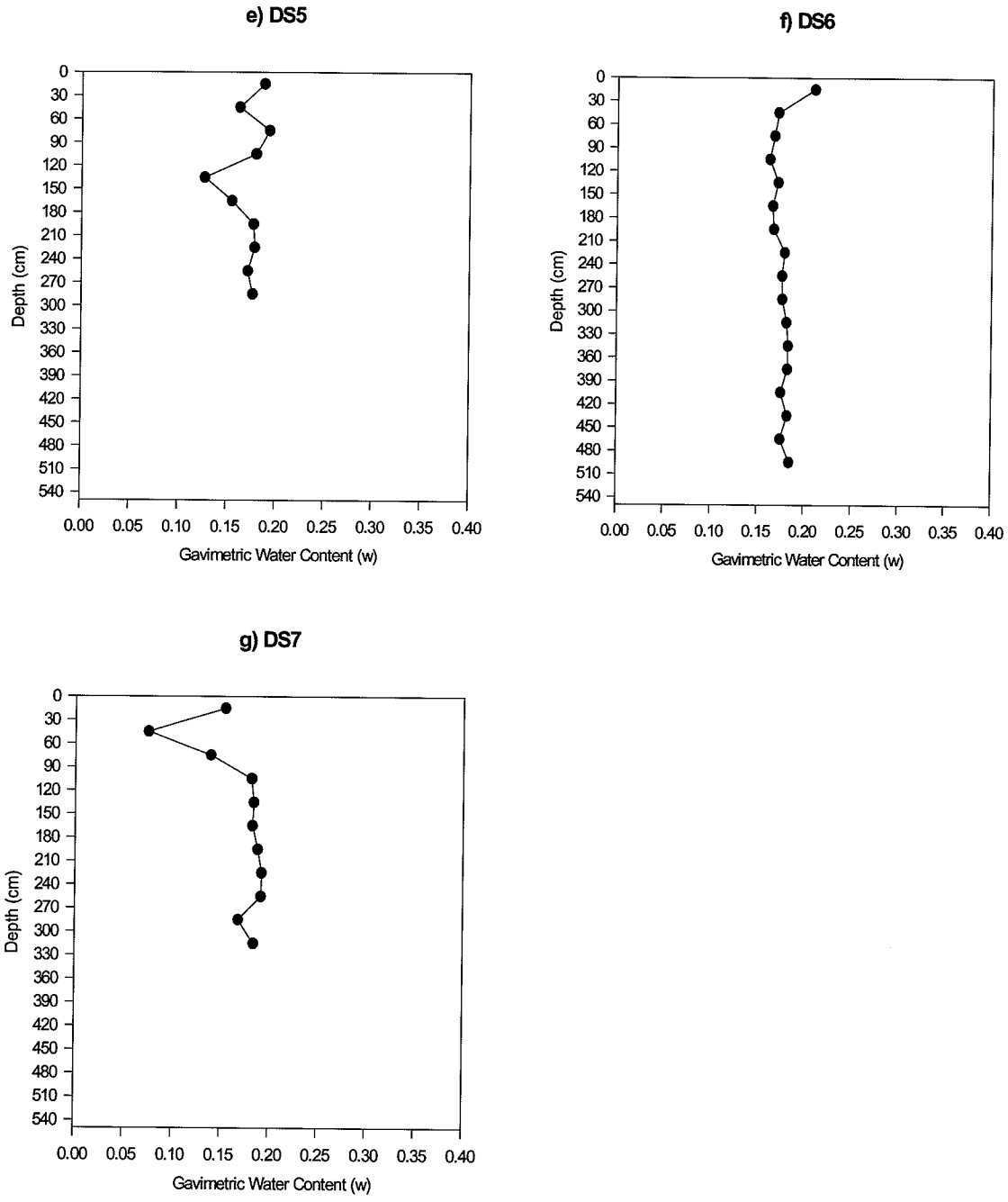


Figure 3.6 continued...

Soil water content values were found to be different between sample positions when the 0-120 cm and 0-300 cm depth increments were examined (Table 3.7). The crest position DS1 was found to have the lowest water contents for both depth increments, while depression position DS4 was found to have the highest (note: soil water content in the 0-30 cm depth increment for DS4 in Figure 3.6 is off-scale). Using the multiple comparison procedure, it was determined that, in both cases, the lower-toe position DS3 and depression position DS4 had significantly higher moisture contents then the crest position DS1.

Table 3.7 Ranks and concordance for soil water content values.

		Ranks (R) by Sample Position						
Depth (cm)		**DS1**	**DS2**	**DS3**	**DS4**	**DS5**	**DS6**	**DS7**
0-30		1	4	6	7	3	5	2
30-60		2	5	6	7	3	4	1
60-90		1	3	5	7	6	4	2
90-120		1	3	6	7	4	2	5
120-150		3	4	6	7	1	2	5
150-180		2	4	6	7	1	3	5
180-210		3	4	2	7	5	1	6
210-240		1	5	7	2	3	4	6
240-270		3	6	5	2	1	4	7
270-300		2	5	6	7	4	3	1
0-120	**Total R[1]**	**5a**	**15ab**	**23bc**	**28b**	**16ab**	**15ab**	**10ac**
	p-value				**<0.005**			
0-300	**Total R**	**19a**	**43ab**	**55bc**	**60b**	**31ac**	**32ac**	**40ab**
	p-value				**<0.005**			

[1] Rank sum total values followed by the same letter were not found to be significantly at experiment-wise $\alpha = 0.20$.

Groupings of ranks sums ($\alpha = 0.20$) for the 0-120 cm increment were:

DS1 < DS7 < DS2 = DS6 < DS5 < DS3 < DS4

Groupings of rank sums ($\alpha = 0.20$) for the 0-300 cm increment were:

DS1 < DS5 < DS6 < DS7 < DS2 < DS3 < DS4

The depression position (DS4) was found to have the highest soil water contents when the 0-120 cm and 0-300 cm depth imcrements were examined, indicating high net water inputs at this location in the landscape following the growing season and the fall period, statistically higher than the crest positions (DS1). Examination of the soil water content profiles provides a snapshot of moisture redistribution following the growing season. Unfortunately, as samples were taken in December, soil water profiles do not provide an indication of relative soil water distribution following spring runoff/infiltration or heavy rainfall events. Manning (1999) found spatial relationships between soil moisture and landscape position to be variable temporally, but found the most notable differences between landscape positions following spring melt. Without an examination of the temporal variability of this very dynamic soil property, few conclusions may be drawn. Discussion of soil water content results, therefore, has been limited.

3.3.3.2 Chloride

Chloride (Cl^-) concentrations ranged from 0 (i.e. below detection limit) to 15.1 ppm, and had a median value of 6.7 ppm. It was difficult to recognize discernible patterns in Cl^- profiles for most of the sample locations, however some observations were notable. There were the occurrences of "bulges", or elevated concentrations, in the Cl^- depth profiles at some of the sample locations that lend some information on the process involved in Cl^- redistribution across the landscape.

At the crest positions DS1 & DS6 there were highly elevated Cl^- concentrations found at the 90 to 120 cm and 60 to 90 cm depth increments, respectively (Figure 3.7). These indicated vertical downward redistribution through these profiles, with accumulation

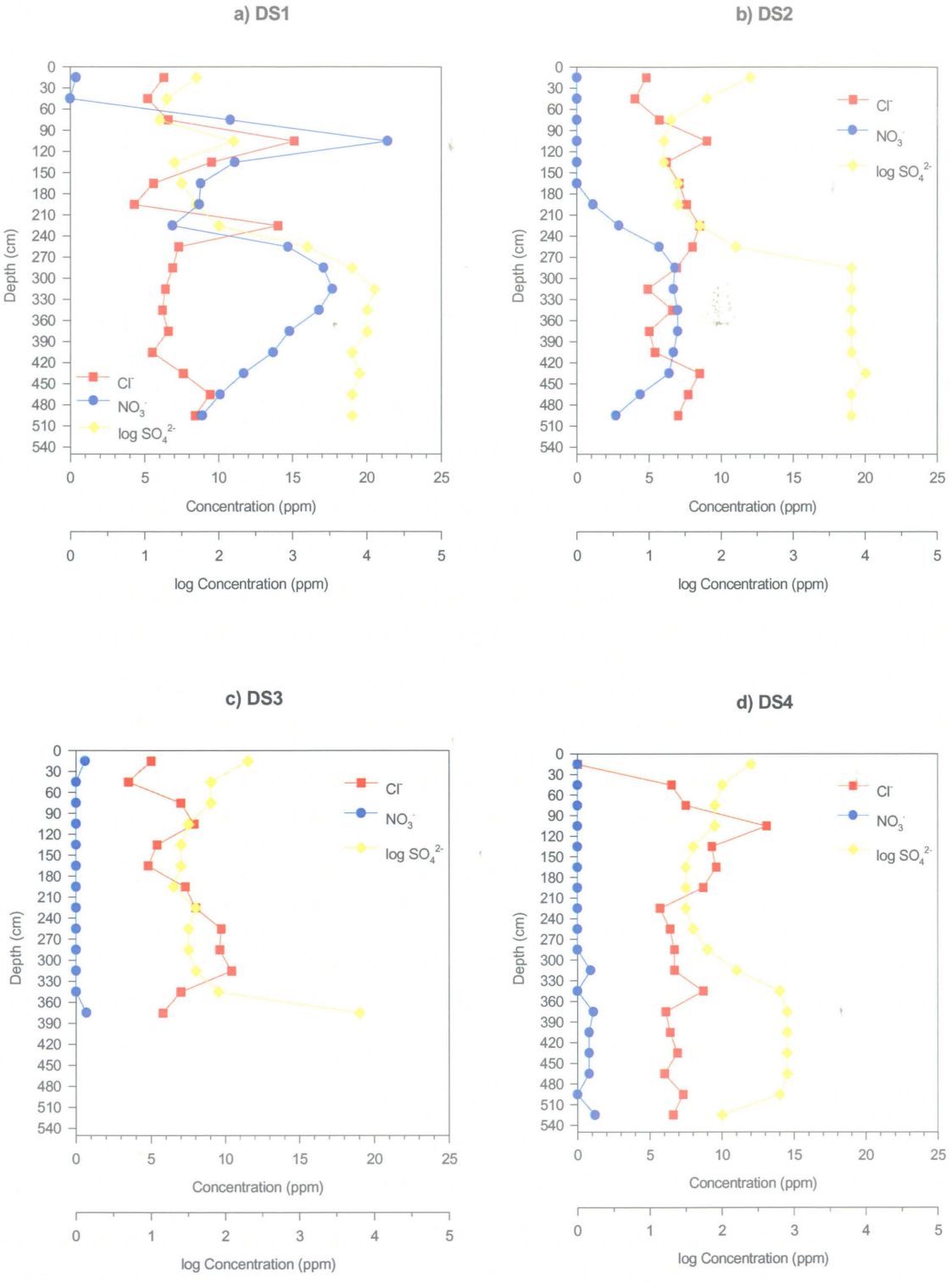


Figure 3.7 Chloride, nitrate and sulfate concentration depth profiles at each sample position.

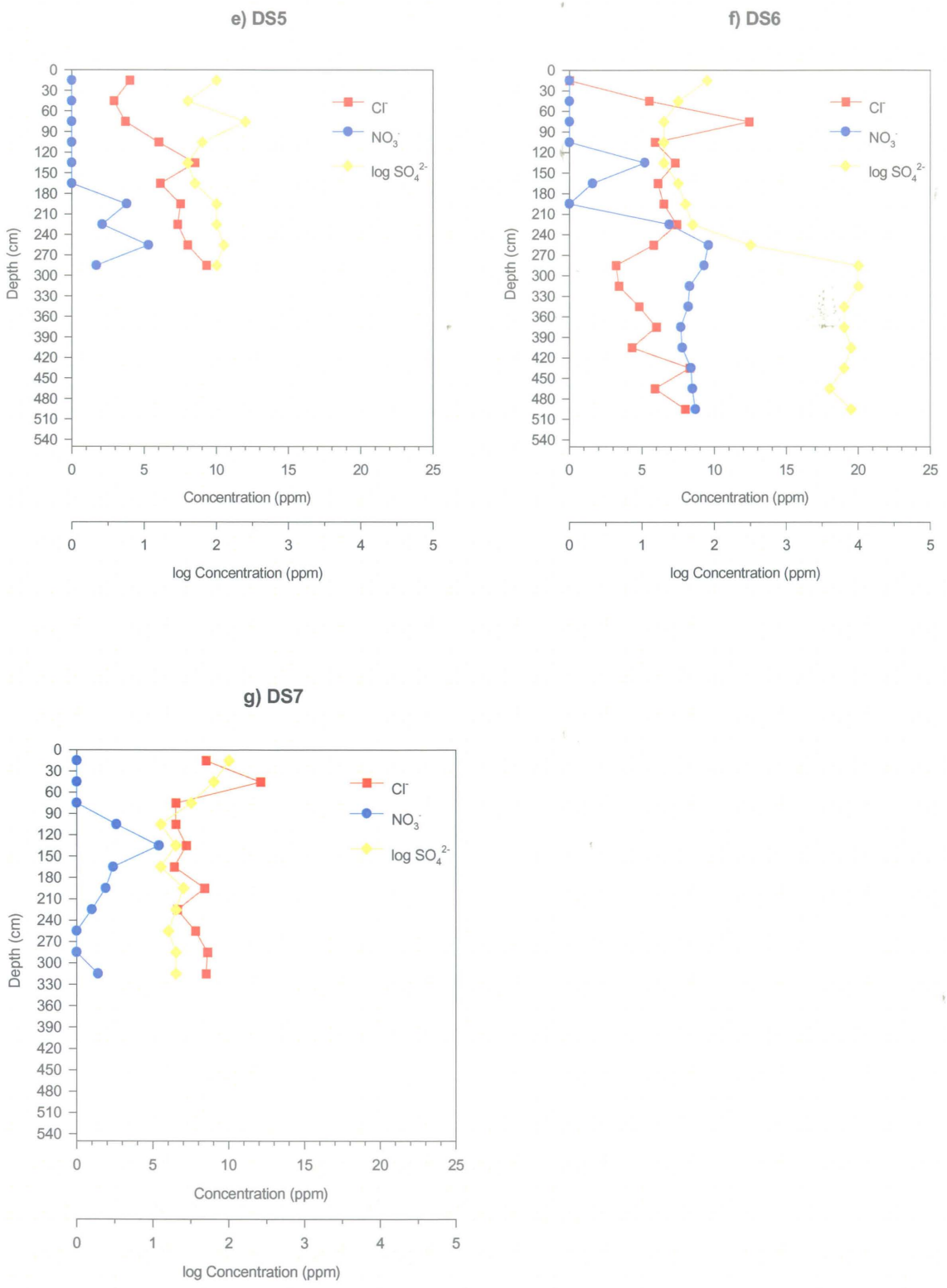


Figure 3.7 continued…

occurring at these depths, which correspond to the extent of the rooting zone. These depths likely correspond to the vertical extent of leaching through these profiles under typical environmental conditions. Dyck et al. (2003) found root zone extraction of soil moisture caused upward movement of Cl^- tracer into the root zone during cropping years. Soil water recharge in subsequent non-cropping years leached the tracer downward again, to the bottom of the rooting zone.

A second "bulge" in the Cl^- depth profile at DS1 at the 210 to 240 cm depth increment is indicative of accumulation above the saturated zone. The source of this accumulation may be throughflow from recharge water from an elevated, recharge depression located directly south of DS1. Accumulation at this position has likely occurred through capillary action above the saturated zone.

At the midslope positions DS2 & DS5 the Cl^- depth profiles indicate removal of Cl^- from the surface of the soil profile (i.e. lixiviation), with noticeable accumulations occurring at 90 to 120 cm and 120 to 150 cm, respectively. The depths of accumulations indicated a stronger leaching regime at these locations relative to the crest positions. This is intuitive as the upslope areas would be expected to contribute surface and intrasoil water flows to the midslope positions, in addition to precipitation inputs, providing more water for infiltration and leaching. Data at lower depths indicated relatively uniform Cl^- concentrations, with no noticeable accumulation or depletion zones, although no data was acquired below 300 cm at DS5.

The lower-toe positions DS3 & DS7 had noticeably elevated Cl^- concentrations in the 60 to 120 and 30 to 60 cm depth increments, respectively. These indicated leaching removal

from the upper portions of the soil profile and accumulation lower in the profile. A second "bulge" in Cl^- concentration was found at DS3 between 240 and 330 cm. This likely corresponds to an accumulation zone above the saturated zone, and has likely occurred as a result of: 1. removal of Cl^- from the upper portions of the soil profile and deep leaching carrying Cl^- deep in the profile, 2. capillary fringe above the saturated zone preventing further downward movement, and 3. deposition in capillary fringe zone from solutes contained in water in the saturated zone.

In the depression position DS4 the Cl^- concentration was very low at the soil surface, indicating strong leaching has occurred at the surface at this location in the landscape. A large "bulge" in the Cl^- depth profile between 90 and 120 cm, likely corresponds to the depth of leaching through this profile under typical environmental conditions. Below this depth, Cl^- concentrations were lower, however, they were not found to have any discernable patterns with depth.

When the Cl^- rank sum values were examined for the 0-120 cm and 0-300 cm depth increments, there were no differences found between sample positions (Table 3.8). There were, therefore, no distinct groupings of rank sums. Groupings of ranks sums ($\alpha = 0.20$) for the 0-120 cm increment were:

DS5 < DS2 < DS6 < DS3 < DS4 < DS7 < DS1

Groupings of rank sums ($\alpha = 0.20$) for the 0-300 cm increment were:

DS6 < DS5 < DS3 < DS2 < DS1 < DS4 < DS7

Table 3.8 Ranks and concordance for chloride values.

Depth (cm)		Ranks (R) by Sample Position						
		DS1	DS2	DS3	DS4	DS5	DS6	DS7
0-30		6	4	5	1.5[2]	3	1.5	7
30-60		4	3	2	6	1	5	7
60-90		4	2	5	6	1	7	3
90-120		7	5	4	6	2	1	3
120-150		7	2	1	6	5	4	3
150-180		2	6	1	7	4	3	5
180-210		1	5	3	7	4	2	6
210-240		7	6	5	1	3	4	2
240-270		3	5	7	2	6	1	4
270-300		3	4	7	2	6	1	5
0-120	**Total R[1]**	**21**	**14**	**16**	**19.5**	**7**	**14.5**	**20**
	p-value				**ns**			
0-300	**Total R**	**44**	**42**	**40**	**44.5**	**35**	**29.5**	**45**
	p-value				**ns**			

[1] Rank sum total values followed by the same letter were not found to be significantly at experiment-wise $\alpha = 0.20$.
[2] Ties assigned mean ranks.

3.3.3.3 Sulfate

Sulfate (SO_4^{2-}) concentrations ranged from 11 to > 12 000 ppm, and had a median value of 75 ppm. In general, SO_4^{2-} concentrations were relatively low and variable in the top 240 cm, and increased greatly at lower depths.

At the crest positions DS1 a "bulge" in the SO_4^{2-} concentration at the 90 to 120 cm depth increment indicated an accumulation zone in the profile (Figure 3.7). The depth of this accumulation corresponded to that found for Cl^-. This supports the conclusion of downward redistribution and accumulation to this depth. The SO_4^{2-} depth profile at the other crest position DS6 demonstrated a slightly elevated SO_4^{2-} concentration at the soil surface and lower, relatively uniform concentrations to 240 cm. The SO_4^{2-} concentrations increased greatly (i.e. >4 000 ppm) below 270 cm and could reflect the unaltered, genetic parent material concentrations, or may be the result of a second, distinct glacial till layer.

At mid-slope position DS2 there was a high concentration of SO_4^{2-} at the soil surface relative to the rest of the profile to 270 cm (Figure 3.7). This may be the result of fertilizer additions and deposition through evapotranspiration. Leaching has removed much of the genetic SO_4^{2-} from the soil profile. At midslope position DS5 a bulge in the SO_4^{2-} depth profile at the 60 to 90 cm depth increment indicated that SO_4^{2-} has been removed from the upper soil profile and deposited at this depth. High SO_4^{2-} concentrations were found below 270 cm for DS2 (similar to DS1 & DS6), however no data was obtained for DS5 below 300 cm, where SO_4^{2-} concentrations were still relatively low.

The lower-toe positions DS3 & DS7 had elevated SO_4^{2-} concentrations at the soil surface relative to the remainder of the soil profile (Figure 3.7), as a result of direct fertilization, SO_4^{2-} contained in run-on and surface deposition through evapotranspiration. Very high SO_4^{2-} concentrations were found below 360 cm at DS3, while data was only acquired to 330 cm at DS7, where SO_4^{2-} concentrations were relatively low. Depths to greatly elevated SO_4^{2-} concentrations were greater at the lower-toe positions relative to mid-slope and crest locations along the transect. No SO_4^{2-} accumulations were noticeable within or below the rooting zone at lower-toe slope positions.

At the depression position DS4 a similar pattern was noted, with a slightly elevated SO_4^{2-} concentration at the soil surface and low concentrations throughout the soil profile. Below 330 cm, SO_4^{2-} concentrations increased and were relatively stable with depth, at approximately 700 ppm. These concentrations were much lower than at the other locations along the transect, and would suggest that lateral subsurface flow is removing SO_4^{2-} from these depths of the profile. No SO_4^{2-} accumulations were apparent within or below the rooting zone at the depression location along the transect.

Significant differences were found between sample positions when rank sums of SO_4^{2-} concentrations were examined in the 0-120 cm depth increment (Table 3.9). Grouping of rank sums ($\alpha = 0.20$), based on the multiple comparison procedure, indicated that crest positions DS1 & DS6 had significantly lower SO_4^{2-} in the 0-120 cm increment than depression position DS4:

DS1 < DS6 < DS7 < DS2 < DS5 < DS3 < DS4

When the 0-300 cm depth increment was examined, significant differences were found between sample positions (Table 3.9). Grouping of rank sums ($\alpha = 0.20$) indicated that lower-toe position DS7 had significantly lower SO_4^{2-} in the 0-300 cm increment than DS4 & DS5:

DS7 < DS3 < DS2 < DS6 < DS1 < DS4 < DS5

Table 3.9 Ranks and concordance for sulfate values.

		Ranks (R) by Sample Position						
Depth (cm)		**DS1**	**DS2**	**DS3**	**DS4**	**DS5**	**DS6**	**DS7**
0-30		1	6	5	7	3	2	4
30-60		1	5	6	7	3	2	4
60-90		1	2	5	6	7	3	4
90-120		7	2	4	6	5	3	1
120-150		4	1	5	7	6	3	2
150-180		6	3	2	5	7	4	1
180-210		6	3	1	4	7	5	2
210-240		6	4	3	2	7	5	1
240-270		7	5	2	3	4	6	1
270-300		6	5	2	3	4	7	1
0-120	**Total R[1]**	**10a**	**15ab**	**20ab**	**26b**	**18ab**	**10a**	**13ab**
	p-value				**<0.100**			
0-300	**Total R**	**45ab**	**36ab**	**35ab**	**50a**	**53a**	**40ab**	**21b**
	p-value				**<0.025**			

[1] Rank sum total values followed by the same letter were not found to be significantly at experiment-wise $\alpha = 0.20$.

3.3.3.4 Nitrate

Nitrate (NO_3^-) concentrations ranged from 0 (i.e. below detection limit) to 21 ppm, and had a median value of 0.8 ppm. Nitrate accumulations within and below the rooting zone were found along the transect, and indicated nitrogen has been applied in excess of crop use at some locations of the landscape.

Large NO_3^- accumulations were found at crest positions DS1 & DS6 (Figure 3.7). Nitrate depth profiles were similar qualitatively, however concentrations were much higher at DS1. Nitrate concentrations were very low from 0 to 60 cm at both locations. A very large bulge in nitrate concentrations was found at 60 to 150 cm at DS1. A smaller, but significant "bulge" was found between 120 and 180 cm at DS6. These indicated nitrogen application above crop utilization, resulting in NO_3^- leaching and accumulation below the crop rooting zone. Large bulges were found at each location at depths below 240 cm for DS1 and 210 cm for DS6.

Significant NO_3^- concentrations were not found within the rooting zone at mid-slope positions DS2 & DS5, however accumulations were found at greater depths. Elevated NO_3^- concentrations were found at each location below 180 cm, and to the depth extent sampled; 510 cm for DS2 and 300 cm for DS5. These data indicated that, although in the short term crop demand appeared to exceed available NO_3^-, historically, deep percolation of NO_3^- beyond the reach of crop roots is an important process at these locations along the transect.

Variable results were found at the lower-toe positions DS3 & DS7. Very little NO_3^- was found in the entire profile at DS3, and indicated that it has not accumulated at this

location in the landscape. Crop utilization and losses through denitrification may have prevented NO_3^- build-up in this relatively wet location of the landscape. This data also suggests the hydrologic function at this location of the landscape has not promoted downward flow of soil water and associated solutes. Accumulation of NO_3^- was, however, found at DS7. A large "bulge" in NO_3^- concentrations was found between 90 and 240 cm, and indicated deep percolation below the root zone has been an important process at this location along the transect. Accumulations of NO_3^- were also found between 300 and 330 cm, the depth extent sampled. Significant amounts of nitrogen may have reached this location of the landscape through surface run-on and intrasoil lateral flow from the large upslope contributing area associated with this position. These findings support the conclusions drawn in previous sections regarding the processes influencing solute redistribution at these hydrologically distinct sites.

The depression position DS4 was not found to have NO_3^- accumulation within the top 300 cm of the profile. One would not expect accumulations at this location in the landscape as it is not under agricultural production, and, therefore, does not receive nitrogen fertilization. Further, denitrification would be a dominant process at this wet location of the landscape and would result in significant losses of any NO_3^- present. Accumulations were found, however, below 300 cm. This suggests that NO_3^- contained in deeply percolated soil water is flowing into this location of the landscape via lateral subsurface flow from upslope contributing areas.

When the rank sum values for NO_3^- contained in the 0-120 cm depth increment were examined, differences between sample positions were not found to be significant (Table

3.10). There were, therefore, no distinct groupings of rank sums ($\alpha = 0.20$) found among sample positions based on the multiple comparison procedure:

DS2 = DS4 = DS5 = DS6 < DS7 < DS3 < DS1

When the 0-300 cm depth increment was examined, significant differences were found between sample positions (Table 3.10). Based on the multiple comparison procedure it was determined that crest position DS1 had significantly greater N relative to sample positions at other landscape location along the transect, except DS6. Groupings of rank sums ($\alpha = 0.20$) for the 0-300 cm increment were:

DS4 < DS3 < DS5 < DS2 < DS7 < DS6 < DS1

Table 3.10 Ranks and concordance for nitrate values.

		Ranks (R) by Sample Position						
Depth (cm)		**DS1**	**DS2**	**DS3**	**DS4**	**DS5**	**DS6**	**DS7**
0-30		6	3	7	3	3	3	3
30-60		4	4	4	4	4	4	4
60-90		7	3.5	3.5[2]	3.5	3.5	3.5	3.5
90-120		7	3	3	3	3	3	6
120-150		7	2.5	2.5	2.5	2.5	5	6
150-180		7	2.5	2.5	2.5	2.5	5	6
180-210		7	4	2	2	6	2	5
210-240		7	5	1.5	1.5	4	6	3
240-270		7	5	2	2	4	6	2
270-300		7	5	2	2	4	6	2
0-120	**Total R[1]**	**24**	**13.5**	**17.5**	**13.5**	**13.5**	**13.5**	**16.5**
	p-value				**ns**			
0-300	**Total R**	**66a**	**37.5b**	**30b**	**26b**	**36.5b**	**43.5ab**	**40.5b**
	p-value				**<0.005**			

[1] Rank sum total values followed by the same letter were not found to be significantly at experiment-wise $\alpha = 0.20$.

[2] Ties assigned mean ranks.

3.3.3.5 Nitrate-nitrogen accumulation and potential impact to groundwater

Residual nitrate-nitrogen (NO_3^--N) concentrations were quite variable among sample positions. Very little NO_3^--N was found within the rooting zone at any of the sample positions, except for crest position DS6, where 33.6 kg NO_3^--N ha^{-1} was recovered (Table 3.11). This indicated that crop demand matched or exceeded soil NO_3^--N concentrations in the 1999 crop year at all sample locations along the transect, except for DS6 where soil NO_3^--N exceeded crop use. However, NO_3^--N accumulations were found below the root zone at all sample positions, and indicated that, over the long-term, nitrogen has been applied in excess of crop demand.

When NO_3^--N accumulations within the entire depth sampled at each sample position was examined, the largest accumulations were found at the crest positions DS1 & DS6, with the equivalent of 199.4 and 92.9 kg NO_3^--N ha^{-1} found at each sample position, respectively (Table 3.11). The lowest accumulations were found at DS3 & DS4, with the equivalent of 1.3 & 5.7 kg NO_3^--N ha^{-1} recovered at each sample position, respectively.

Table 3.11 Nitrate-nitrogen accumulations at each sample location.

Sample Location	Total Depth Sampled	NO_3^--N 0-120 cm	NO_3^--N 120-300 cm	NO_3^--N All Depths	NO_3^--N All Depths Below 120 cm	Depth of Potential GW Impact[2]
	— cm —	kg ha^{-1}				— m —
DS1	510	33.6[1]	69.3	199.4	165.8	3.9
DS2	510	<1.0	17.1	59.3	59.3	1.4
DS3	390	<1.0	<1.0	1.3	1.3	<0.1
DS4	540	<1.0	<1.0	5.7	5.7	0.1
DS5	300	<1.0	13.3	13.3	13.3	0.3
DS6	510	<1.0	33.5	92.9	92.9	2.2
DS7	330	2.7	11.0	15.2	12.5	0.3

[1] All values determined based on an average bulk density value of 1 520 kg m^{-3}.
[2] Maximum depth of groundwater potentially impacted to 10 mg L^{-1} NO_3^--N, assuming porosity of 0.43 and total saturation, based on NO_3^--N recovered at all depths below 120 cm.

The 120-300 cm depth increment was examined to provide a more useful comparison between sample positions, as total depths sampled were not uniform among sample positions. The largest accumulations were again found at the crest positions DS1 & DS6, with the equivalent of 69.3 and 33.5 kg NO_3^--N ha^{-1} found at each sample position, respectively (Table 3.11). Mid-slope positions were found to have intermediate accumulations, with sample positions DS2 & DS5 found to have the equivalent of 17.1 and 13.3 kg NO_3^--N ha^{-1}, respectively. Accumulations at DS3 & DS4 were not detected in the depths sampled.

The Canadian Council of Ministers of the Environment (CCME) (1999) drinking water quality guidelines maximum acceptable concentration (MAC) for NO_3^--N is 10 mg L^{-1}. Based on an average bulk density of 1 520 kg m^{-3} (average value measured in the 60-120 cm depth increment at various sites throughout the field during the bromide tracer study - see Chapter 3), the estimated porosity of the subsurface soil is:

$$\begin{aligned} \text{Porosity} &= 1 - (\text{Bulk Density} / \text{Particle Density}) \\ &= 1 - (1\,520 \text{ kg m}^{-3} / 2\,650 \text{ kg m}^{-3}) \\ &= 0.43 \end{aligned} \qquad [2.2]$$

Using the total residual NO_3^--N found below the root zone (i.e. 120 cm) to the total depth sampled, the theoretical maximum volume of water that could be impacted uniformly to a concentration of 10 mg NO_3^--N L^{-1} was calculated for each sample location, as follows:

$$\begin{aligned} \text{Water volume} &= \text{soil } NO_3^-\text{-N concentration} / \text{MAC} \\ &= 165.8 \text{ kg } NO_3^-\text{-N ha}^{-1} * 1\,000\,000 \text{ mg kg}^{-1} / 10 \text{ mg L}^{-1} \\ &= 16\,580\,000 \text{ L ha}^{-1} / 1\,000 \text{ L m}^{-3} \\ &= 16\,580 \text{ m}^3 \text{ ha}^{-1} \end{aligned} \qquad [2.3]$$

Considering the approximate total water-filled void space in the saturated zone, the equivalent depths of shallow groundwater (GW) that could potentially be impacted to CCME guidelines at each sample position were calculated as follows:

$$\begin{aligned} \text{Depth of GW} &= \text{water volume / porosity / land area} \\ &= 16\,580\ m^3\ ha^{-1} / 0.43 / 10\,000\ m^2\ ha^{-1} \\ &= 3.62\ m \end{aligned} \qquad [2.4]$$

It was found that the greatest depths of potential groundwater impacts were found at the crest positions, with sufficient NO_3^--N found below DS1 & DS6 to potentially impact groundwater to 10 mg L^{-1} to 3.9 & 2.2 m, respectively (Table 3.11). The potential impact was estimated to be 1.4 m at midslope DS2, while at DS5 the estimate was minimal.

These data indicated that nitrogen application rates based on generalized field recommendations have resulted in over-application at the crest locations along the transect. Nitrogen application in exceedance of crop nutrient demand at the crest positions appears to have allowed for removal of residual NO_3^--N from the crop rooting zone following heavy rainfall events or during spring snowmelt and recharge periods. Deep percolation over time has resulted in large accumulations of NO_3^--N at significant depths at the crest locations along the transect. Results suggest that, although the leaching potential is lowest at crest locations of the landscape, these areas of this landscape should not be ignored when considering potential impact to groundwater sources. Although the source (i.e. NO_3^--N below the rooting zone) exists at these locations, the importance of the pathway to the receptor (i.e. groundwater) is unkown.

The intermediate accumulations found at the mid-slope positions are of practical importance. These are typically the slope positions of the landscape to which fertilizer

inputs are tailored. Data collected at these locations suggest that, although for the 1999 crop year soil NO_3^--N concentrations were deficient in the rooting zone, deep percolation below the rooting zone has occurred on a historical basis. The greater accumulations at DS2 may be the result of lower crop potential and concomitant nutrient demand relative to DS5, due to water redistribution at these positions.

The lower-toe positions along the transect would be considered to have a relatively high leaching potential. However, leaching potential is not dependent on topographic factors alone, and hydrologic regime must be considered. Of the lower-toe positions, DS3, which is not considered a recharge zone of the landscape, does not appear to be at high risk in terms of direct impact to groundwater sources. This is supported by regressive soil profile development and low NO_3^--N concentrations throughout the entire depth sampled. On the other hand, the more highly leached DS7 location would be considered relatively high risk, due to the relatively high leaching potential, based on topographic factors, hydrologic regime and proximity to the water table. This is supported by more progressive soil profile development at this sample location.

Although depressional areas of the landscape are typically considered to have the greatest leaching potential, the depression position will not be considered further in this discussion, as the different land-use precludes it from useful comparison to the other positions. Having said that, depressional areas of these landscapes under agricultural crop production would be considered high risk, as they can act as a direct conduit to groundwater sources.

3.3.4 Pedologic Attributes and Solute Redistribution Parameters Among Landscape Element Complexes

Based on the landform element complexes (LECs) derived from the Landform Description Program (MacMillan and Pettapiece 1987), upper slope (UPS) segments included sample positions DS1, DS2 & DS6, while DS5 & DS7 were considered mid-slopes (MID) and DS3 & DS4 were considered lower slopes (LOW) (Figure 3.8). Of note, no areas along the transect were considered depression (DEP) segments. In a previous study by Manning (1999), general trends were observed in topographic descriptors and static soil properties among LECs. However, statistical significance of correlations between topographic variables and soil properties were generally weak among LECs, but improved when relationships were examined by LECs.

In the current study, trends were apparent when topographic variables were examined by LEC. When slope gradient was examined, MID was found to have the highest values (Figure 3.9), while values for UPS and LOW were lower and similar. Surface flows would be expected to be highest at MID relative to the other LECs. Slope curvature (Kh and Kv) values were found to be positive for UPS and negative for MID and LOW (Figure 3.9). These indicated general divergent character for UPS and, conversely, convergent character for MID and LOW, as per criteria of the LECs. Catchment areas (CA) were found to be very low at UPS relative to MID and LOW. The MID LEC had the highest CA value, although this was skewed due to a very high CA value at DS7. When CA and gradient were considered, topographic index (TI) values increased in the order UPS to MID to LOW. This indicated that the greatest extent of flow accumulation would be found in the LOW LEC.

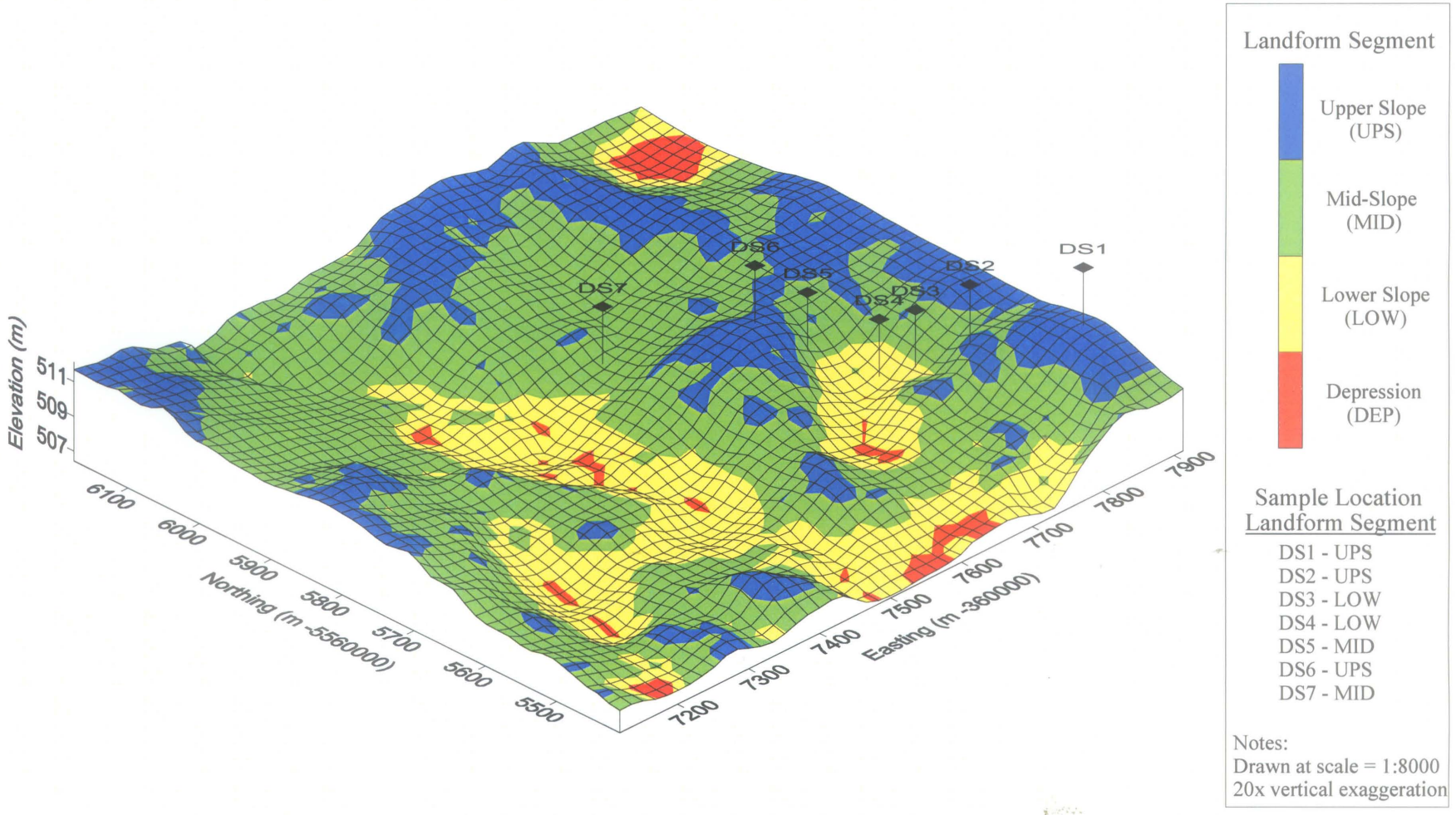


Figure 3.8 Landform segmentation model for the field site with sample positions.

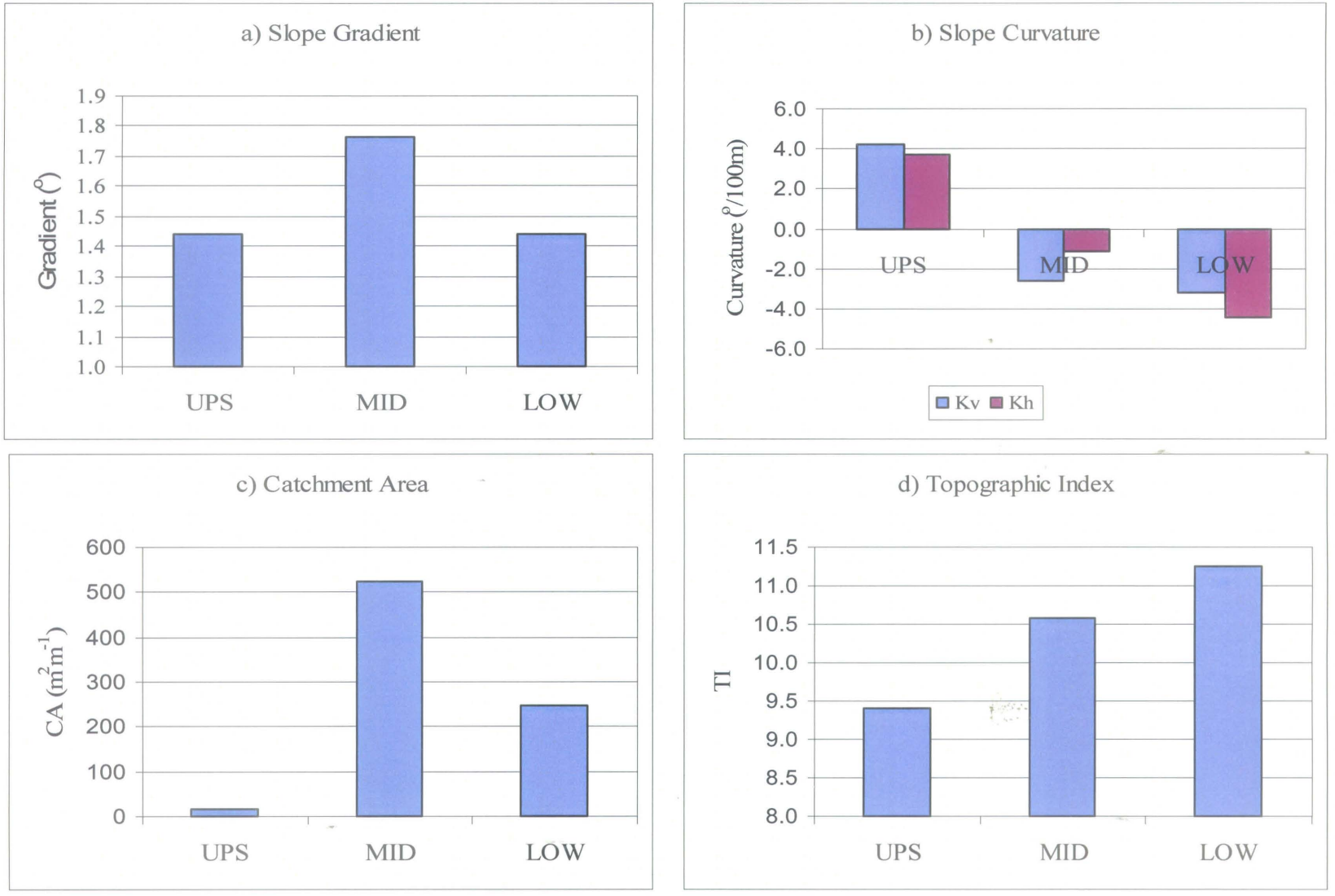


Figure 3.9 Select topographic variables by LEC.

Trends were noticeable in static soil properties when examined by LEC. A horizon depth, solum thickness and organic carbon were greatest in LOW and least in UPS (Figure 3.10), which indicated that organic matter accumulation and translocation within the profile were greatest in lower portions of the landscape. Depth to carbonate (CO_3) increased from UPS to MID to LOW (Figure 3.10). This indicated stronger leaching of carbonate has occurred from upper to lower slope positions in the landscape along the transect. These results are similar to those of Manning (1999), who found soil organic carbon, A horizon depth, solum depth and depth to CO_3 all increased from LOW to MID to UPS. The profile development index (PDI) was found to be highest at MID and lowest at LOW (Figure 3.10). The average PDI for UPS was found to be just over 2.0, while for MID it was just over 3.0. The UPS sample positions DS1, DS2 and DS6 had poorly developed profiles (thin solum, carbonates close to the surface) relative to MID positions DS5 and DS7. The LOW position DS3, as previously discussed, exhibited regressive profile development, and acted to lower the PDI for this LEC. In a stronger recharge area of the landscape, the LOW LEC would be expected to have a higher PDI relative to MID or UPS. So, the prediction of soil properties based on topographically-derived LECs alone, without a priori knowledge of hydrologic processes occurring within the landscape, appears somewhat limited. This confirms the conclusion by Manning (1999) that while LECs were useful in describing gross variability of soil properties, they did not account for differing hydrologic and pedogenic regimes within LECs.

Indicators of solute redistribution were compared between LECs using Kendall's coefficient of concordance, as previously discussed. Indicators found to be significantly different between LECs are discussed below.

Figure 3.10 Select soil properties by LEC.

Electrical conductivity rank sum values in the 0 to 300 cm increment were found to be significantly different between LECs (p-value <0.05). When the multiple comparison procedure was conducted (experiment-wise $\alpha = 0.15$), groupings of rank sum values were:

LOW < MID < UPS

Results indicate the UPS LEC has had less removal of soluble salts relative to MID and LOW, indicating a weaker leaching environment there.

When pH values were examined, both pH in the 0 to 120 cm increment (p-value <0.10) and 0 to 300 cm increment (p-value <0.01) were found to be significantly different between LECs. Groupings for pH ($\alpha = 0.15$) in the top 120 cm, based on the multiple comparison procedure, were:

LOW = MID < UPS

And in the top 300 cm, were:

MID < LOW < UPS

In both cases, pH was significantly higher in UPS LEC relative to LOW or MID. These data indicate less leaching has occurred at UPS LECs, and, therefore, fewer bases have been removed from profiles in these LECs, and, it is assumed, less organic acid production has occurred.

When soil water content was examined, groupings ($\alpha = 0.15$) for the 0 to 120 cm depth increment were found to be:

UPS = MID < LOW

And for the 0 to 300 cm depth increment:

UPS < MID < LOW

In both cases, the LOW was found to have higher water content relative to MID or UPS.

When NO_3^- was examined, significant differences were found between LECs when the 0 to 300 cm depth increment was considered. Groupings ($\alpha = 0.15$) for NO_3^- in the top 300 cm were:

LOW < MID < UPS

Results based on LECs indicate that, although topographic and pedologic indicators demonstrate greater leaching potential from UPS to MID to LOW, the greatest NO_3^- accumulations have occurred at UPS. Reasons for this have been discussed previously.

No significant differences were found between LECs when SO_4^{2-} was examined.

As mentioned for soil properties, there appears to be some utility in the concept of LECs for explaining solute redistribution across the landscape, and associated indicators. However, other environmental conditions must be considered, including differing hydrologic regimes (i.e. nature and degree of surface and groundwater processes occurring at a given location in the landscape) and pedogenic processes occurring within LECs in the landscape, to reduce associated limitations of use.

3.3.5 Relationship Between Topographic Variables, Soil Properties and Solute Redistribution Parameters

Based on Spearman rank correlations, topographic variables were found to be good predictors of measured soil properties (Table 3.12). Relative elevation (*RE*) was found to be negatively correlated to A horizon depth (Ahor) (-0.85), organic carbon (OrgC) (-0.95) and depth to carbonate (CO_3) (-0.95). The general drainage characteristic appears to be an important factor in pedogenic processes occurring in this landscape. It is intuitive that the lower the *RE*, the more water is available to drive soil development, including organic matter production and leaching processes. When vertical curvature (*Kv*) was examined, an inverse relationship was found to CO_3 (-0.81) and Ahor (-0.82), while horizontal curvature (*Kh*) was also inversely related to Ahor (-0.78). These findings are similar to other researchers (Pennock et al. 1987; Manning 1999; Manning et al. 2001a; Florinsky et al. 2002) who found the strength of certain soil properties increased with convergent landscape character. For example, they all found A horizon depth, and depth to CO_3 significantly correlated to indices of convergence. With convergence and deceleration of surface flows, soil processes of organic matter accumulation and leaching were found to be more evident. Catchment area (*CA*) was found to be positively correlated to CO_3 (0.92), Ahor (0.82) and solum thickness (solum) (0.79). Topographic index (*TI*) was also found to be a good predictor of CO_3 (0.92), Ahor (0.82) and solum (0.79). *CA* and *TI* provide an estimate of the amount of surface and intrasoil water available to a given point in the landscape. They appear to be good indicators of select soil properties, in that the greater the upslope contributing area, relative to a given point in the landscape, the stronger were the processes of organic matter accumulation and leaching. These results support findings by Florinsky et al. (2002) of high correlation coefficients for solum

Table 3.12 Spearman rank correlations between various parameters ($p<0.05$).

	CO_3	Ahor	Solum	PDI	OrgC	EC_{30}	pH_{30}	Cl_{30}	Cl_{60}	Cl_{120}	Cl_{300}	$Cl_{120\text{-}300}$
CO_3	1.00											
Ahor	ns	1.00										
Solum	ns	0.85	1.00									
PDI	ns	ns	ns	1.00								
OrgC	ns	0.89	ns	ns	1.00							
EC_{30}	ns	ns	ns	-0.87	ns	1.00						
pH_{30}	-0.76	ns	ns	ns	-0.79	ns	1.00					
Cl_{30}	ns	ns	ns	ns	ns	ns	ns	1.00				
Cl_{60}	ns	ns	ns	ns	ns	ns	ns	0.95	1.00			
Cl_{120}	ns	ns	ns	ns	ns	ns	ns	ns	ns	1.00		
Cl_{300}	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	1.00	
$Cl_{120\text{-}300}$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	1.00
$SO4_{30}$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
$SO4_{60}$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
$SO4_{120}$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
$SO4_{300}$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
$SO4_{120\text{-}300}$	-0.81	-0.85	-0.93	ns	ns	ns	ns	ns	ns	ns	ns	ns
$NO3_{30}$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
$NO3_{60}$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
$NO3_{120}$	ns	ns	ns	ns	ns	ns	ns	0.87	0.77	ns	0.81	ns
$NO3_{300}$	-0.85	-0.89	ns	ns	-0.89	ns	ns	ns	ns	ns	ns	ns
$NO3_{120\text{-}300}$	-0.84	-0.95	-0.85	ns	-0.85	ns	ns	ns	ns	ns	ns	ns
W_{30}	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
W_{60}	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
W_{120}	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
W_{300}	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
$W_{120\text{-}300}$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
RE	-0.95	-0.85	ns	ns	-0.79	ns	ns	ns	ns	ns	ns	ns
A	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
G	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Kv	-0.81	-0.82	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Kh	ns	-0.78	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CA	0.92	0.82	0.79	ns	ns	ns	ns	ns	ns	ns	ns	ns
TI	0.77	0.78	ns	ns	0.79	ns	ns	ns	ns	ns	ns	ns

Table 3.12 continued...

	$SO4_{30}$	$SO4_{60}$	$SO4_{120}$	$SO4_{300}$	$SO4_{120-300}$	$NO3_{30}$	$NO3_{60}$	$NO3_{120}$	$NO3_{300}$	$NO3_{120-300}$
CO_3										
Ahor										
Solum										
PDI										
OrgC										
EC_{30}										
pH_{30}										
Cl_{30}										
Cl_{60}										
Cl_{120}										
Cl_{300}										
$Cl_{120-300}$										
$SO4_{30}$	1.00									
$SO4_{60}$	1.00	1.00								
$SO4_{120}$	ns	ns	1.00							
$SO4_{300}$	ns	ns	ns	1.00						
$SO4_{120-300}$	ns	ns	ns	0.89	1.00					
$NO3_{30}$	ns	ns	ns	ns	ns	1.00				
$NO3_{60}$	ns	ns	ns	ns	ns	1.00	1.00			
$NO3_{120}$	ns	ns	ns	ns	ns	ns	ns	1.00		
$NO3_{300}$	ns	ns	-0.79	ns	ns	ns	ns	ns	1.00	
$NO3_{120-300}$	-0.76	-0.76	ns	0.77	0.88	ns	ns	ns	0.95	1.00
W_{30}	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
W_{60}	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
W_{120}	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
W_{300}	0.82	0.82	ns	ns	ns	ns	ns	ns	ns	ns
$W_{120-300}$	0.79	0.79	ns	-0.82	ns	ns	ns	ns	ns	-0.77
RE	ns	ns	ns	0.79	0.89	ns	ns	ns	0.89	0.94
A	0.89	0.89	ns	ns	ns	ns	ns	ns	ns	ns
G	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Kv	ns	ns	ns	ns	0.82	ns	ns	ns	ns	ns
Kh	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CA	ns	ns	ns	-0.79	-0.93	ns	ns	ns	ns	-0.85
TI	ns	ns	ns	-0.79	-0.79	ns	ns	ns	ns	-0.83

Table 3.12 continued...

	W_{30}	W_{60}	W_{120}	W_{300}	$W_{120-300}$	*RE*	*A*	*G*	*Kv*	*Kh*	*CA*	*TI*
CO_3												
Ahor												
Solum												
PDI												
OrgC												
EC_{30}												
pH_{30}												
Cl_{30}												
Cl_{60}												
Cl_{120}												
Cl_{300}												
$Cl_{120-300}$												
$SO4_{30}$												
$SO4_{60}$												
$SO4_{120}$												
$SO4_{300}$												
$SO4_{120-300}$												
$NO3_{30}$												
$NO3_{60}$												
$NO3_{120}$												
$NO3_{300}$												
$NO3_{120-300}$												
W_{30}	1.00											
W_{60}	0.96	1.00										
W_{120}	0.86	0.89	1.00									
W_{300}	0.96	0.93	0.82	1.00								
$W_{120-300}$	ns	ns	ns	ns	1.00							
RE	ns	ns	ns	ns	ns	1.00						
A	ns	ns	ns	ns	ns	ns	1.00					
G	ns	ns	ns	ns	ns	ns	ns	1.00				
Kv	ns	ns	ns	ns	ns	0.82	ns	ns	1.00			
Kh	ns	ns	ns	ns	ns	ns	ns	ns	0.93	1.00		
CA	ns	ns	ns	ns	ns	-0.93	ns	ns	-0.89	-0.79	1.00	
TI	ns	ns	ns	ns	0.79	-0.89	ns	ns	-0.79	ns	ns	1.00

depth, depth to CO_3 and organic carbon with *TI*. The relationship between topographic variables and soil properties has been explored by patterns of water movement and distribution by many researchers (Pennock et al. 1987; Moore et al. 1993; Manning 1999; Florinsky et al. 2002). Of note, no relationship was found between slope gradient (*G*) and any other variables. This would suggest that perhaps infiltration is more important than overland flow in this semi-arid landscape with gently sloping topography. Aspect (*A*) was found to be weakly correlated to soil properties. These results are consistent with Florinsky et al. (2002) and support their conclusion that *A* is a poor predictor of soil properties in this relatively flat landsurface and northern climate. Further, the circular nature (i.e. 0-360°) of this property may preclude it from simple statistical determinations.

It is intuitive that the influence topographic conditions have on static soil properties would be similar to the influence they have on more dynamic ones over a different temporal scale, such as water and solute redistribution in the landscape. However, Florinsky et al. (2002) caution that relationships between topography and soil properties are temporally variable, because the processes that determine those properties are variable. While few strong relationships were found between topographic variables and one-time soil water content measurements, the topographic variables most strongly related to measured soil properties were also found to be the best predictors of solute redistribution, and included *RE*, *CA* and *TI*. However, interpretation of these relationships is not straightforward. As was evident in the examination of chloride (Cl^-) redistribution among sample positions, patterns were such that strong relationships to topographic variables, or soil properties, were not found. Patterns of Cl^- redistribution may not be apparent due to fertilizer (e.g. KCl) additions over time and little crop uptake and

removal. While relationships were found between topographic variables and SO_4^{2-} and NO_3^- redistribution parameters, they were not found for depths within the top 120 cm. These results indicate that topographic variables do not appear to provide a predictive tool for solute redistribution for those depths within this landscape. These findings are somewhat similar to Florinsky et al. (2002), who found that while there were some correlations between topographic variables and soil properties in the 0-30 cm depth increment, these relationships were generally weak with depth increments to 120 cm. They suggested the variability in relationships with depth may stem from spatial variability in the rate of decline of hydraulic conductivity with depth. The researchers also noted the importance of temporal variability in soil-topography relationships. The transient nature of root zone water and solute fluxes, noted by Dyck et al. (2003) may contribute to the difficulty in determining relationships between dynamic soil properties and topographic factors.

RE was found to be positively correlated to SO_4^{2-} within the top 300 cm ($SO4_{300}$) (0.79) and SO_4^{2-} between 120 and 300 cm ($SO4_{120\text{-}300}$) (0.89), as well as with $NO3_{300}$ (0.89) and $NO3_{120\text{-}300}$ (0.94). *CA* was found to be inversely related to $SO4_{300}$ (-0.79), $SO4_{120\text{-}300}$ (-0.93) and $NO3_{120\text{-}300}$ (-0.85). *TI* was also found to be inversely related to $SO4_{300}$ (-0.79), $SO4_{120\text{-}300}$ (-0.79) and $NO3_{120\text{-}300}$ (-0.83). These data indicate, as previously discussed, that the areas of the landscape with the highest leaching potential (i.e. those with low *RE*, and high *CA* and *TI* values) were not those that have the greatest accumulation of solute deep in the profile, for the depths sampled. Results demonstrate that upper slope positions, with relatively high *RE*, and low *CA* and *TI* values, had the greatest accumulation of NO_3^- and SO_4^{2-} deep in the profile. That stronger relationships were

found between topographic variables and solute redistribution parameters below 120 cm supports the statement by Dyck et al. (2003) that water content and matric potentials below the root zone approach quasi-steady states in semi-arid landscapes. This would act to reduce the temporal variability of these relationships, as, at depths below the rooting zone, the solute redistribution parameters, in effect, become less dynamic.

Similarly, soil properties found to be the best predictors of solute redistribution included CO_3, Ahor, Solum and OrgC. Again, important relationships were not found between soil properties and solute redistribution within 120 cm. CO_3 was found to be inversely related to $SO4_{120\text{-}300}$ (-0.81), $NO3_{300}$ (-0.85) and $NO3_{120\text{-}300}$ (-0.84). Ahor was found to be inversely related to $SO4_{120\text{-}300}$ (-0.85), $NO3_{300}$ (-0.89) and $NO3_{120\text{-}300}$ (-0.95). Solum was also found to be inversely related to $SO4_{120\text{-}300}$ (-0.93) and $NO3_{120\text{-}300}$ (-0.85). OrgC was found to be inversely related to $NO3_{300}$ (-0.89) and $NO3_{120\text{-}300}$ (-0.85). Areas of the landscape along the transect where soil properties were indicative of well developed profiles, where moisture is available to drive pedogenic processes, were found to be areas where solute is not accumulating deep in the profile.

At first glance, these results appear counter-intuitive, in that the areas of the landscape where pedogenic processes reliant on soil water, including leaching, are strongest, solute accumulations deep in the profile are relatively low. There are two possible explanations for this. Firstly, there is the importance of the role of crop nutrient removal, whereby the areas of the landscape where soil water is most limiting to the crop (i.e. upper slopes with high *RE* and low *CA/TI*) nutrients are not removed at rates of supply, resulting in residual nutrient available for leaching below the rooting zone. Secondly, the areas of the landscape receiving relatively high amounts of water through direct precipitation inputs,

as well as run-on via surface and intrasoil water flow (i.e. lower slopes with low *RE*, and high *CA* and *TI*), while utilizing nutrients in a more efficient manner, are more completely losing residual nutrients due to greater importance of subsurface flows. These conclusions would indicate that both "high-dry" and "low-wet" areas of the landscape are potential areas of impacts to groundwater sources, although the mechanism of said impacts are different. As mentioned previously, the risk pathway associated with the "high-dry" portions of this landscape is unkown.

3.4 Summary and Conclusions

Soil profile morphology was found to be related to topography of the land surface. Crest positions had relatively poor soil profile development, with thin A horizons and solums, and shallow depth to CO_3. Mid-slope positions had relatively good profile development, with greater A horizon and solum depths, and depth to CO_3. Lower-toe and depressional positions had variable soil development, as a result of the impact of near surface water tables and varying hydrologic regimes acting at different locations in the landscape.

Very low NO_3^- concentrations were found in the rooting zone at most sample positions, indicating that crop demand during the growing season matched or exceeded supply. Accumulations of NO_3^- below the rooting zone were found along the transect, which indicate that, deep percolation of NO_3^- is an important process throughout much of this landscape. The largest accumulations were found at crest and mid-slope positions. Little NO_3^- accumulation was found at lower-toe position DS4, where the profile indicated little

net downward water movement, while at DS7, where net downward flow was apparent, accumulations were found.

Topographic variables were found to be good predictors of static soil properties. General drainage characteristic of the landscape was found to be an important factor in the development of static soil properties, with a strong inverse relationship found between *RE* and Ahor, OrgC and CO_3. Soil properties of Ahor and CO_3 were found to increase with convergent character, as evidenced by strong negative correlations to *Kh* and *Kv*. Strong positive correlations were found for *CA* and *TI* with Ahor, Solum and CO_3, indicating the importance of the extent of flow accumulation and the amount of surface and intrasoil water available to drive the pedogenic processes responsible for the development of these properties.

Topographic variables and soil properties were found to be poor predictors of solute redistribution parameters within the crop rooting zone (i.e. 120 cm). The temporal variability of these dynamic properties overshadowed the influence of topography on spatial distribution of solute for this depth increment. When greater depths (i.e. below the root zone) were considered, stronger relationships were apparent and statistically significant. Topographic variables found to be the best predictors of static soil properties were also found to be the best predictors of deep solute redistribution. Variables *RE*, *CA* and *TI* were found to best describe the spatial variability of deep solute redistribution. Strong positive correlations were found between *RE* and $SO4_{120\text{-}300}$, $SO4_{300}$, $NO3_{120\text{-}300}$ and $NO3_{300}$. Location parameters *CA* and *TI* were found to be negatively correlated to $SO4_{120\text{-}300}$, $SO4_{300}$ and $NO3_{120\text{-}300}$. Similar relationships were found between these solute redistribution parameters and static soil properties Ahor, Solum and OrgC. The higher

solute accumulations at upper slope positions may be attributed to greater crop uptake of nutrients at lower slopes where water is not as limiting to crop growth, and/or higher solute removal rates from profiles at lower slopes where convergent character results in greater accumulations of surface and intrasoil water flows and where there are greater impacts from near-surface water tables.

Trends consistent with those found in a previous study on site (Manning 1999) were found between static soil properties and LECs. Among LECs Ahor, Solum, CO_3 and OrgC increased with convergent character in the order UPS to MID to LOW. The LEC concept as a predictive tool for soil properties in this landscape is limited by differing hydrologic regime and pedogenic processes occurring at lower slope positions.

Greater significance was found between LECs for dynamic soil properties of solute redistribution when greater depths were considered. Between LECs, EC, pH and NO_3^- in the 0-300 cm depth increment increased in the order LOW < MID < UPS, with UPS being the most statistically distinct. When the 0-120 depth increment was examined, only pH was found to be significantly different between LECs, with UPS significantly higher than MID or LOW. The utility of LECs as a predictive tool for temporally variable dynamic soil properties associated with solute redistribution in the rooting zone, characterized by transient flow conditions, appears to be very limited.

The use of topographic variables and the concept of LECs have some utility for determining spatial variability of deep solute redistribution and areas of the landscape with the greatest potential for impacts to shallow groundwater sources. However, *a priori*

knowledge of soil-landscape relationships and an understanding of associated pedogenic processes and hydrologic regimes are required to achieve sensible results.

4 BROMIDE REDISTRIBUTION AS INFLUENCED BY LANDSCAPE MORPHOLOGY AND PEDOGENIC PROPERTIES IN A VARIABLE GLACIAL TILL LANDSCAPE

4.1 Introduction

Infiltration and redistribution of water and solutes through agricultural field soils are important processes that determine the availability of water and soluble nutrients to crops, and influence the entry of these constituents into shallow groundwater systems. The movement of soluble nutrients, such as nitrate, through the soil profile has important agronomic, economic and environmental implications. Redistribution of soluble nutrients through the soil profile and below the rooting zone of agricultural crops can result in reduced crop yields, economic losses of valuable fertilizer resources and negative environmental impact on groundwater sources.

The bromide ion has been used extensively in field studies as a tracer for water and solute movement through the soil profile (Smith and Davis 1974; Bruce et al. 1985; Butters et al. 1989; Bathke and Cassel 1991; Bathke et al. 1992; Afyuni et al. 1994; Olson and Cassel 1999). The use of bromide allows for the study of processes of water and soluble nutrient movement in natural soil environments. Bromide movement has been found to be very similar to that of nitrate (NO_3^-), particularly in subsoils (Smith and Davis 1974). However, in surface soils, Smith and Davis (1974) note that biological influences, such as denitrification and plant uptake of NO_3^-, can result in more rapid bromide movement, relative to nitrate.

The chemical and physical processes of solute transport are relatively well understood, particularly in laboratory soil systems and homogeneous field soils (Biggar and Nielsen 1967; Bruce et al. 1985; Afyuni et al. 1994). However, knowledge of these processes in natural field soils and complex topography is not as well developed. Most published field studies have been conducted on level landscapes (Afyuni et al. 1994). In complex soil-landscapes, processes of infiltration and redistribution of water and solutes are influenced by pedologic, topographic and hydrologic conditions. The spatial and temporal variability of these conditions across the landscape result in diverse patterns of water and solute redistribution throughout the landscape. It is well known that soil properties, such as profile depth, horizonation, water content, and physical and chemical properties vary with landscape position (Bathke and Cassel 1991; Afyuni et al. 1994). Manning (1999) found that delineation of a landscape within the experimental field into upper, mid and lower landscape element complexes was useful in explaining variability in static and dynamic soil properties. For example, A horizon depth, solum depth, depth to carbonates, percent organic carbon and soil pH were all found to increase with convergent character in the landscape. The systematic variation in soil property distribution in relation to landscape morphology may be used to explain variability in water and solute redistribution across the landscape. Knowledge of the influence of soil properties on vertical and lateral redistribution of soluble nutrients in relation to landscape morphology may be applied to an improved agronomic and environmental nutrient management system.

The objective of this study was to determine the influence of pedogenic properties in relation to landscape morphology on vertical and lateral redistribution of a bromide tracer in a variable glacial till landscape under zero tillage agricultural management.

4.2 Materials and Methods

4.2.1 Site Description

The study site was located in the Newdale Plain physiographic sub-section, which is characterized by undulating to hummocky topography on ground moraine with numerous potholes, sloughs and small, intermittent lakes (Podolsky 1988). The dominantly loam to clay loam textured soils were developed on glacial till consisting of a heterogeneous mixture of boulders, cobbles, gravel, sand, silt and clay, derived from shale, limestone and granitic fragments. The complex topography precludes a developed surface drainage network, with variable surface drainage that ranges from excessive runoff on steeper slopes to prolonged inundation in depressional areas (Podolsky 1988). Removal of water from small catchment areas is generally through evapotranspiration and shallow groundwater flow.

Detailed soil information (1:5 000) of the study site indicates it is a typical recharge area in the region, where infiltration and leaching are dominant processes acting on the soil-landscape (Fitzmaurice et al. 1999). The well-drained Newdale series (Orthic Black) is the dominant soil at the study site, and occurs in mid to upper slopes. Crest positions are characterized by well to rapidly drained Cordova series (Calcareous Black), while the imperfectly drained Angusville series (Gleyed Eluviated Black) is found in lower to mid positions. Detailed soil series descriptions are found in Appendix I.

In a previous study, conducted in a similar glacial till landscape near Hamiota, Manitoba, Stolte et al. (1992) found the saturated permeability of the till parent material to be

approximately 1 x 10^{-04} m h^{-1}. They noted the 1 m of topsoil had a higher permeability, measured to be approximately 0.02 m h^{-1}, and attributed this to biopores and desiccation cracks in this layer.

Climate data from one of the closest Environment Canada weather stations, in Virden, Manitoba, indicate the study site near Miniota, Manitoba has a mean annual temperature of 2.5°C and a mean annual frost free period of 120 days (Fitzmaurice et al. 1999). The climatic data indicate mean annual precipitation is approximately 460 mm, of which 298 mm occurs during the growing season (i.e. May 1 to September 30).

The study field has been under continuous annual crop production since 1976 and zero tillage management since 1988 (Ron Bell, personal communication). Field crops for the 1999 and 2000 cropping seasons were wheat and canola, respectively. Mechanical soil disturbance through field operations consisted of anhydrous ammonia application (¾" knife opener) in the fall of 1999, and direct spring seeding and fertilizer application (narrow opener).

4.2.2 Bromide Application and Soil Sampling

In November 1999, 3 sites were established in the study field (SE32-14-25W) to conduct the landscape-scale bromide tracer experiment. The sites encompassed similar soil-slope complexes at different locations throughout the field, selected following groundtruthing to confirm the occurrence of distinct soil-landscape complexes. Three representative soil-slope associations were selected for the study:

- Cordova series (Calcareous Black) – Crest;
- Newdale series (Orthic Black) – Midslope; and,

- Angusville series (Gleyed Eluviated Black) – Depression.

The qualitative landscape positions of crest, midslope and depression were selected to represent quantitative analogies of dissipation, transit and accumulation zones of surface water flows, respectively. These quantitative zones of the landscape are discussed later. A total of 15 bromide tracer plots were established at the 3 sites; 9 at site 1, and 3 at each of sites 2 and 3 (Figure 4.1). Site 1 was established as the main plot, with 3 plots replicated within each soil-slope association. Sites 2 & 3 each consisted of 1 plot within each soil-slope association. A photo mosaic provides an indication of the slope morphology at site 1, with marker stakes located at environmental monitoring sites at the crest, midslope and depression plots (Figure 4.2).

Each plot received bromide application on November 5, 1999 in 0.3 m x 3.0 m = 0.9 m^{-2} bands oriented perpendicular to the dominant slope direction. Bromide was hand-applied in granular potassium bromide (KBr) form, at a rate of 600 g KBr m^{-2} (403 g Br^{-} m^{-2}). An application frame, sub-divided into six areas of 0.3 m x 0.5 m was used to ensure KBr was applied precisely and uniformly over each plot. Prior to KBr application, loose surface residue was carefully removed from each plot. Residue was re-applied following solute application.

Intact soil cores were taken in close proximity to each plot on November 1, 1999, using a Gidding's trailer-mounted hydraulic soil exploration device. The cores were taken in 3.7 cm diameter polyethylene sleeves to a maximum depth of 120 cm, and were returned to the laboratory for analysis. Detailed soil profile descriptions were conducted on the intact cores in a manner consistent with the guidelines established by the Expert Committee on

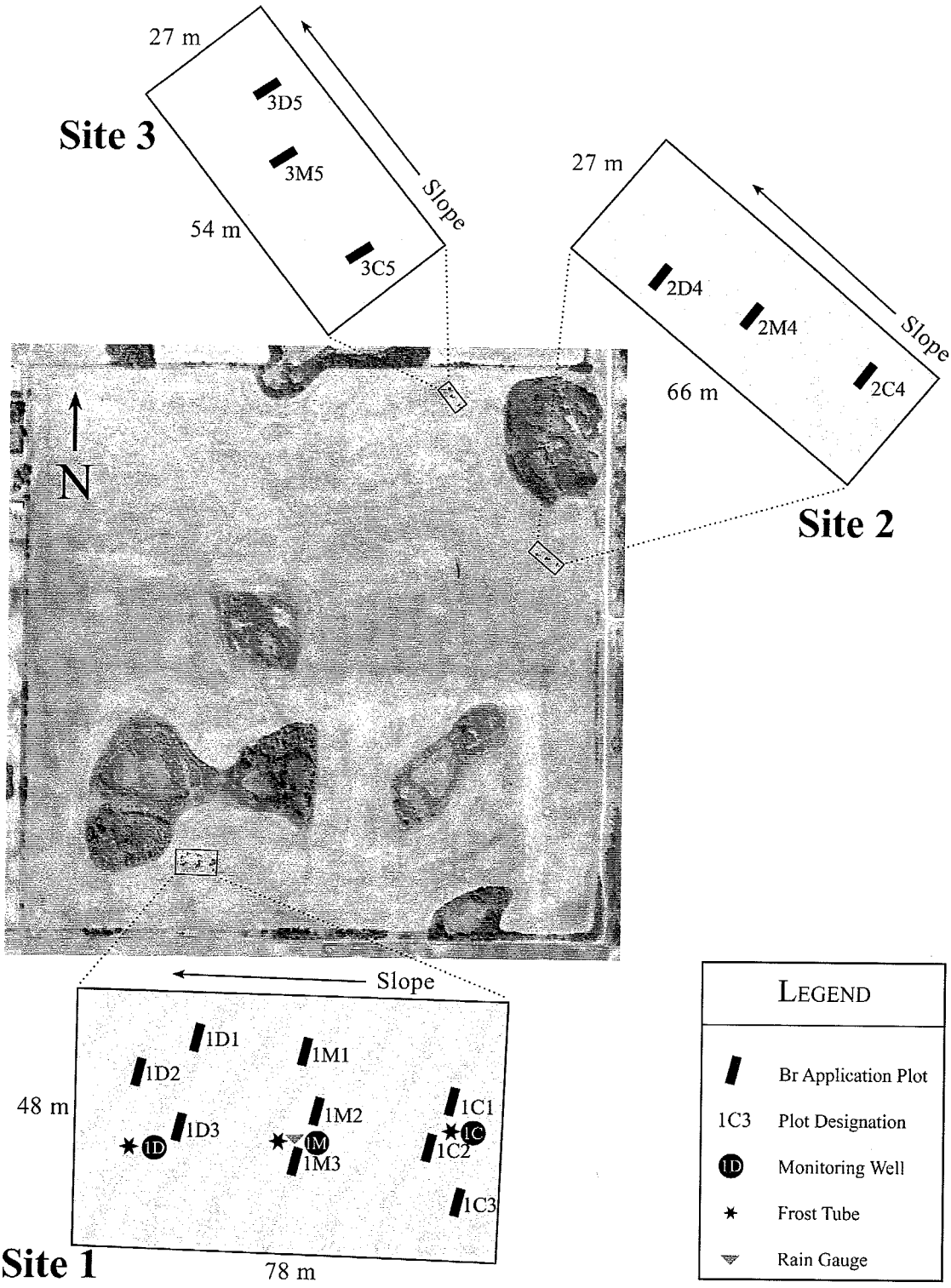


Figure 4.1 Aerial photograph of the study field, and relative site and plot layouts.

Figure 4.2 Photo mosaic of Site 1.

Soil Survey (1983) and the Soil Classification Working Group (1998). Detailed soil profile descriptions are found in Appendix V, while soil profile terminology is defined in Appendix III. Indicators of pedogenic and hydrologic processes include the A horizon depth (the depth of all A horizons), the solum depth (depth of A & B horizons combined), depth to carbonates (indicated by presence of effervescence upon addition of dilute HCl), and profile development index (PDI) (Fuller, personal communication, AXYS Environmental Consulting Ltd.). The profile development index provides a relative measure of the degree of soil profile development between landscape positions (Manning 1999). The PDI is based on depths of B horizon development relative to solum depth. In calculating the PDI, B horizons are given relative weightings of 0, 1, 2 3 and 4 for no B horizon, Bmk, Bm, Btj and Bt, respectively. The PDI calculation is as follows:

$$PDI = \sum (\text{B horizon depths x relative weights}) / (\text{solum depth}) \qquad [3.1]$$

Organic Carbon analysis was conducted on Ap/Ah horizon soils from each plot. Inorganic carbon was removed prior to organic carbon measurement by adding 10 ml of 6M HCl in distilled water to soil and heating the soil slurry on a hot plate for 10 minutes (Tiessen et

al. 1983). Samples were rinsed with 240 ml of distilled water to remove inorganic ions present. Soil organic carbon was determined by dry combustion of 0.12 g of oven-dried soil with a LECO 2000 CNS determinator (Nelson and Sommers 1982).

Additional bulk soil samples were taken in very close proximity to each plot on November 1 & 6, 1999 using the Gidding's soil exploration device and 6 cm solid stem auger. Samples were taken to a depth of 120 cm in increments of 0-15, 15-30, 30-60, 60-90, and 90-120 cm. A total of 15 plots x 5 depths = 75 samples were taken. Samples were returned to the laboratory and were frozen until analyses were conducted. Particle size analysis (PSA) was conducted using the hydrometer method, modified from Gee and Bauder (1986). All samples were pre-treated using a chemical dispersing solution consisting of 47.6 g L^{-1} Na-hexametaphosphate (HMP) and 10.6 g L^{-1} Na_2CO_3. Organic matter removal was conducted on samples where organic matter content was deemed greater than 5% using a pre-treatment of 10% H_2O_2. Electrical conductivity (EC), as a measure of soluble salts, and 1:2 pH in water values were determined using the fixed-ratio extract method (Hendershot et al. 1993; Janzen 1993). While not discussed in the text, EC and pH values are found in Appendix VI with the PSA data.

Soil bulk density was determined in-field using the Auger method (Zwarich and Shaykewich 1969). Bulk density samples were taken on June 18 & October 26, 2001 with an Iwan-type 12 cm flat-bottom auger. Wet soil, from depth increments of 0-15, 15-30, 30-60, 60-90 and 90-120 cm, was weighed in-field to provide a total wet mass. Approximately 300 g of the wet soil was sub-sampled and returned to the laboratory for determination of gravimetric moisture content (Topp 1993). Using the measured moisture content, the total dry mass for each sampled increment was calculated. Bulk density

values were determined using the total dry mass and the calculated hole volume (Appendix VI). Attempts were made to measure in-situ hydraulic conductivity using a Guelph permeameter. However, these results were extremely variable due to the variable nature of the zero tillage rooting zone in this glacial till environment, and, therefore, are not presented here. Variability was attributed primarily to biopores of varying sizes.

Samples were taken to quantify bromide redistribution through exploratory and detailed sampling events. Initial exploratory sampling events were conducted prior to each detailed sampling event to determine the vertical and lateral extent of bromide redistribution. Exploratory sampling events were conducted on May 18 and September 17, 2000. The objective of these sampling events was to provide information to allow for design of the detailed sampling schemes to most adequately assess the bromide plumes. Samples were taken at various depths and distances from the bromide application plots at 3 select plots (1 from each soil-slope association), using a JMC Backsaver probe with a 1.9 cm diameter coring tube. Soil bromide concentrations were measured in-field using a Br^- ion selective electrode (Orion 9635BN) in fixed ratio soil to water (1:1) mixtures (data not presented).

Detailed soil sampling for bromide and water content was conducted on 2 sampling dates: 1. "May" – May 31, June 3 & 4, 2000; and, 2. "October" – October 14 & 15, 2000. Samples were taken at each plot along transects located at 3 distances along plot (DAP), and at various downslope distances from plot (DFP), for a total of 14 and 17 sample locations for the May and October sampling dates, respectively (Figure 4.3). Samples were taken using a JMC Backsaver probe with a 1.9 cm diameter coring tube to variable depths, to a maximum depth of 120 cm, in increments of 0-15, 15-30, 30-60, 60-90 and

90-120 cm. Samples were sealed in air-tight plastic bags, returned to the laboratory, and frozen until analysis. The total numbers of samples taken were:

- May – 15 plots x 14 locations/plot x variable depths = 885 samples
- October – 15 plots x 17 locations/plot x variable depths = 975 samples

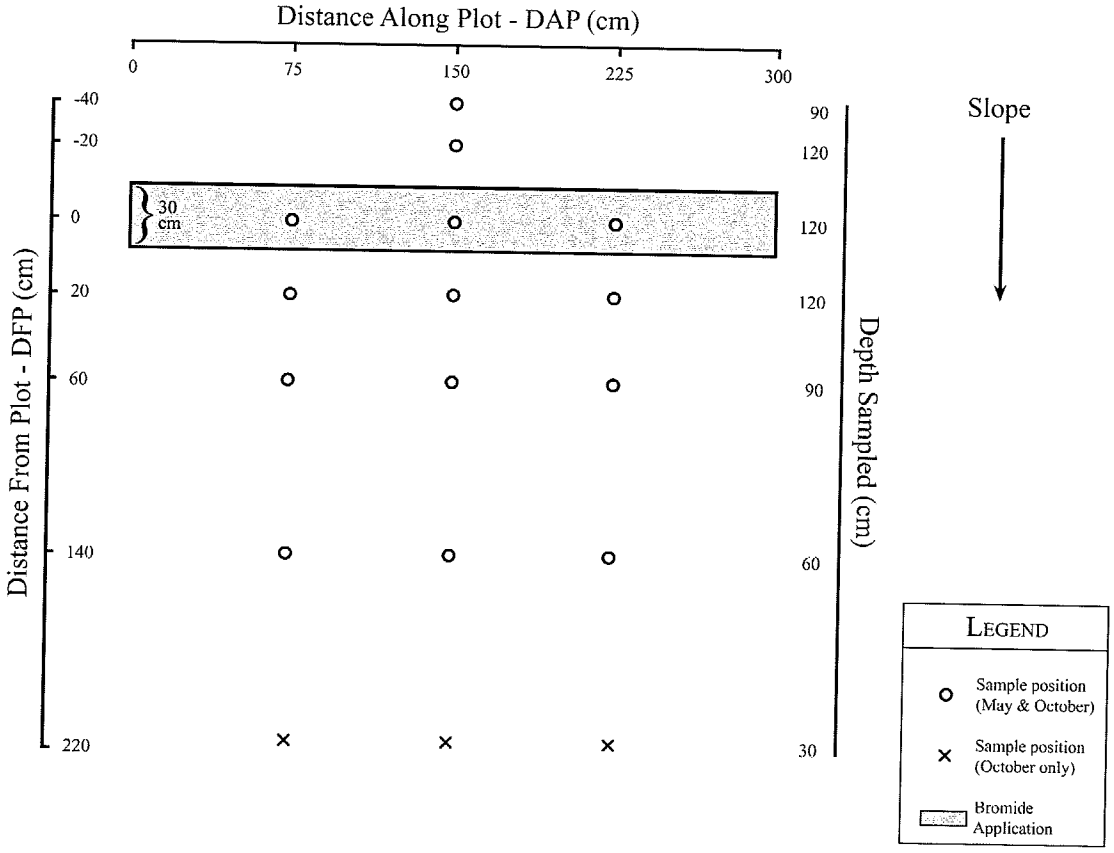


Figure 4.3 Individual plot layout and detailed bromide sampling locations.

Samples were oven-dried at 105°C for 48 hours to determine gravimetric moisture content (Topp 1993), were ground with a mortar and pestle, and were passed through a 2 mm sieve to remove clods and stones. Sub-samples of 10.0 g (+/- 0.1 g) of oven-dried soil were placed into 50 mL plastic centrifuge tubes with 30 mL dH_2O (+/- 0.1 mL), shaken mechanically for 30 min on a flat-bed shaker, vortexed to remove suspended soil from

tube sides, and solution-filtered using pre-rinsed Whatman #42 filter paper into 20mL scintillation vials (United States Environmental Protection Agency (USEPA) 1994; American Public Health Association (APHA) 1998). Scintillation vials were capped, refrigerated and stored until analysis. Samples were analyzed for bromide (Br^-), chloride (Cl^-) and nitrate (NO_3^-) using a Dionex Liquid Chromatography system with a conductivity detector (Eluant: 1.7mM $NaHCO_3$, 1.8mM Na_2CO_3 50mM H_2SO_4; sample loop: 100 µL; flow: 2.0 mL min^{-1}; column: Dionex AG4A and AS4A). Chloride and nitrate results are not discussed in the text.

Gravimetric water content (not discussed in text) and solute concentrations are found in Appendix VII for the May sampling event and Appendix VIII for the October sampling event.

4.2.3 Environmental Conditions

An Onset recording rain gauge was installed at site 1 in June 1999 and was used to monitor rainfall throughout the course of the study. Weather data was collected from the closest Environment Canada weather stations (i.e. Virden, Birtle, Hamiota & Shoal Lake, Manitoba) and was used in conjunction with data collected on site to provide precipitation estimates. Precipitation data throughout the course of the study is found in (Figure 4.4). A total of 149.0 mm of cumulative precipitation, 90.6 mm of which fell as rain, had occurred by May 31 (209 days following application), the date of the first bromide sampling event. By October 15 (346 days following bromide application), the date of the second bromide sampling event, a total of 352.9 mm of precipitation had occurred, with 203.9 mm occurring between sampling dates.

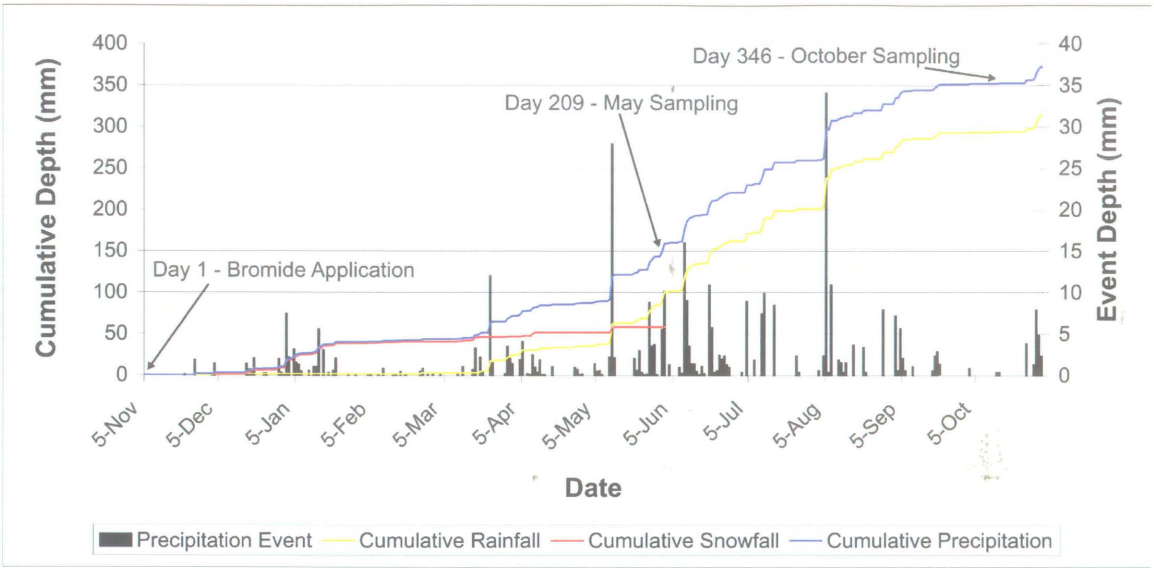


Figure 4.4 Precipitation throughout the course of the study.

Based on regional averages, between November 26, 1999 and May 12, 2000, 58.4 mm of water-equivalent snowfall had occurred, and peak snow depths were found to be 26.7 cm on January 22. One-time snow depths measured at site 1 on January 23, were found to be 15.4, 13.5 and 12.6 cm for crest, midslope and depression positions, respectively. At site 2, they were found to be 12.7, 10.8 and 12.3 cm for crest, midslope and depression positions, respectively, while at site 3, snow depths were 14.8, 9.1 and 28.6 cm, respectively. Snow depths measured on-site generally corresponded to stubble depths, and indicated that snow redistribution was an important process. Snow depths were notably greater around willow-ringed wetland areas. Snow redistribution may have resulted in an overestimation of snow contribution to total precipitation estimates in this agricultural field environment.

Groundwater monitoring wells were installed to monitor water table fluctuations throughout the course of the study. Wells were located at each landscape position

examined at site 1, in close proximity to the bromide plots (Figures 4.1 & 4.2). The wells consisted of 2" PVC screen pipe installed to depths sufficient to monitor near-surface water table fluctuations over the duration of the study (i.e. 3-4 metres). The crest well remained dry throughout the course of the study. Depth to shallow groundwater was measured at the three landscape positions periodically throughout the course of the study, and estimated water table surfaces were drawn based on collected data (Figure 4.5). Frost tubes, installed adjacent to the well positions at site 1, were used to monitor depth to and thickness of the frost table throughout the course of the study. Measured frost depths were greatest on March 11, 2000, with depths of 113, 114 and 98 for crest, midslope and depression positions, respectively. Frost layers extended from 32 to 102 cm, 41 to 105 cm and 17 to 90 cm on April 16, and 54 to 100 cm, 65 to 103 cm and 41 to 90 cm on April 23 for crest, midslope and depression positions, respectively. No frost was found on May 15.

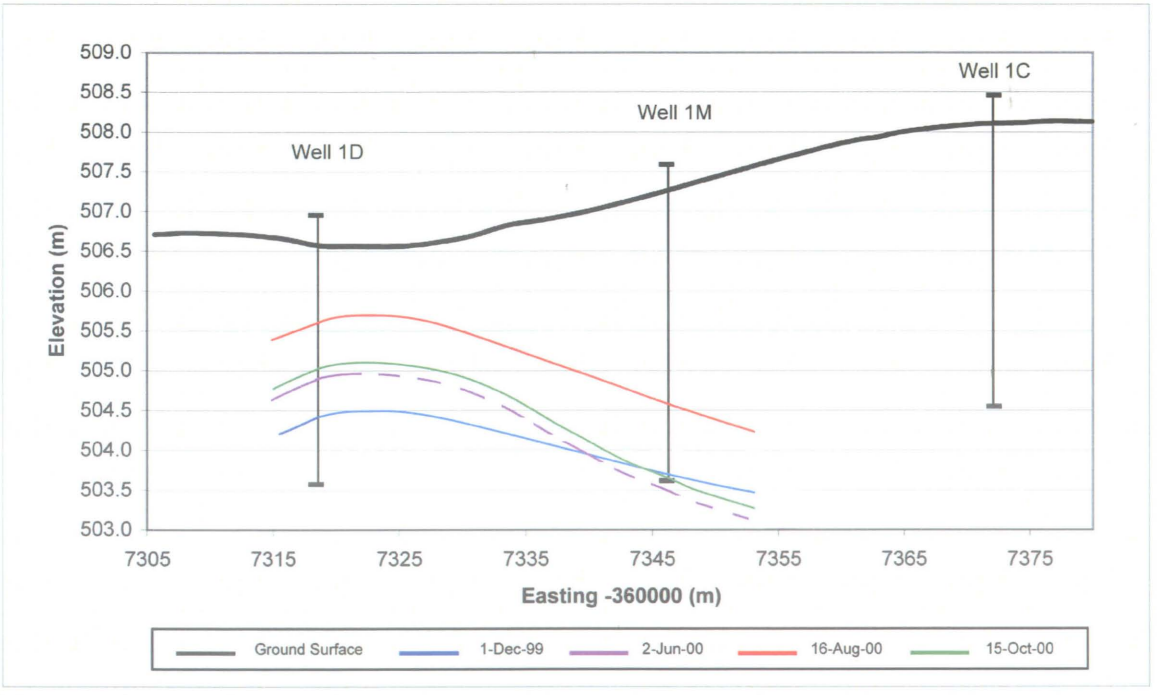


Figure 4.5 Estimated water table depths throughout the course of the study.

4.2.4 Bromide Redistribution Parameters

Several parameters were calculated and used to quantify bromide redistribution. Bromide recovery rates were determined by conducting a mass-balance of applied bromide recovered during each sampling period. Bromide recovery rates, expressed as a percentage of total applied bromide, were determined for the total sampling depth (% Br), the top 30cm (% Br_{30}) and the top 60cm (% Br_{60}). Vertical and lateral redistribution functions were determined to provide a relative measure of bromide redistribution in the vertical and lateral directions. The vertical redistribution function (V_f) was calculated using depth-weighted values of the mass of bromide recovered below the surface sample layer, as follows:

$$V_f = \{(g\ Br^-_{15\text{-}30cm})(22.5) + (g\ Br^-_{30\text{-}60cm})(45) + (g\ Br^-_{60\text{-}90cm})(75) + (g\ Br^-_{90\text{-}120cm})(105)\} / (\%\ Br) * 100 \quad [3.2]$$

where 22.5, 45, 75 and 105 represent the mean depth sampled in cm. The depth-weighted values were adjusted for the total Br recovered (% Br).

The lateral redistribution function (L_f) was calculated using downslope-distance-weighted values of the mass of bromide recovered beyond the area of bromide application, as follows:

$$L_f = \{(g\ Br^-_{DFP20cm})(20) + (g\ Br^-_{DFP60cm})(60) + (g\ Br^-_{DFP140cm})(140) + (g\ Br^-_{DFP220cm})(220)\} / (\%\ Br) * 100 \quad [3.3]$$

where 20, 60, 140 and 220 are the representative distances downslope from the bromide application band in cm. The downslope distance-weighted values were adjusted for the total Br recovered (% Br).

The ratio between the vertical and lateral redistribution functions was determined as V_f/L_f.

The vertical depth to the center of mass (Q50) of recovered bromide was determined by dividing the cumulative amount of bromide recovered at a sample location by 2, then estimating by interpolation the depth above which this amount was recovered (Bathke et al. 1992; Olson and Cassel 1999). This value represents the depth to which 50 % of measured bromide has leached and corresponds to the piston or matrix front of solute movement. Depth to center of mass was determined at the center of each plot (DFP = 0 cm) ($Q50_0$) and at a distance of 20 cm downslope (DFP = 20 cm) of each plot ($Q50_{20}$).

4.2.5 Topographical Survey and Data Analysis

Detailed topographic surveys were conducted over all sites using a Sokkia Total Station. Site toposurveys were conducted at grid intervals of 3.0 m x 3.0 m. Plot toposurveys were conducted at 0.3 m x 0.3m grid intervals (data not presented). Site toposurvey origins and plot positions were geo-referenced (UTM coordinates) using a differentially-corrected Trimble Global Positioning System. Irregular Digital Elevation Models (DEMs) were produced using the topographic data, with all grid points geo-corrected using the collected UTM data. Irregular DEMs were converted to regular DEMs by Delaunay triangulation and piecewise smooth interpolation (Watson 1992). Using the regular DEMs, Digital Terrain Models (DTMs) were produced for slope gradient (G), horizontal curvature (K_h), vertical curvature (K_v), mean curvature (H) and accumulation curvature (K_a) (Table 4.1) using Landlord software (Florinsky et al. 1995). Using data on mean and accumulation curvatures, models of dissipation, transit and accumulation zones of surface

flows were produced for each DEM. The concept of dissipation, transit and accumulation zones provides rigorous, quantitative delineations of the landscape, which are analogous to commonly used qualitative geomorphic terms of crest, midslope and depression (Florinsky et al. 2002).

All plot positions were triangulated using wells and steel markers in November 1999, to ensure plot positions could be precisely relocated following field operations.

4.2.6 Statistical Procedures

Statistical analyses of all data were conducted primarily using Statistical Analysis Systems 8.02 software (SAS Institute 2001). Nonparametric statistical procedures were utilized due to the non-normality of data distribution. Kruskal-Wallis one-way analysis of variance by ranks was used to determine the effect of landscape position on bromide redistribution (Daniel 1990). One-way analysis of variance was conducted for site 1, site 2 and site 3 separately, as well as for all sites combined. When effects due to landscape position were determined to be significant, Dunn's multiple comparison using rank sums procedure was utilized to determine differences between samples (Daniel 1990). Friedman two-way analysis of variance by ranks was used to test for effects of landscape position on bromide redistribution over all sites, using site as a blocking factor (Daniel 1990). Spearman rank correlation coefficients were determined to examine the relationship between bromide redistribution parameters, pedologic attributes and topographic variables (Daniel 1990).

Table 4.1 Definition and physical interpretation of topographic variables.

Variable[1]	**Definition**	**Physical interpretation**
Slope gradient (G), °	An angle between a tangent plane and a horizontal one at a given point on the landscape	Velocity of substance flows
Vertical curvature (Kv), m^{-1}	A curvature of a normal section of a landsurface by a plane, including gravity acceleration vector at a given point on the landsurface	Relative deceleration of substance flows
Horizontal curvature (Kh), m^{-1}	A curvature of a normal section of the landsurface, orthogonal to the section of vertical curvature at a given point on the landsurface	Convergence of substance flows
Mean curvature (H), m^{-1}	A half-sum of horizontal and vertical curvatures	Flow convergence and relative deceleration with equal weights
Accumulation curvature (Ka), m^{-2}	A product of horizontal and vertical curvatures	Degree of flow accumulation

[1] Shary (1991); Shary (1995); Florinsky and Kurykova (1996); Florinsky et al. (2002).

4.3 Results and Discussion

4.3.1 Soil Profile Attributes

Detailed soil profile descriptions conducted at each plot and laboratory soil analysis provided measures of pedologic attributes that influence pedogenic and hydrologic processes occurring throughout the study area. Three soil subgroups and corresponding series were encountered in the study: Calcareous Black Chernozem (CA.BL) – Cordova series (CVA), Orthic Black Chernozem – Newdale series (NDL), Gleyed Eluviated Black Chernozem (GLE.BL) – Angusville series (ANL). Soil morphological differences between theses soils are apparent in representative soil profiles of the Cordova, Newdale and Angusville series (Figures 4.6, 4.7 & 4.8, respectively). Detailed soil profile descriptions are found in Appendix V, while soil profile terminology is defined in Appendix III. Select indicators of pedologic and hydrologic condition, including soil subgroup, A horizon thickness (A hor), solum thickness (Solum), depth to carbonates (CO_3), profile development index (PDI) and organic carbon (Org C) are found in Table 4.2.

Soil profile development results in variable soil hydraulic properties within a soil profile and across the landscape, due to changes in soil profile characteristics (Bathke et al. 1992; Richardson et al. 1992; Thompson et al. 1998; Olson and Cassel 1999). Physical discontinuity in soil properties occurs at transitions within the soil profile located at horizon boundaries. Transitions between horizons may be abrupt or gradual in nature, and differences in physical characteristics between horizons vary in degree. The nature and

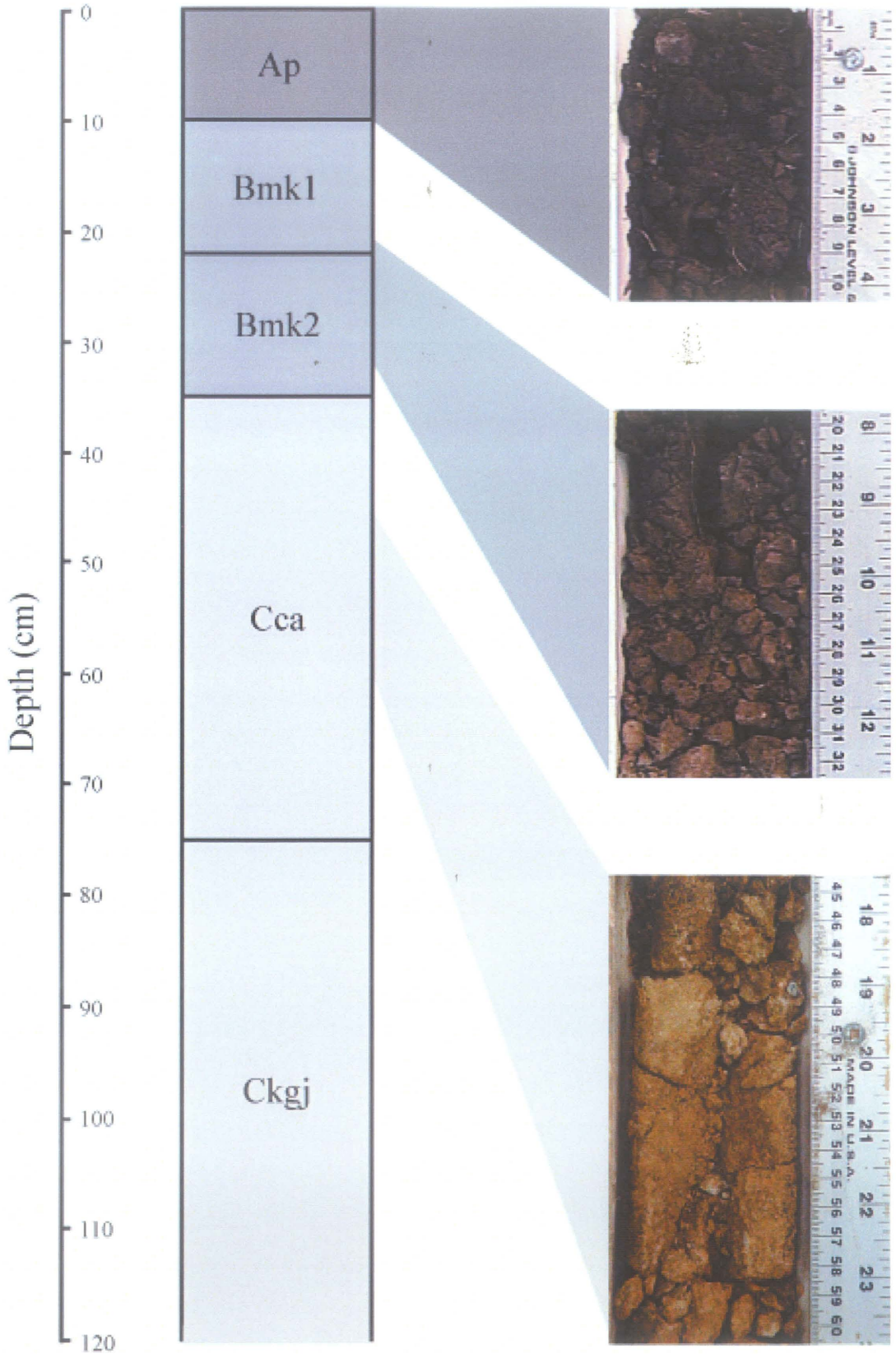


Figure 4.6 Representative Cordova series profile for the crest position.

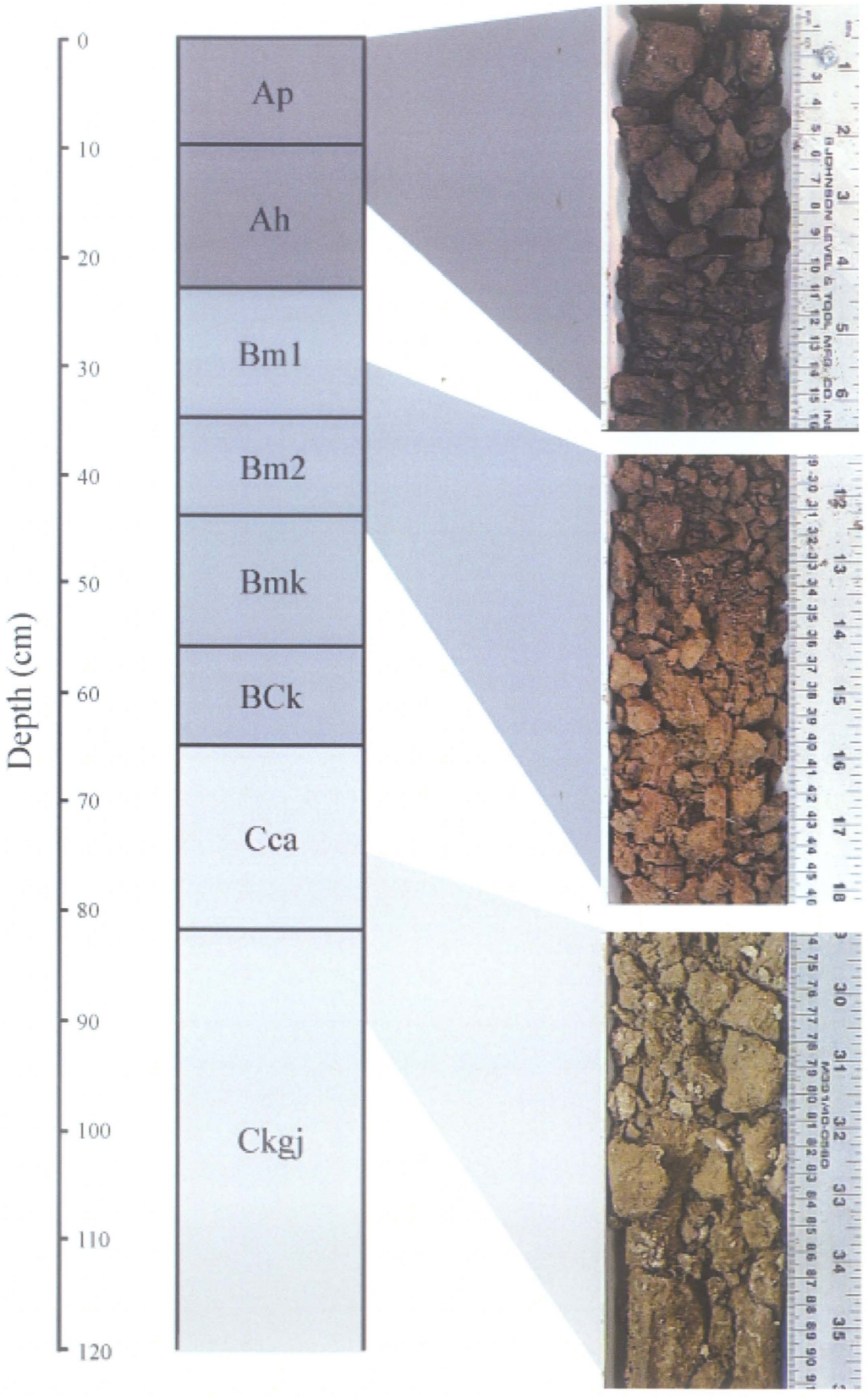


Figure 4.7 Representative Newdale series profile for the midslope position.

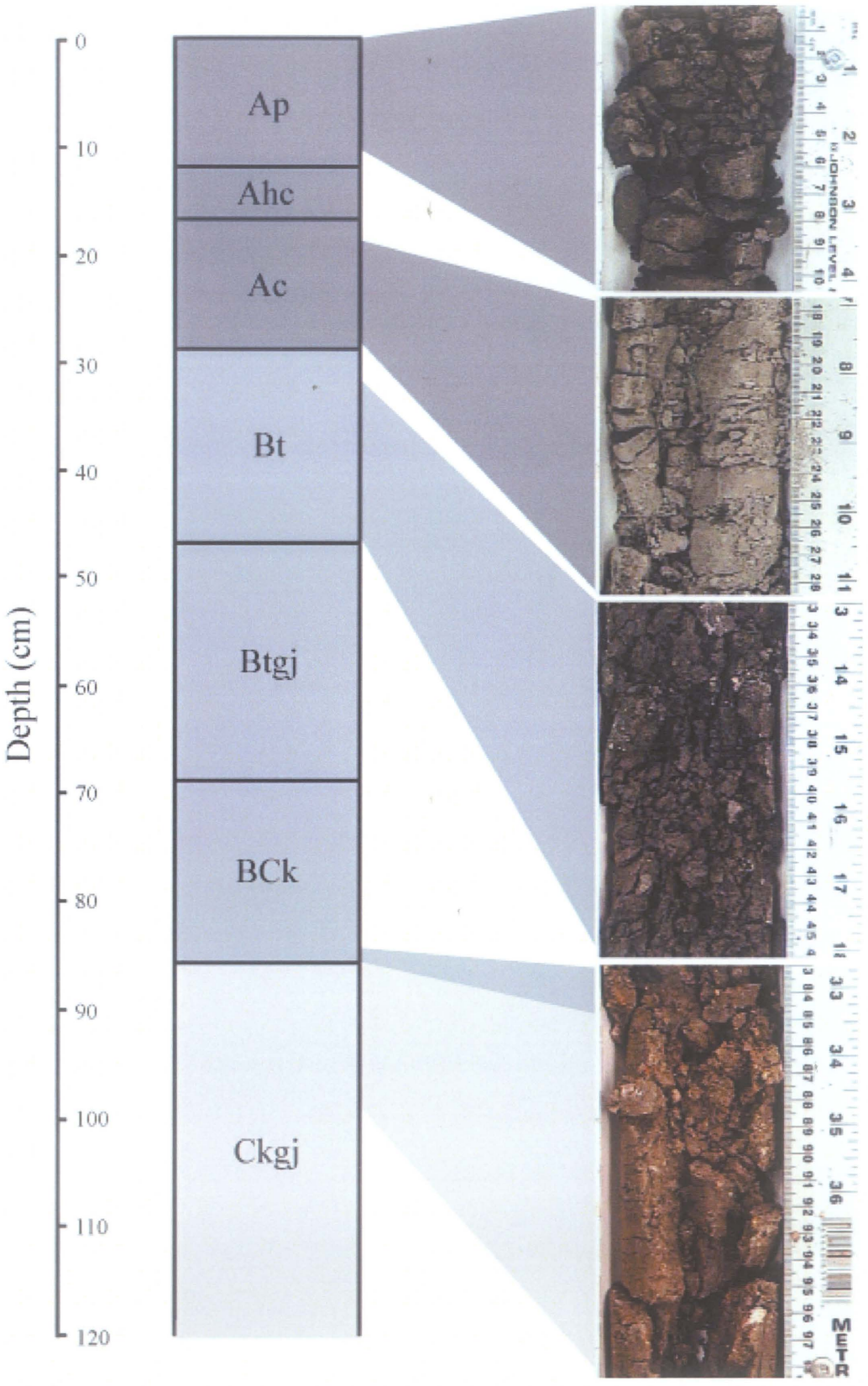


Figure 4.8 Representative Angusville series profile for the depression position.

Table 4.2 Indicators of pedologic and hydrologic condition for all plots.

Plot ID	Soil Subgroup	Soil Series	A Horizon Thickness	Solum Thickness	Depth to CO_3	PDI	Org C
			cm				- % -
			Site 1				
			Crest				
1C1	CA.BL	CVA	13	28	0	1.54	2.10
1C2	CA.BL	CVA	18	33	18	1.64	1.47
1C3	O.BL	NDL	20	44	32	1.18	1.62
			Midslope				
1M1	O.BL	NDL	23	65	36	2.05	2.34
1M2	O.BL	NDL	14	49	37	1.92	1.86
1M3	O.BL	NDL	10	42	26	1.62	1.82
			Depression				
1D1	GLE.BL	ANL	34	82	63	2.45	2.80
1D2	GLE.BL	ANL	29	74	61	2.66	3.04
1D3	GLE.BL	ANL	23	61	50	2.70	3.17
			Site 2				
			Crest				
2C4	O.BL	NDL	8	35	22	1.66	2.48
			Midslope				
2M4	O.BL	NDL	16	48	43	2.17	2.84
			Depression				
2D4	GLE.BL	ANL	29	105	69	2.73	2.20
			Site 3				
			Crest				
3C5	CA.BL	CVA	10	35	10	2.00	2.91
			Midslope				
3M5	O.BL	NDL	11	46	35	2.57	1.96
			Depression				
3D5	GLE.BL	ANL	30	92	92	3.71	1.56

degree of change in physical characteristics at these transitions affect, to varying degrees, hydraulic characteristics throughout the soil profile. Of particular importance to water flow in this recharge environment, where net water movement is downward through the

soil profile, are the occurrence of eluvial and illuvial horizons, characterized by transportation and deposition, respectively, of suspended and dissolved soil material within the solum. Evidence of illuvial and eluvial processes were apparent at all sites and increased in importance from crest < midslope < depression. Little evidence of illuvial processes were found at crest plots, as evidenced by the occurrence of clay skins on B horizon ped faces at only 2 of 9 crest plots (Appendix V). Thicker B horizons, clay skins on B horizon ped faces and the occurrence of an illuvial Btj horizon in the midslope plot at site 3 (3M5) provided evidence to suggest that illuvial processes have been relatively stronger at this landscape position (Figure 4.7). The occurrence of well developed eluvial horizons (i.e. Ahe, Ae) overlying illuvial horizons (i.e. Bt) at all depression plots indicated that downward water flux has played an important role in pedogenic and hydrologic processes at this position in the landscape (Figure 4.8). The occurrence of clay skins on ped faces, a characteristic of Bt horizons, has been shown to reduce solute entry into the soil matrix, resulting in more solute available for preferential flow (Chen et al. 1997). However, Chen et al. (1997) note that when solute does enter the soil matrix, clay coatings may reduce leaching losses via preferential flow.

An important physical factor which influences soil hydraulic properties is soil structure. The nature and degree of soil structure, as well as the transition between different structures, are all important to consider when analyzing water flow pathways through a soil profile. Jabro and Fritton (1990) found lateral movement was more important than vertical at a structural discontinuity between sub-angular blocky- and prismatic-structured B horizons. A well-structured clay loam soil may permit more water flow than a poorly-developed one, however a greater proportion of this water flow may be considered by-

pass, or preferential, flow in that it does not enter the soil matrix. This is of particular importance in blocky-structured clay soils. The degree of blocky structure development generally increased from Bm < Btj < Bt (Figures 4.6, 4.7 & 4.8), and hence one would expect rapid preferential flow through B horizons to increase in the same order. Another important consideration is platy-structured eluvial A horizons, where structure is dominantly horizontal planar in nature (Figure 4.8). The degree of platy structure generally increased from Ahe < Aej < Ae. Little research has been conducted on the influence of platy structure on water flow through the soil profile. Some patterns of soil structure between profiles at different landscape positions were notable. Structure development in soil profiles generally increased from crest < midslope < depression. Crest plots were generally characterized by Apk / Bmk / Ck horizon sequences with granular / granular – angular blocky / prismatic – massive structures (Figure 4.6, Appendix V). Midslope plots were generally characterized by Ap / Bm / Ck horizon sequences with granular / blocky / prismatic – massive structures (Figure 3.6), while depression plot horizons generally followed the trend Ap / Ae / Bt / Ck with corresponding granular / platy / sub-angular blocky / prismatic – massive structures (Figure 4.8). It would be expected that the better-structured blocky soils in the midslope and depression plots would favour rapid preferential flow in relation to the more poorly structured soils in the crest plots.

Considerable variability in soil properties was found both among and within sites, however less variability occurred within each landscape position. Soil development, as indicated by soil subgroup, increased from crest < midslope < depression. The Cordova series dominated crest plots, while the Newdale and Angusville series were found

exclusively at midslope and depression plots, respectively. Mean values of soil development indicators demonstrate that certain trends were consistent with landscape position, both within site 1 and among all sites (Figure 4.9). Thickness of A horizon was similar between crest and midslope plots, however was much greater at depression plots (Figure 4.9a). Solum thickness, depth to CO_3 and Profile Development Index all increased from crest < midslope < depression (Figure 4.9b,c,d). Organic carbon levels also followed the trend crest < midslope < depression (Figure 4.9e). These results demonstrate systematic variability of pedologic attributes across the landscape.

Particle size distribution was most consistent with depth at crest plots, as indicated by clay depth profiles (Figure 4.10) Clay content increased markedly with depth at midslope and depression plots, indicating illuviation, or translocation of clay particles, is an important process at these locations of the landscape. The depth of maximum clay content generally corresponded to illuvial Bt horizons in these profiles. An abrupt decrease in clay content in depression plots, generally in the 15-30 cm depth increment, corresponded to the occurrence of eluvial Ae horizons in these profiles. Particle size distributions indicate that translocation of clay particles through the soil profile increased from crest < midslope < depression. This trend, a result of illuvial processes, indicates the relative importance of water movement acting across the landscape. Soil profiles within site 2 tended to have slightly finer soil textures than did sites 1 and 3. Within site 1, particle size distribution with depth was more consistent between depression plots, than between either crest or midslope plots. These results are consistent with Stolt et al. (1993), who found more variability in particle size distribution in C horizons relative to eluvial or illuvial horizons. Variable levels of influence of pedogenic and hydrologic processes across the

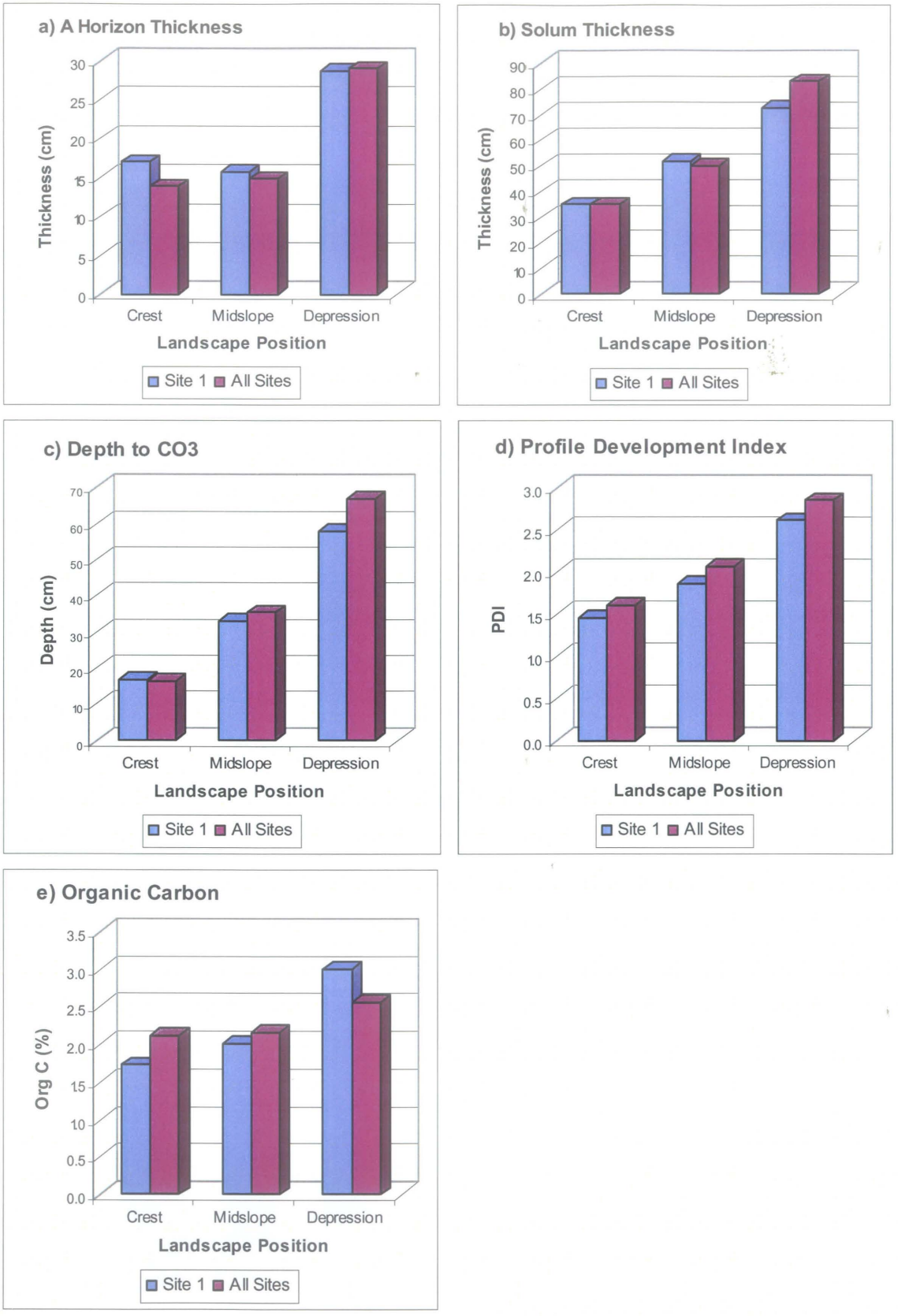


Figure 4.9 Mean values of indicators of pedologic and hydrologic processes.

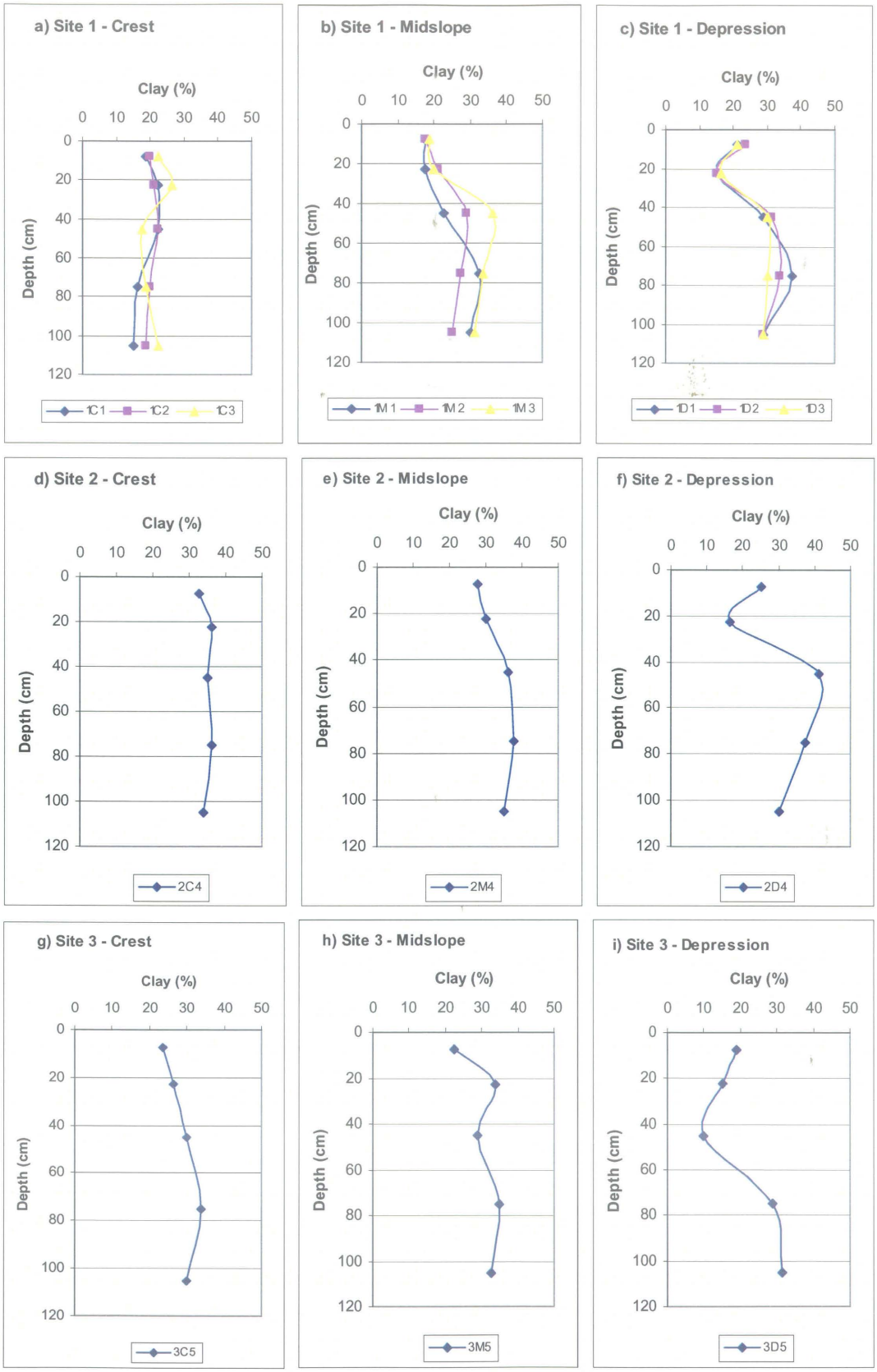


Figure 4.10 Clay depth profiles for all plots.

landscape has resulted in more change or ordering of horizons, and hence soil properties, from crest to midslope to depression. Increased water input into the profile occurs from crest to midslope to depression due to the fact that crest positions receive only direct input (i.e. precipitation), while midslope and depression positions receive run-on from upslope positions, in addition to direct inputs.

Bulk density depth profiles indicate that, within each plot, bulk density was lowest at the soil surface and increased with depth (Figure 4.11). The lower bulk density values at the soil surface can be attributed to higher organic matter levels, biological activity and mechanical soil disturbance during agricultural field operations, which Elliot and Efetha (1999) note all increase under zero tillage management. In many of the profiles abrupt changes in bulk density between layers are apparent. These abrupt physical discontinuities in the soil profile result in anisotropic conditions, where hydraulic conductivity is not equal in vertical and lateral directions. Where an abrupt increase in bulk density occurs between two soil layers, vertical downward flow is "deflected" in the lateral downslope direction (Bathke and Cassel 1991). In a soil profile where bulk density is consistent with depth, it would be expected that vertical downward flow would be favoured, relative to a soil profile where there is an increase in bulk density with depth. If this is the case, ceteris paribus, it would follow that there would be less lateral downslope flow at site 1 crest plots (eg. 1C1), where bulk density is relatively uniform with depth, compared to crest plots at site 2 or 3 (2C4 or 3C5). Consistent trends in bulk density values between landscape positions were not obvious.

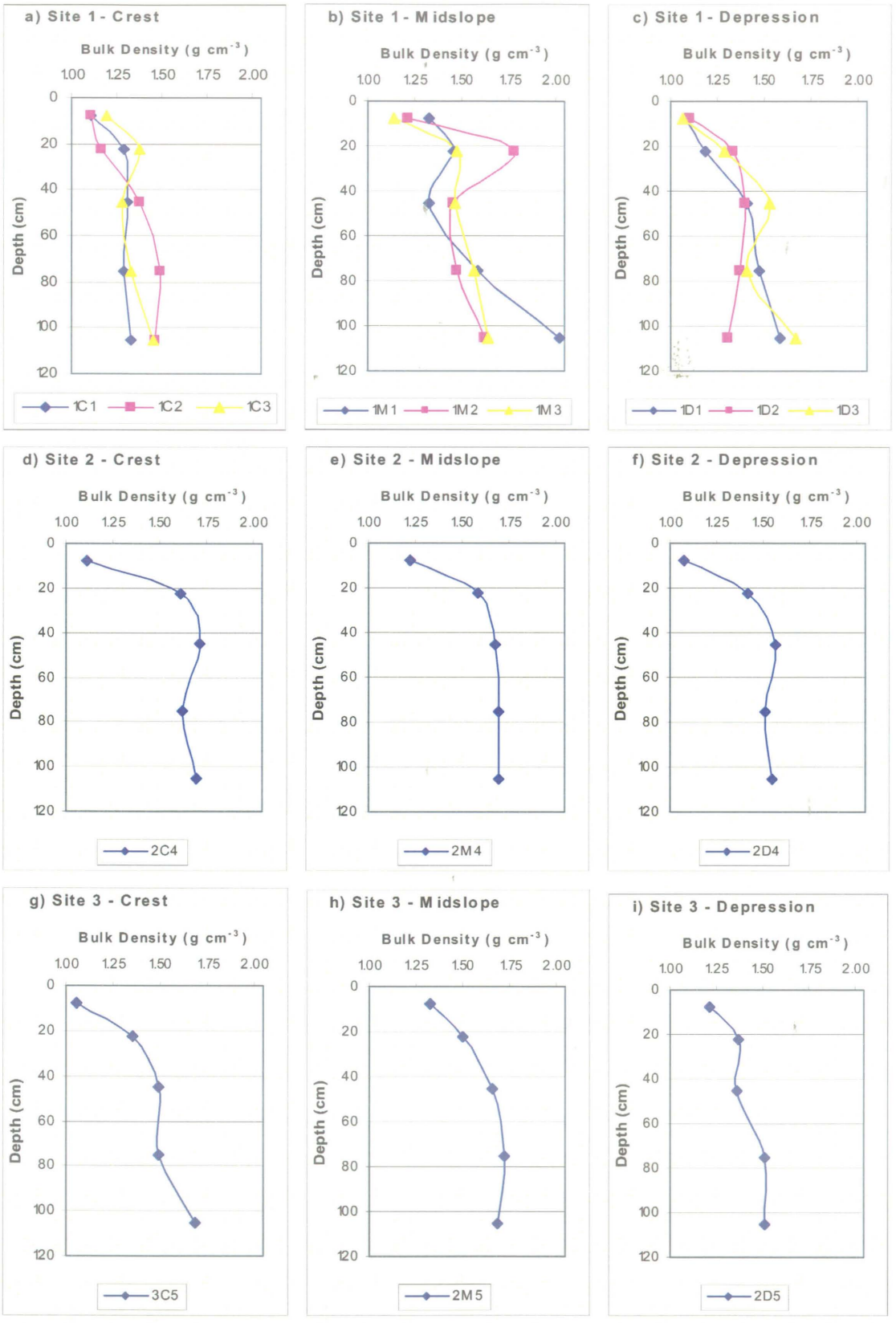


Figure 4.11 Bulk density depth profiles for all plots.

4.3.2 Bromide Redistribution Patterns

Graphical plots of bromide redistribution, generated using mean bromide concentrations at each plot, were used to examine general patterns of solute movement at each plot. Although conclusions gained from these are not based on rigorous quantitative examination, they provide valuable qualitative insight into redistribution within and among plots.

4.3.2.1 Site 1 – Crest.

Bromide redistribution at crest plots at site 1 was dominantly in the vertical downward direction (Figure 4.12). Bromide plume centres were located at depths of approximately 30 to 40 cm and 50 to 60 cm in May and October, respectively. There was very little lateral character in the bromide plumes following May sampling, as evidenced by the generally circular shape of bromide plumes around plume centres. It appeared that dispersion resulted in bromide redistributed radially outwards from plume centres. In May, plume centres at plots 1C1 and 1C2 were located directly below plots, indicating little lateral movement by mass flow. Some lateral character of redistribution was found at plot 1C3 in May and October, as evidenced by the centre of the plume located slightly downslope from the plot. Lateral redistribution along the surface is evident at plot 1C3 on both sampling dates. Bromide plumes appeared to be contained within sampling depths in May, however bromide had migrated below sampling depths by October, particularly in plot 1C1.

4.3.2.2 Site 1 – Midslope.

Bromide plumes for all midslope plots at site 1 indicate the importance of lateral redistribution at this landscape position (Figure 4.13). Lateral character in the bromide plumes was apparent in May, particularly at plots 1M1 and 1M2, and in October at all plots. More lateral movement occurred at midslope plots relative to crest plots. Centre of plumes occurred at depths of approximately 40 to 50 cm and 40 to 70 cm in May and October, respectively. Bromide plumes appeared to be contained within sampling depths for plots 1M1 and 1M2 in May, however leaching beyond 120 cm was apparent directly below plot 1M3. The bromide plume appeared to be contained within sampling depths at plot 1M1 in October, however this was not the case for plots 1M2 and 1M3. Mass flow appeared to be an important mechanism of bromide redistribution in both vertical and lateral downslope directions, while dispersion occurred, as evidenced by the upslope movement of bromide radially from plume centres.

4.3.2.3 Site 1 – Depression.

Patterns of bromide redistribution at depression plots at site 1 were not as consistent relative to crest or midslope positions. Bromide plumes did not appear to have a dominant vertical or lateral character at either sampling date (Figure 4.14). Centre of plumes occurred at depths of approximately 30 cm and 50 to 70 cm in May and October, respectively. Bromide appeared to have been redistributed via mass flow in both vertical and lateral directions, however direction and extent of movement in these directions is somewhat inconsistent between plots. Dispersion of bromide from plume centres also appeared to be important. Sampling schemes generally appeared to be inadequate to

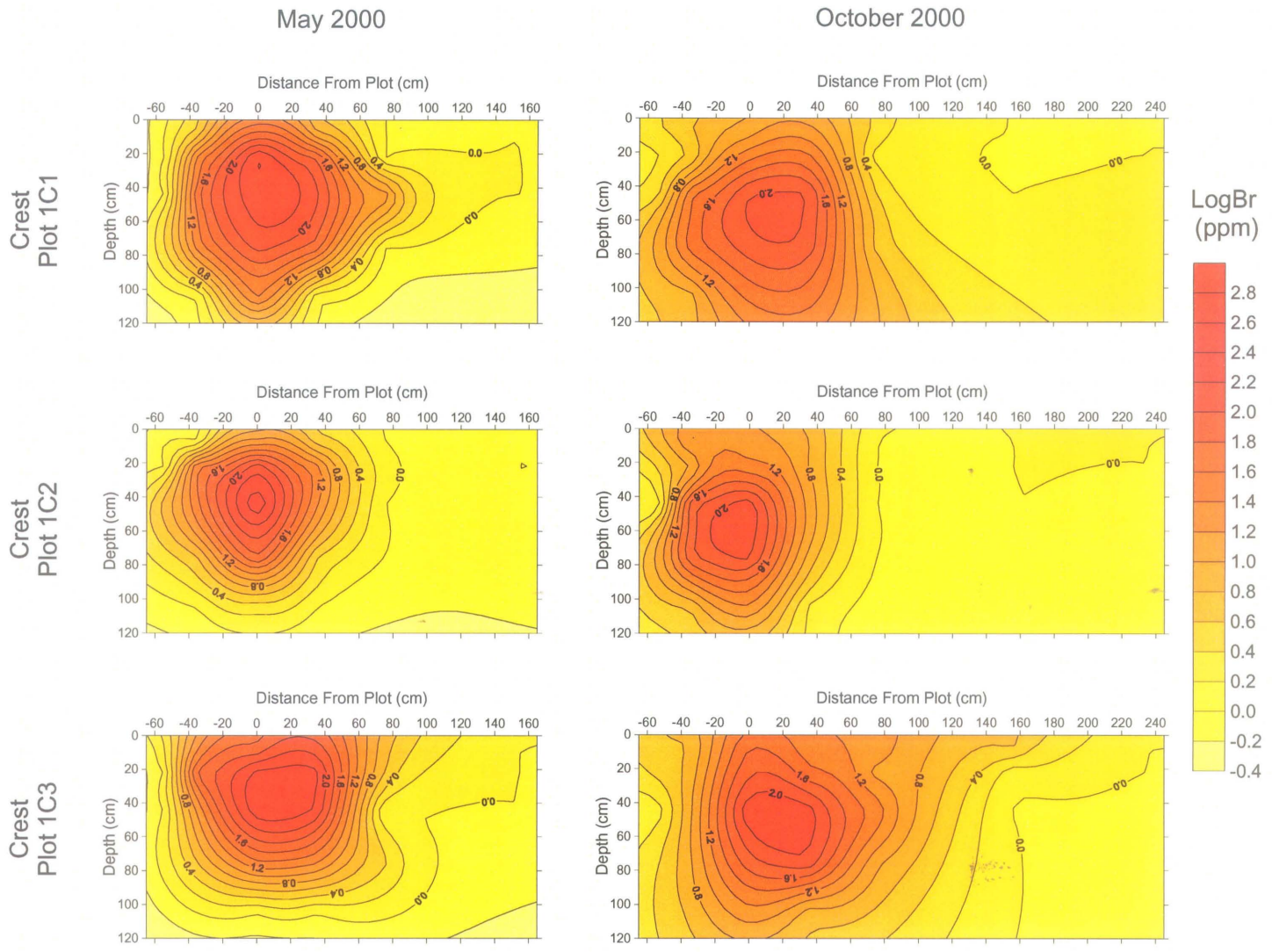


Figure 4.12 Bromide redistribution at the crest position at site 1

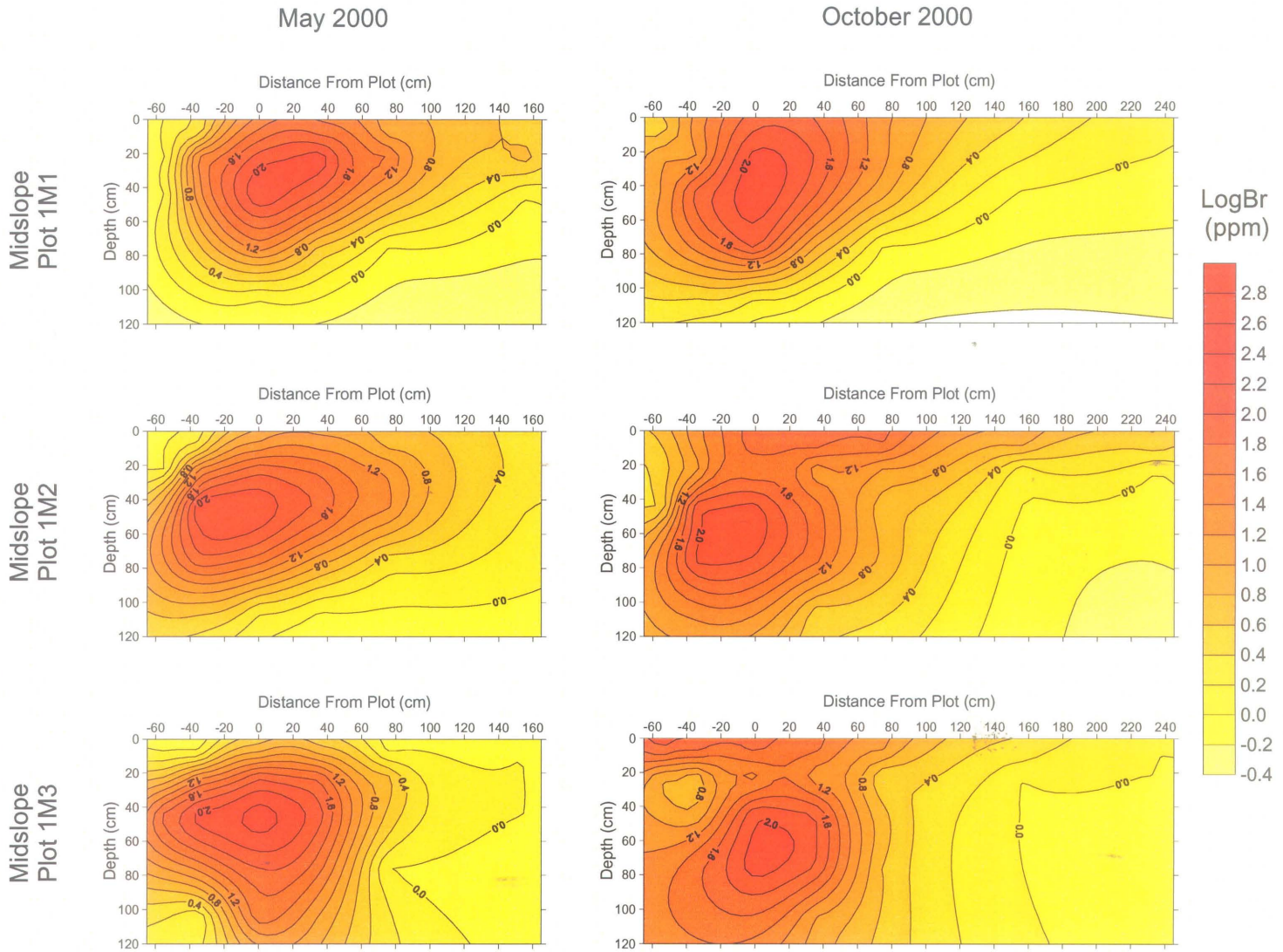


Figure 4.13 Bromide redistribution at the midslope position at site 1.

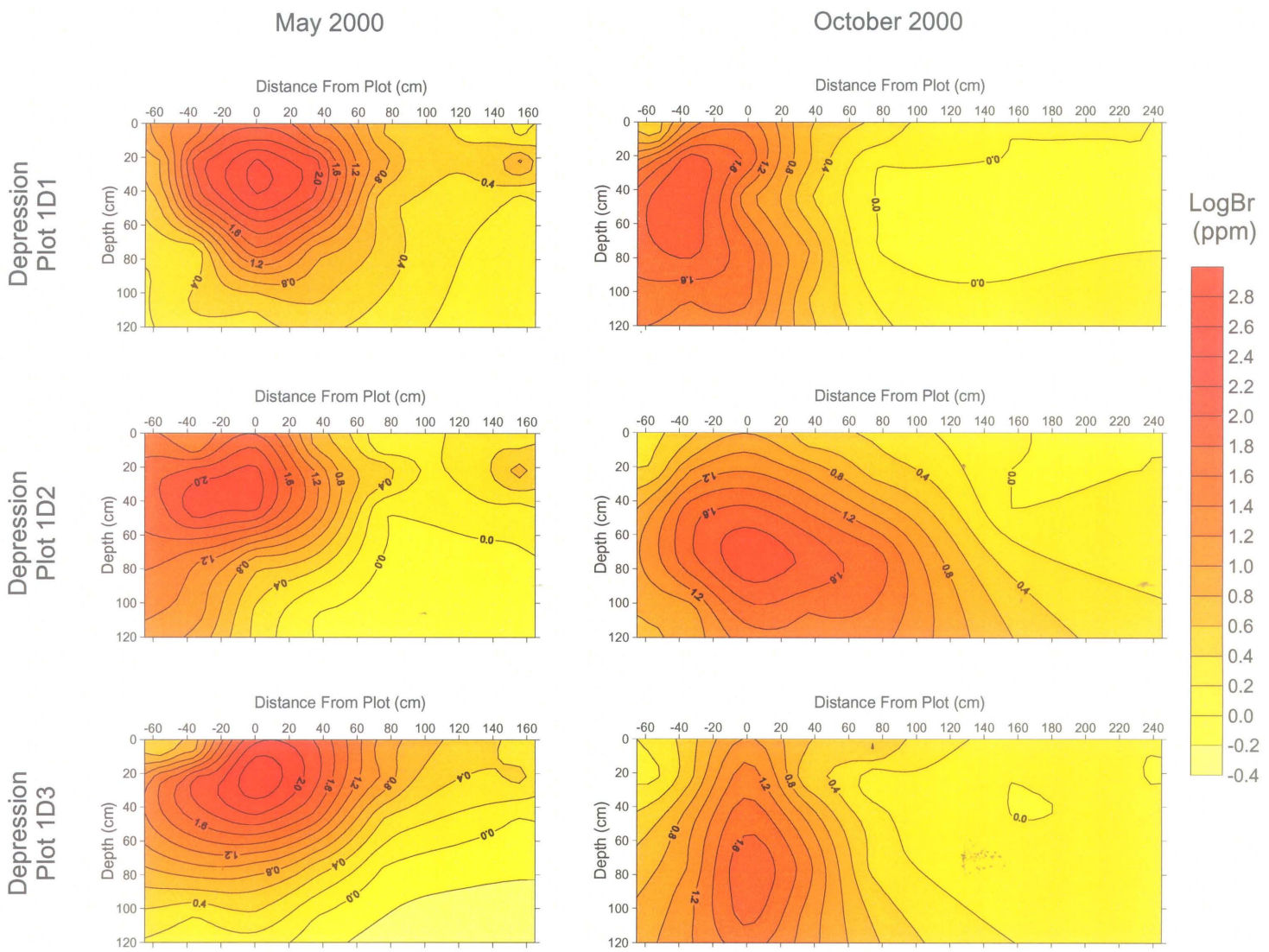


Figure 4.14 Bromide redistribution at the depression position at site 1.

capture the extent of bromide plumes in vertical or lateral directions at both sampling dates. Lateral movement was apparent in downslope and upslope directions, suggesting multi-directional lateral water fluxes at this landscape position. Bromide was recovered at downslope distances of more than 150 cm from all depression plots at site 1 in May. Much of this bromide appeared to have been removed from the near surface by October. The movement of bromide plumes appeared to correspond to water table fluctuations. The depth to water table decreased from 219 cm below ground on December 1, 1999 to 166 cm on January 2, 2000 and reached 100 cm by August 16, 2000 (Figure 4.5). By October 15, 2000 the depth to water table had dropped to 158 cm below ground. The rise in the water table during the spring of 2000 could have acted as a barrier preventing deep leaching of bromide during the spring runoff and recharge period. As the water table dropped back down in the fall, deeper leaching would be favoured. This phenomenon would explain the deeply leached bromide at this location in the landscape in October.

4.3.2.4 Site 2 – Crest.

The main bromide plume was located directly below the plot at the crest position at site 2 at both sampling dates (Figure 4.15). The centre of the plume occurred at depths of approximately 20 cm and 40 cm in May and October, respectively. In May, bromide was recovered approximately 70 to 80 cm laterally downslope from the plot, at a depth of approximately 70 cm, indicating a potential preferential flow path. Much lateral movement along the surface was evident following sampling in October, with an average of approximately 10 ppm recovered more than 150 cm from plot 2C4. The plume appeared to be contained within sampling depths for both sampling dates.

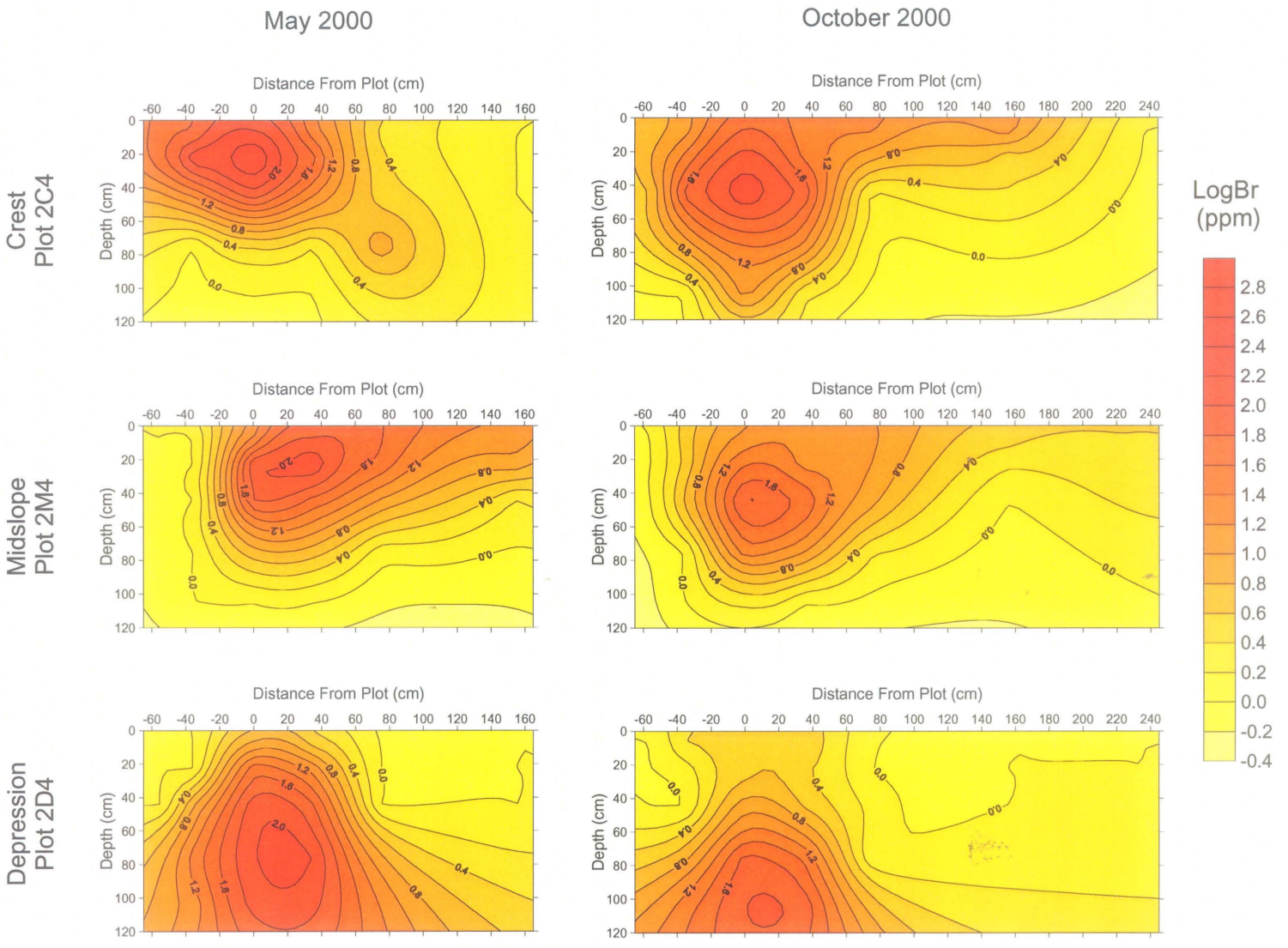


Figure 4.15 Bromide redistribution at site 2.

4.3.2.5 Site 2 – Midslope.

Strong vertical and lateral components of bromide redistribution are evident at the midslope position at site 2 (Figure 4.15). The centre of the plume was located at depths of approximately 20 to 30 cm and 30 to 50 cm in May and October, respectively. The centre of the bromide plume had moved downslope beyond the plot boundary by May, with lateral movement of bromide evident beyond 150 cm downslope of the plot. By October, bromide redistribution laterally along the surface was detected more than 240 cm downslope from plot 2M4. The bromide plume appeared to be adequately sampled in May and October.

4.3.2.6 Site 2 – Depression.

Strong vertical redistribution was evident at the depression plot at site 2 (Figure 4.15). The centre of the plume was located directly below plot 2D4 at depths of approximately 80 cm and 110 cm in May and October, respectively. Very little lateral movement via mass flow was apparent at this plot. Some lateral dispersion appeared to have occurred deeper in the soil profile at both sampling dates. The sampling scheme was not adequate to capture the bromide plume in the vertical direction for either sampling date. More vertical and less lateral redistribution occurred at the depression position than the crest or midslope positions at site 2.

4.3.2.7 Site 3 – Crest.

Primarily vertical downward redistribution occurred at the crest plot at site 3 (Figure 4.16). The centre of the bromide plume was located directly below plot 3C5 at depths of

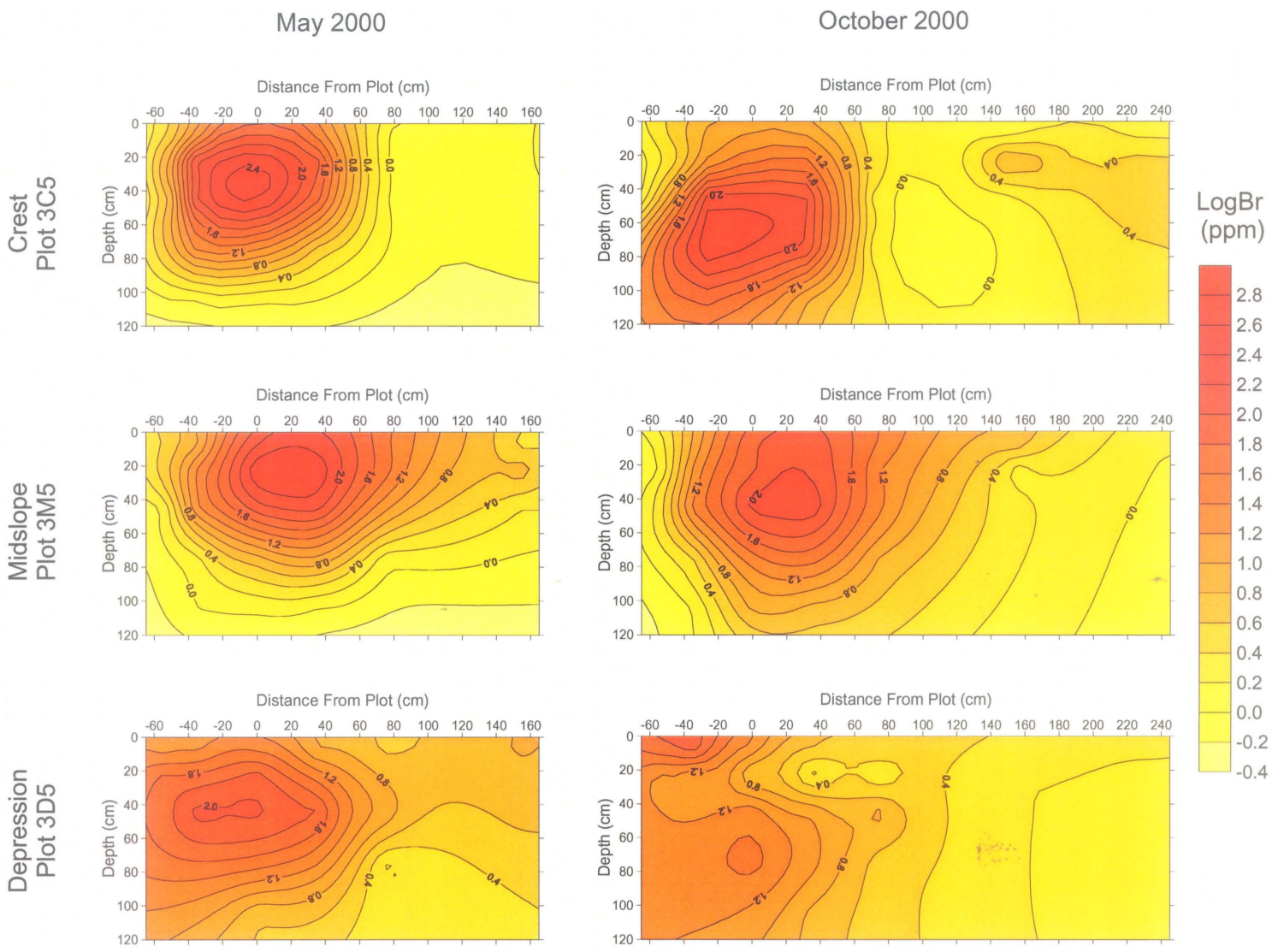


Figure 4.16 Bromide redistribution at site 3.

approximately 30 to 40 cm and 60 to 80 cm in May and October, respectively. Some lateral movement had occurred by May, however no bromide was detected beyond a distance of 75 cm from the plot. Bromide was detected 155 cm downslope from the plot in October. Sampling appeared to be adequate to assess the bromide plume in May, however the plume had migrated beyond sampling depths by October.

4.3.2.8 Site 3 – Midslope.

There was more lateral redistribution at the midslope position of site 3 relative to the crest position (Figure 4.16). The centre of the plume had migrated to a depth of approximately 20 cm, and had moved downslope to a distance of approximately 20 cm from the plot in May. By October, the plume centre had moved to a depth of approximately 30 to 50 cm and had moved downslope to a distance of approximately 20 to 30 cm from the plot. Lateral redistribution by mass flow appeared to be important at plot 3M5, as evidenced by the recovery of bromide to a distance from the plot of more than 150 cm in May. The sampling scheme seemed to adequately capture the plume in May, and appeared to have captured most of the plume in October.

4.3.2.9 Site 3 – Depression.

The sampling scheme was not adequate to capture the bromide plume in either vertical or lateral directions at the depression plot at site 3 for either sampling date (Figure 4.16). Both vertical and lateral redistribution were important at plot 3D5. In May, the centre of the bromide plume was at a depth of approximately 40 to 50 cm and was located slightly upslope from the centre of the plot. The plume had migrated to a depth of approximately 70 to 80 cm directly below the plot in October. There was more movement in vertical and

lateral directions than at the crest or midslope plots. However, definitive patterns of this movement were less apparent. More lateral movement was detected in the upslope direction than downslope, potentially indicating an influence of a near-surface water table. The occurrence of an impenetrable layer was encountered at a depth of approximately 30 cm at some sampling locations at plot 3D5. However, the nature of this layer could not be determined. Near-surface movement of bromide along this layer during periods of high water table, or ponded conditions, may explain the lateral character in redistribution at this plot. Alternatively, upslope migration and deposition of bromide may have occurred at the periphery of the saturated zone due to capillary action. This is a common occurrence at the periphery of recharge zones in the landscape. High bromide levels (i.e. > 60 ppm) were detected beyond 60 cm upslope from the centre of the plot in May, while bromide (~6 ppm) was detected beyond 150 cm downslope from the plot.

4.3.2.10 All Sites.

Similar patterns of bromide redistribution were found within landscape positions at all sites. Redistribution was consistent primarily in the vertical direction at crest plots at both sampling dates, with little lateral redistribution detected (with the exception of plots 1C3 and 3C5 in October). With the exception of plots 1C3 and 3C5 in October, the sampling scheme appeared to be adequate to assess redistribution at crest plots. Lateral redistribution was consistently the most important at the midslope plots. The sampling scheme appeared to be adequate to assess redistribution in May, however by October bromide had moved beyond sampling depths in some cases. For depression plots, vertical redistribution was consistently more important than lateral redistribution. The sampling scheme was not adequate to fully assess the bromide plumes at the depression landscape

position, particularly in October, when bromide had moved beyond sampling depths at all plots. In general, bromide movement increased from crest < midslope < depression. This is likely due to the fact that water inputs to the 3 portions of the landscape increase in the same order. The crest position receives only direct inputs of water from precipitation, with midslope and depression plots receiving both direct inputs as well as run-on from upslope portions of the landscape. Further to this, crest and midslope positions of the landscape lose water via runoff, while depression positions do not. Depression locations of this landscape were influenced by shallow groundwater sources, as evidenced by depth to the water table at site 1 (Figure 4.5). More consistent patterns of redistribution were found at crest and midslope plots relative to those at depression positions. This is likely due to the influence of the water table on near-surface water dynamics, and hence bromide redistribution, at the depression plots. As well, water inputs into depression positions across the landscape are more variable relative to crest and midslope positions, due to the fact that the amount of water inputs from run-on is dependent on the size of contributing upslope areas.

Vertical movement was favoured over lateral movement at the crest position relative to the midslope positions. The relatively uniform soil properties with depth would favour vertical flow relative to the other positions due to the relatively low degree of anisotropy in these profiles. Examination of midslope soil profiles indicated higher degrees of profile development, including increased horizonation, clay translocation, and more variable bulk density levels with depth. These factors would increase anisotropy in these profiles, and hence would favour lateral flow relative to the crest positions, which was supported through examination of bromide redistribution parameters. The most vertical

redistribution occurred at the depression, where water inputs were the highest. These profiles were the most developed, and had the most variable soil properties with depth. The well developed Bt horizons, with clay coatings on ped faces, may have been more important in influencing vertical and lateral redistribution partitioning than the degree of anisotropy. The frost table may have retarded vertical redistribution, or favoured lateral redistribution, during spring runoff periods at all positions.

4.3.3 Bromide Recovery Rates

Rates of applied bromide recovered offer a valuable measure of redistribution. Recovery rates determined included total % bromide recovery (% Br), % bromide recovery in the top 30 cm (% Br_{30}) and % bromide recovery in the top 60 cm (% Br_{60}). Of particular interest are the relative values of % Br, % Br_{30} and % Br_{60} between plots. Total recovery rates on a plot basis for May ranged from 48 to 85 %, while in October they ranged from 19 to 110 %. High spatial variability in bromide recovery rates is common. For example, Bronswijk et al. (1995) found recoveries ranged from 65 to 200 % 6 days after bromide application. Sources of error which may contribute to variable recovery rates include sampling, analytical and calculation error. However, bromide not accounted for may have moved beyond the sampled depth or may be in preferential flow paths not captured by the sampling technique. Bromide recovery rates may be considered indicative of bromide recovered from the soil matrix, and, therefore, may be used to provide an indication of the preferential flow component, relative to the matrix flow component.

4.3.3.1 Site 1.

In May at site 1, mean total bromide recovery (Br %) rates were 72, 67 and 67 % for crest, midslope and depression plots, respectively (Table 4.3). Sampling was similarly effective at recovering total bromide at all landscape positions. Approximately 28 to 33 % of applied bromide was not accounted for. Bromide recovery rates from the top 30 cm were found to be significantly different between landscape positions, with mean rates of 20, 14 and 28 % for crest, midslope and depression plots, respectively. In May, significantly more bromide was recovered in the top 30 cm at the depression position, than at the crest or midslope positions, indicating leaching had removed more bromide from the surface layers (i.e. 0 to 15 cm and 15 to 30 cm). No evidence was found to suggest a difference in bromide recovery in the top 60 cm between landscape positions in October.

In October, total bromide recovery was found to be significantly different between landscape positions, with mean rates of 56, 70 and 42 % for crest, midslope and depression plots, respectively. The depression plots had significantly lower recovery than crest or midslope plots, indicating deeper leaching had occurred in the depression. Recovery rates from the top 30 cm were found to be significantly different between landscape positions, with mean rates of 6, 16 and 5 % for crest, midslope and depression plots, respectively. The midslope position was found to have significantly higher recovery than the crest or depression, indicating less vertical downward redistribution had occurred there. Recovery rates from the top 60 cm were found to be significantly lower in the depression plots, relative to crest or midslope plots, indicating bromide had been leached deeper at that position of the landscape.

Table 4.3 Descriptive statistics and one-way analysis of variance for bromide recovery at site 1.

Landscape	May 2000					October 2000				
	Mean	Median	Minimum	Maximum	p-value	Mean	Median	Minimum	Maximum	p-value
	%					%				
	Total Bromide Recovery (% Br)									
Crest	71.6	69.4	47.1	110.3		56.4	56.6 a[1]	34.7	73.3	
Midslope	66.6	76.7	43.8	82.4	0.9335	70.1	70.8 a	39.2	95.8	0.0038
Depression	66.7	60.7	54.1	95.7		41.6	43.4 b	24.9	63.3	
	Bromide Recovery Top 30 cm (% Br_{30})									
Crest	20.3	11.0 a	5.4	64.8		6.3	5.2 a	2.3	18.0	
Midslope	14.3	12.8 a	15.2	38.7	0.0250	15.6	17.2 b	6.5	28.4	0.0061
Depression	28.1	29.1 b	5.7	34.2		5.3	3.7 a	2.3	11.2	
	Bromide Recovery Top 60 cm (% Br_{60})									
Crest	59.3	53.6	39.5	98.3		32.7	30.2 a	13.8	51.9	
Midslope	54.5	58.8	37.4	66.7	0.7165	41.5	48.0 a	15.7	58.1	0.0018
Depression	61.8	58.1	50.1	82.3		17.4	16.6 b	8.7	28.0	

[1] Median values followed by different letters were determined to be significantly different using a multiple comparison procedure at an experiment-wise error rate of α=0.15.

4.3.3.2 Site 2

Total mean recovery rates at site 2 in May were found to be 56, 48 and 70 % for crest, midslope and depression plots, respectively (Table 4.4). Bromide recovery from the top 30 cm were found to be significantly different between landscape positions, with mean rates of 37, 31 and 3 % for crest, midslope and depression plots, respectively. In the top 60 cm, mean recovery rates of 54, 46 and 21 % were found for crest, midslope and depression positions, respectively. Significantly lower recovery rates in the top 30 and 60 cm were found at the depression, when compared to the crest or midslope, indicating relatively deeper leaching had occurred there. Most of the recovered bromide was found in the top 60 cm at the crest and midslope positions, while at the depression position most was beyond that depth.

In October at site 2, differences in total mean recovery rates due to landscape were found to be significant, with mean rates of 59, 29 and 31 % at the crest, midslope and depression, respectively. The depression and midslope plots were found to have significantly lower total recovery rates than the crest plots. Mean recovery rates from the top 30 cm were found to be significantly different between landscape positions, with mean rates of 15, 7 and 1 % for crest, midslope and depression plots, respectively. Bromide recovery in the top 30 cm was significantly lower in the depression than at the crest. Very little bromide remained in the top 30 cm at any of the landscape positions. Bromide recovery from the top 60 cm was found to be significantly different due to landscape position, with mean rates of 51, 24 and 4 % for crest, midslope and depression plots, respectively. The depression and midslope were found to have significantly lower

Table 4.4 Descriptive statistics and one-way analysis of variance for bromide recovery at site 2.

Landscape	May 2000					October 2000				
	Mean	Median	Minimum	Maximum	p-value	Mean	Median	Minimum	Maximum	p-value
	%					%				
	Total Bromide Recovery (% Br)									
Crest	56.3	57.6	31.8	79.6		59.3	52.0 a[1]	41.2	84.6	
Midslope	48.3	48.9	4.3	55.5	0.1479	29.0	31.4 bc	21.6	34.1	0.0665
Depression	70.4	66.5	5.6	81.4		30.8	30.6 c	27.0	34.8	
	Bromide Recovery Top 30 cm (% Br_{30})									
Crest	37.4	34.9 a	22.2	55.0		15.4	12.0 a	11.1	23.1	
Midslope	30.7	31.5 a	21.0	39.7	0.0594	7.0	6.4 ab	5.4	9.1	0.0273
Depression	3.4	3.5 b	3.2	3.5		1.3	1.2 b	1.1	1.7	
	Bromide Recovery Top 60 cm (% Br_{60})									
Crest	54.1	56.6 a	31.3	74.4		50.6	40.2 a	35.4	76.3	
Midslope	46.3	48.1 a	37.3	53.5	0.0608	24.1	23.7 ab	18.9	29.7	0.0273
Depression	20.8	18.3 b	17.4	26.6		3.5	3.7 b	2.8	3.9	

[1] Median values followed by different letters were determined to be significantly different using a multiple comparison procedure at an experiment-wise error rate of α=0.15.

recovery rates than the crest, indicating deeper leaching had occurred at those positions of the landscape. Very little bromide remained in the top 60 cm at the depression plot in October. Most of the recovered bromide remained in the top 60 cm at the crest, with very little moving below 60 cm between May and October.

4.3.3.3 Site 3

In May, bromide recovery in the top 30 cm was found to be significantly different between landscape positions at site 3 (Table 4.5). Mean % Br_{30} values were found to be 28, 50 and 14 % for crest, midslope and depression plots, respectively. The recovery rate in the top 30 cm was found to be significantly lower in the depression than at the midslope position, indicating more bromide had been removed from the surface layers at the depression. Most of the recovered bromide had moved beyond 30 cm for the crest and depression positions. Although not found to be statistically significant, % Br or % Br_{60} values were similar between crest and midslope positions and were lower at the depression. Most of the bromide recovered at all positions of the landscape was found in the top 60 cm of the profile.

At site 3 in October, a large range in total recovery rates were found, with 110, 77 and 20 % of applied bromide recovered at crest, midslope and depression plots, respectively. Recovery at the depression position was found to be significantly lower than the crest, indicating higher deep leaching losses had occurred there. Recovery rates from the top 30 cm were found to differ significantly between landscape positions, with mean rates of 7, 24 and 9 % recovered at crest, midslope and depression plots, respectively. Bromide recovery from the top 30 cm was found to be significantly lower at the depression and

Table 4.5 Descriptive statistics and one-way analysis of variance for bromide recovery at site 3.

Landscape	May 2000					October 2000				
	Mean	Median	Minimum	Maximum	p-value	Mean	Median	Minimum	Maximum	p-value
	%					%				
	Total Bromide Recovery (% Br)									
Crest	85.5	84.2	76.9	95.4		110.1	114.0 a[1]	99.5	116.7	
Midslope	85.4	98.5	51.8	105.9	0.1767	76.5	78.2 ab	66.5	84.7	0.0273
Depression	50.0	37.1	34.2	78.7		19.5	22.7 b	12.7	23.0	
	Bromide Recovery Top 30 cm (% Br_{30})									
Crest	28.0	29.8 ab	22.6	31.6		6.9	4.1 a	1.9	14.8	
Midslope	49.5	52.7 a	33.5	62.2	0.0273	23.5	26.0 b	15.4	29.0	0.0608
Depression	13.6	14.2 b	8.6	18.1		8.9	8.9 a	8.6	9.3	
	Bromide Recovery Top 60 cm (% Br_{60})									
Crest	81.0	79.2	72.9	90.9		47.4	47.3 ab	28.0	66.8	
Midslope	83.1	95.0	50.3	104.0	0.1133	65.3	64.8 a	61.6	69.5	0.0509
Depression	44.8	33.8	33.7	67.0		9.5	9.2 b	7.9	11.4	

[1] Median values followed by different letters were determined to be significantly different using a multiple comparison procedure at an experiment-wise error rate of α=0.15.

crest positions than at the midslope. Mean recovery rates from the top 60 cm were found to be 47, 64 and 10 % for crest, midslope and depression plots, respectively. Deeper leaching occurred at the depression position, relative to the midslope, with most of the recovered bromide found in the top 60 cm at the midslope.

4.3.3.4 All Sites

When all sites are examined together, there was no evidence to suggest recovery rates in May were significantly different due to landscape position (Table 4.6). Most of recovered bromide remained in the top 60 cm at all landscape positions. However, when October recovery rates are examined, differences due to landscape for % Br, % Br_{30} and % Br_{60} were all found to be significant. Total mean recovery rates of 68, 63 and 35 were found for crest, midslope and depression plots, respectively. There was significantly lower total recovery found at the depression than the midslope or crest, indicating more deep leaching losses at that position in the landscape, possible due to preferential flow. Mean bromide recovery rates in the top 30 cm were found to be 8, 16 and 5 % for the crest, midslope and depression plots, respectively. Very little bromide remained in the top 30 cm at any landscape position. Significant lower recovery rates were found in the top 60 cm at the crest and depression plots relative to the midslope, indicating that more bromide remained in the top 30 cm at the midslope. Mean recovery rates from the top 60 cm were found to be 39, 43 and 13 % for crest, midslope and depression positions, respectively. Bromide recovery in the top 60 cm was found to be significantly lower at the depression position, compared to the crest and midslope positions. Lower levels of applied bromide were in the top 60 cm at the depression, indicating deeper leaching losses there. Most of the bromide recovered remained in the top 60 cm at the crest and midslope positions. However, most of the applied bromide was not recovered in this depth.

Table 4.6 Descriptive statistics and one-way analysis of variance for bromide recovery at all sites.

Landscape	May 2000					October 2000				
	Mean	Median	Minimum	Maximum	p-value	Mean	Median	Minimum	Maximum	p-value
	%					%				
	Total Bromide Recovery (% Br)									
Crest	71.3	76.9	31.8	110.3		67.7	60.6 a[1]	34.7	116.7	
Midslope	66.7	61.6	40.5	105.9	0.6857	63.2	68.1 a	21.6	95.8	0.0003
Depression	64.1	63.4	34.2	95.7		35.0	34.0 b	12.7	63.3	
	Bromide Recovery Top 30 cm (% Br_{30})									
Crest	25.3	22.2	5.4	64.8		8.3	5.3 a	1.9	23.1	
Midslope	24.6	24.6	5.7	62.2	0.7918	15.5	15.4 b	5.4	29.0	0.0021
Depression	20.3	18.1	3.2	38.7		5.2	3.7 a	1.1	11.2	
	Bromide Recovery Top 60 cm (% Br_{60})									
Crest	62.6	64.0	31.3	98.3		39.2	35.4 a	13.8	76.3	
Midslope	58.6	58.6	37.3	82.3	0.3438	42.8	48.0 a	15.7	69.5	<0.0001
Depression	50.2	53.0	17.4	104.0		13.0	11.4 b	2.8	28.0	

[1] Median values followed by different letters were determined to be significantly different using a multiple comparison procedure at an experiment-wise error rate of α=0.15.

When variability of site was accounted for, there was no evidence to suggest that bromide recovery rates were significantly different between landscape positions in May (Table 4.7). In October, however, all variables were found to be significantly different between landscape positions, indicating that landscape position was more important than site in terms of variability of bromide recovery rate.

Table 4.7 Friedman two-way analysis of variance by ranks for bromide recovery.

Parameter	May 2000	October 2000
Total Bromide Recovery (% Br)	0.9185	0.0014
Bromide Recovery Top 30 cm (% Br_{30})	0.2327	0.0017
Bromide Recovery Top 60 cm (% Br_{60})	0.9553	0.0001

4.3.4 Vertical and Lateral Redistribution Functions

The vertical redistribution and lateral redistribution functions provide measures of the relative strength of vertical downward solute movement and lateral downslope movement, respectively. The vertical redistribution function (V_f) provides a depth-weighted measure of solute moved vertically beyond the 0 to 15 cm depth. The lateral redistribution function (L_f) provides a measure of solute moved laterally downslope of the plot boundary, weighted by distance from plot. Although the absolute values of these measures are of limited utility, the relative values provide an indication of the importance of each redistribution function. Of particular interest is the ratio of V_f to L_f, expressed as Vf/Lf, which provides a single measure of this relationship

4.3.4.1 Site 1

The vertical redistribution function (V_f) was found to be significantly different between landscape positions at site 1 in May (Table 4.8). The V_f was significantly lower at the depression plot than the crest or midslope plots, indicating that, for this sampling period, there was less vertical redistribution at the depression plot. There was no evidence to suggest a significant effect of landscape on the lateral redistribution function (L_f) or V_f/L_f in May.

In October, the V_f was found to be significantly different between landscape positions at site 1, with the V_f at the depression position found to be significantly lower than at the midslope. The V_f/L_f values were found to be significantly higher at the depression compared to the midslope, indicating that the greatest vertical relative to lateral redistribution was found at this position in the landscape.

4.3.4.2 Site 2

The vertical redistribution function was found to be significantly higher at the depression position than the crest or midslope positions in May at site 2 (Table 4.9). The lateral redistribution function was determined to be significantly higher at the midslope position than at the crest or depression position, indicating that lateral redistribution was most important at this position in the landscape. The V_f/L_f values were found to be significantly higher at the depression position compared to the midslope, indicating that, relative to lateral redistribution, vertical redistribution was most important at the depression at site 2.

Table 4.8 Descriptive statistics and one-way analysis of variance for vertical and lateral redistribution functions at site 1.

Landscape	May 2000					October 2000				
	Mean	Median	Minimum	Maximum	p-value	Mean	Median	Minimum	Maximum	p-value
	Verical Redistribution Function (V_f)									
Crest	5239	5412 a[1]	3265	6537		6852	7090 ab	4978	8081	
Midslope	5417	5474 a	3774	6620	0.0202	6214	6072 a	4302	7894	0.0158
Depression	4293	4257 b	3419	5059		7747	7905 b	6202	8759	
	Lateral Redistribution Function (L_f)									
Crest	860	853	183	1550		1264	1196	293	2673	
Midslope	1385	1210	378	2453	0.2750	1235	1142	623	2337	0.9518
Depression	1039	970	724	1566		1100	1215	257	2455	
	V_f/L_f									
Crest	16.5	9.4	2.4	42.7		22.0	10.7 ab	3.2	69.8	
Midslope	8.4	6.4	2.5	19.7	0.5213	9.2	6.7 a	3.0	16.7	0.0679
Depression	7.0	6.8	3.4	11.8		28.8	22.4 b	5.4	61.6	

[1] Median values followed by different letters were determined to be significantly different using a multiple comparison procedure at an experiment-wise error rate of α=0.15.

Table 4.9 Descriptive statistics and one-way analysis of variance for vertical and lateral redistribution functions at site 2.

Landscape	May 2000					October 2000				
	Mean	Median	Minimum	Maximum	p-value	Mean	Median	Minimum	Maximum	p-value
	Verical Redistribution Function (V_f)									
Crest	3395	3400 a[1]	3351	3435		5123	4927 a	4796	5646	
Midslope	3369	3740 a	2419	3948	0.0608	5139	4887 a	4758	5772	0.0665
Depression	8923	8856 b	8816	9097		10588	10688 b	10311	10766	
	Lateral Redistribution Function (L_f)									
Crest	763	687 a	591	1012		2136	2312	1020	3075	
Midslope	3902	3408 b	2420	5879	0.0273	2632	2657	2013	3227	0.2019
Depression	1341	1341 ab	1276	1406		1393	1308	1199	1673	
	V_f/L_f									
Crest	9.9	10.1 ab	4.2	15.3		5.7	3.9 a	2.5	10.6	
Midslope	2.2	2.8 a	0.8	2.9	0.0665	7.3	8.3 a	4.4	9.1	0.0608
Depression	9.6	9.7 b	8.1	10.9		25.5	23.5 b	21.1	31.8	

[1] Median values followed by different letters were determined to be significantly different using a multiple comparison procedure at an experiment-wise error rate of α=0.15.

In October, V_f values were found to be significantly higher at the depression compared to the crest or midslope, indicating that vertical redistribution was highest at the depression. Relative to lateral redistribution, vertical redistribution was most important at the depression position, as indicated by the significantly higher V_f/L_f values there.

4.3.4.3 Site 3

In May at site 3, lateral redistribution was found to be significantly lower at the depression compared to the midslope (Table 4.10). The V_f/L_f ratio was found to be significantly lower at the midslope compared to the crest. These results indicate that, relative to lateral movement, vertical redistribution was most important at the crest and least important at the midslope.

In October, the V_f values increased in the order midslope < depression < crest, with differences found to be significant between the midslope and the crest. Lateral redistribution function values were found to be significantly greater at the midslope than at the crest. When the ratio between V_f and L_f values were examined, values increased in the order midslope < crest < depression, with values at the midslope found to be significantly different than the depression. These results are consistent with those in May, in that lateral redistribution was greatest at the midslope and, relative to the L_f, vertical redistribution was least important at that position in the landscape. Results indicate that vertical redistribution was most important at the crest and lateral redistribution was most important at the midslope at site 3.

Table 4.10 Descriptive statistics and one-way analysis of variance for vertical and lateral redistribution functions at site 3.

Landscape	May 2000					October 2000				
	Mean	Median	Minimum	Maximum	p-value	Mean	Median	Minimum	Maximum	p-value
	Verical Redistribution Function (V_f)									
Crest	4592	4499	4396	4882		7657	7741 a[1]	6872	8359	
Midslope	3453	3370	3362	3628	0.1133	4772	4911 b	4071	5335	0.0766
Depression[2]	4699	5094	3587	5417		5154	5154 ab	4842	5465	
	Lateral Redistribution Function (L_f)									
Crest	449	398 a	363	586		1189	912 a	747	1909	
Midslope	2345	2400 b	1802	2832	0.0509	2459	2447 b	2256	2675	0.0992
Depression	2037	1975 ab	1766	2371		2815	2126 ab	1835	4484	
	V_f/L_f									
Crest	12.4	13.4 a	9.7	14.1		7.2	7.4 ab	3.1	11.2	
Midslope	1.9	2.0 b	1.3	2.3	0.0273	2.6	2.6 a	2.3	2.8	0.0513
Depression[2]	5.3	5.3 ab	2.9	7.8		11.4	11.4 b	11.2	11.6	

[1] Median values followed by different letters were determined to be significantly different using a multiple comparison procedure at an experiment-wise error rate of α=0.15.

[2] Only 2 replications for October 2000.

4.3.4.4 All Sites

In May, when all sites were examined as one, there was no evidence to suggest a significant effect of landscape on the vertical redistribution function in May (Table 4.11). However, the L_f values and the V_f/L_f ratios were found to be significantly different due to landscape. Lateral redistribution was found to be significantly lower at the crest compared to midslope and depression positions. The V_f/L_f values were found to be significantly lower at the midslope than at the crest. These results indicate that more vertical redistribution occurred at the crest than at the other positions, while, relative to lateral redistribution, vertical redistribution was least important at the midslope.

In October, the V_f values were found to be significantly lower at the midslope compared to the depression. The V_f/L_f values were found to be significantly higher at the depression compared to the crest or midslope. These results indicate that there was the least amount of vertical redistribution at the midslope position. Relative to lateral redistribution, vertical distribution was most important at the depression position.

When the effects due to site were removed, only the lateral redistribution function was found to be significantly different due to landscape position in May (Table 4.12). In October, both V_f and V_f/L_f were found to be significantly different between landscape positions.

The similarity in results between the two-way analysis of variance and the one-way analysis of variance indicate the influence of landscape position was more important than the influence of site in determining vertical and lateral redistribution functions.

Table 4.11 Descriptive statistics and one-way analysis of variance for vertical and lateral redistribution functions at all sites.

Landscape	May 2000					October 2000				
	Mean	Median	Minimum	Maximum	p-value	Mean	Median	Minimum	Maximum	p-value
	Verical Redistribution Function (V_f)									
Crest	4741	4882	3265	6537		6667	6872 ab[1]	4796	8359	
Midslope	4615	4288	2419	6620	0.8568	5711	5605 a	4071	7894	0.0015
Depression[2]	5300	4795	3419	9097		7985	8114 b	4842	10766	
	Lateral Redistribution Function (L_f)									
Crest	758	687 a	183	1550		1423	1196	293	3075	
Midslope	2080	2006 b	378	5879	0.0005	1759	1588	623	3227	0.4879
Depression	1299	1276 b	724	2371		1501	1342	257	4484	
	V_f/L_f									
Crest	14.4	10.1 a	2.4	42.7		15.8	8.7 a	2.5	69.8	
Midslope	5.9	3.1 b	0.8	19.7	0.0110	7.5	6.0 a	2.3	16.7	0.0015
Depression[2]	7.2	7.8 ab	2.9	11.8		25.6	21.8 b	5.4	61.6	

[1] Median values followed by different letters were determined to be significantly different using a multiple comparison procedure at an experiment-wise error rate of α=0.15.

[2] Only 2 replications for October 2000.

Table 4.12 Friedman two-way analysis of variance by ranks for vertical and lateral redistribution.

Parameter	May 2000	October 2000
Vertical Redistribution (V_f)	0.1405	0.0047
Lateral Redistribution (L_f)	0.0423	0.7260
V_f/L_f	0.1815	0.0115

Trends for vertical redistribution indicate the importance of temporal variability. In May, vertical redistribution was highest at crest plots, while in October it was highest at the depression position, likely due to the water table effects previously discussed. Vertical redistribution was lowest at the midslope for both dates, indicating it was less important at that landscape position. Results for V_f/L_f indicate the same trends. Lateral redistribution values demonstrate the importance of lateral flow at the midslope.

4.3.5 Depth to Centre of Bromide Mass

Comparison between Q50 values and visual redistribution plots suggest that Q50 values may underestimate actual leaching depths. However, trends and relational conclusions appear to be the same.

4.3.5.1 Site 1

In May, mean depths to centre of bromide mass directly below the plots ($Q50_0$) at site 1 were 24, 28 and 17 cm for crest, midslope and depression plots, respectively (Table 4.13). It was found that the $Q50_0$ at the depression position was significantly lower than the crest and midslope positions. Mean depths to centre of bromide mass 20 cm downslope of the plot boundaries ($Q50_{20}$) were determined to be 24, 22 and 19 cm

Table 4.13 Descriptive statistics and one-way analysis of variance for depth to centre of bromide mass at site 1.

Landscape	May 2000					October 2000				
	Mean	Median	Minimum	Maximum	p-value	Mean	Median	Minimum	Maximum	p-value
	cm					cm				
	Depth to centre of mass, DFP = 0 cm ($Q50_0$)									
Crest	24.2	26.2 a[1]	13.8	30.9		30.9	31.4	19.7	38.1	
Midslope	27.5	27.8 a	20.1	35.9	0.0017	28.1	29.0	18.5	36.5	0.4610
Depression	17.2	18.0 b	11.3	21.9		32.7	34.4	11.8	49.0	
	Depth to centre of mass, DFP = 20 cm ($Q50_{20}$)									
Crest	23.8	24.3 a	13.1	35.3		28.4	30.7 ab	13.6	38.9	
Midslope	22.9	22.2 a	15.8	32.4	0.016	20.6	22.0 a	5.7	38.2	0.0238
Depression	15.9	18.9 b	4.1	22.9		34.9	38.7 b	12.7	45.3	

[1] Median values followed by different letters were determined to be significantly different using a multiple comparison procedure at an experiment-wise error rate of α=0.15.

for the crest, midslope and depression plots, respectively. It was determined that the $Q50_{20}$ at the depression position was significantly lower than the crest and midslope positions. These results indicate that the depth to centre of bromide mass was similar between crest and midslope, while it was lower at the depression following the spring runoff and recharge period.

Results from October at site 1 did not provide any evidence to suggest an effect of landscape on $Q50_0$. Mean values for $Q50_{20}$ were found to be 31, 22 and 39 cm for crest, midslope and depression plots, respectively. The $Q50_{20}$ was found to be significantly greater at the depression than at the midslope, indicating more leaching had occurred there.

These results support the hypothesis that the close proximity of the water table to the surface in the depressional area may have prevented deep leaching during the spring recharge period. However, as growing season progressed and the water table receded, deeper leaching at the depression was permitted, or even favoured by the receding water table. With the exception of $Q50_{20}$ at the midslope in May, all depths to centre of bromide mass increased over the growing season period between sampling dates.

Another interesting trend to note was that $Q50_{20}$ was less than $Q50_0$ at the midslope position, while this was not the case at the other landscape positions, indicating that depth to centre of bromide mass was less downslope of the midslope plots then directly under them. This supports the conclusion that lateral downslope redistribution was more important at the midslope that at the other positions.

4.3.5.2 Site 2

In May at site 2, mean $Q50_0$ values were determined to be 15, 20 and 39 cm for crest, midslope and depression plots, respectively (Table 4.14). The $Q50_0$ at the depression was found to be significantly higher than at the crest, indicating more leaching had occurred there. Mean values of $Q50_{20}$ were 16, 14 and 44 cm for crest, midslope and depression plots, respectively. Mean depth of leaching 20 cm downslope of the plot was found to be significantly higher at the depression than at the crest and midslope.

In October, $Q50_0$ mean values were 22, 26 and 50 for the crest, midslope and depression plots, respectively, while $Q50_{20}$ mean values were 19, 21 and 51 cm for the crest, midslope and depression plots, respectively. In both cases, mean values were found to be significantly higher at the depression than at the crest and midslope positions.

At site 2, depths to centre of bromide mass were consistently deeper at the depression position than the crest and midslope positions, even in May. This indicates that vertical downward leaching was strongest at this position of the landscape. The lower temporal variability found at the depression position suggests the influence of the water table was not as important at site 2 relative to site 1, although no water table data was collected at site 2 to support this conclusion. Depths to centre of bromide mass increased from May to October for all plots, indicating that leaching occurred at all positions of the landscape at site 2 over the growing season. Important to note was the trend in $Q50_0$ values of crest < midslope < depression, and in $Q50_{20}$ values of midslope < crest < depression, for both May and October. These trends suggest that vertical downward movement was greatest at the depression plot, while lateral downslope redistribution was more important at the midslope, which was more evident by October.

Table 4.14 Descriptive statistics and one-way analysis of variance for depth to centre of bromide mass at site 2.

Landscape	May 2000					October 2000				
	Mean	Median	Minimum	Maximum	p-value	Mean	Median	Minimum	Maximum	p-value
	cm					cm				
	Depth to centre of mass, DFP = 0 cm ($Q50_0$)									
Crest	15.4	14.4 a[1]	12.8	19.1		21.5	21.2 a	15.5	27.7	
Midslope	20.2	24.0 ab	16.2	25.5	0.0509	25.9	24.6 a	24.4	28.7	0.0509
Depression	39.2	37.8 b	37.5	42.4		49.8	49.0 b	48.6	51.7	
	Depth to centre of mass, DFP = 20 cm ($Q50_{20}$)									
Crest	16.4	18.4 a	11.9	19.0		19.0	22.1 a	6.8	28.0	
Midslope	14.2	13.5 a	12.1	17.0	0.0608	20.4	20.2 a	13.6	27.4	0.0665
Depression	43.9	45.3 b	40.2	46.1		50.6	50.3 b	50.0	51.7	

[1] Median values followed by different letters were determined to be significantly different using a multiple comparison procedure at an experiment-wise error rate of α=0.15.

4.3.5.3 Site 3

In May at site 3, mean $Q50_0$ values were 21, 15 and 26 cm for the crest, midslope and depression plots, respectively (Table 4.15). The depression was found to have significantly greater depths to centre of bromide mass directly under the plot than the midslope position. The mean values were found to be $Q50_{20}$ 17, 15 and 28 cm for the crest, midslope and depression plots, respectively. However, there was no evidence to suggest a significant influence of landscape on $Q50_{20}$ in May at this site.

In October, mean values of $Q50_0$ were found to be 35, 19 and 33 cm for the crest, midslope and depression plots, respectively. There was no evidence to suggest the differences between these values were significant. However, the $Q50_{20}$ values were found to be significantly greater in the depression and crest plots than the midslope. Mean values were found to be 34, 17 and 35 cm for the crest, midslope and depression plots, respectively.

At site 3, $Q50_0$ and $Q50_{20}$ values consistently followed the trend midslope < crest < depression. These results indicate that there was deeper leaching at the depression position relative to the other positions. The results also suggest that lateral downslope redistribution was most important at the midslope position.

4.3.5.4 All Sites

When all sites are examined as one, there is no evidence to suggest a landscape effect on depths to centre of bromide mass in May. However, in October, $Q50_0$ and $Q50_{20}$ values were found to be significantly different between landscape positions (Table 4.16). Mean

Table 4.15 Descriptive statistics and one-way analysis of variance for depth to centre of bromide mass at site 3.

Landscape	May 2000					October 2000				
	Mean	Median	Minimum	Maximum	p-value	Mean	Median	Minimum	Maximum	p-value
	cm					cm				
	Depth to centre of mass, DFP = 0 cm ($Q50_0$)									
Crest	21.0	19.0 ab[1]	18.5	25.3		35.4	35.5	30.5	40.3	
Midslope	14.6	13.7 a	13.6	16.4	0.0622	19.3	18.7	13.1	26.2	0.1492
Depression[2]	25.8	25.8 b	24.0	27.6		32.8	32.8	23.6	42.0	
	Depth to centre of mass, DFP = 20 cm ($Q50_{20}$)									
Crest	17.4	16.4	15.1	20.9		33.9	34.4 a	27.8	39.6	
Midslope[2]	14.8	14.8	12.0	17.5	0.3041	17.8	17.3 b	11.8	24.5	0.0821
Depression[3]	28.4	28.4	-	-		34.5	34.5 a	33.7	35.2	

[1] Median values followed by different letters were determined to be significantly different using a multiple comparison procedure at an experiment-wise error rate of α=0.15.

[2] Only 2 replications for May 2000 and October 2000.

[3] Only 1 replication for May 2000 and 2 replications for October 2000.

Table 4.16 Descriptive statistics and one-way analysis of variance for depth to centre of bromide mass at all sites.

Landscape	May 2000					October 2000				
	Mean	Median	Minimum	Maximum	p-value	Mean	Median	Minimum	Maximum	p-value
	cm					cm				
	Depth to centre of mass, DFP = 0 cm ($Q50_0$)									
Crest	21.8	23.0	12.8	30.9		29.9	31.4 ab[1]	15.5	40.3	
Midslope	23.4	25.5	13.6	35.9	0.7895	25.9	26.2 a	13.1	36.5	0.0273
Depression[2]	23.1	20.0	11.3	42.4		36.3	40.0 b	11.8	51.7	
	Depth to centre of mass, DFP = 20 cm ($Q50_{20}$)									
Crest	21.0	20.9	11.9	35.3		27.6	28.0 a	6.8	39.6	
Midslope[2]	19.9	18.6	12.0	32.4	0.8278	20.0	20.2 a	5.7	38.2	0.0002
Depression[3]	23.3	19.7	4.1	46.1		38.2	39.5 b	12.7	51.7	

[1] Median values followed by different letters were determined to be significantly different using a multiple comparison procedure at an experiment-wise error rate of α=0.15.

[2] Only 14 replications for May 2000 and October 2000.

[3] Only 13 replications for May 2000 and 14 replications for October 2000.

$Q50_0$ values were found to be 30, 26 and 36 cm for crest, midslope and depression plots, respectively, while $Q50_{20}$ values for these positions were found to be 28, 20 and 40 cm, respectively. The depression position was found to have significantly greater $Q50_0$ values than the midslope, while $Q50_{20}$ values were found to be significantly greater in the depression than at the crest or midslope plots. These results indicate that the greatest vertical downward movement occurred at the depression plots. As well, the results suggest that lateral downslope redistribution was more important at the midslope position than at the crest or depression.

When the influence of site was accounted for, the effect of landscape was found to be significant for $Q50_0$ and $Q50_{20}$ for May (Table 4.17). In October, $Q50_{20}$ values were found to be significantly different due to landscape. However, there was no evidence to suggest a landscape effect on $Q50_0$ values.

Table 4.17 Friedman two-way analysis of variance by ranks for depth to centre of bromide mass.

Parameter	May 2000	October 2000
Depth to centre of mass, DFP = 0 cm ($Q50_{0cm}$)	0.0221	0.2183
Depth to centre of mass, DFP = 20 cm ($Q50_{20cm}$)	0.0756	0.0036

4.3.6 Bromide Redistribution in Relation to Topographic Variables and Soil Profile Attributes

4.3.6.1 Digital Terrain Models

Elevations decreased approximately 1.5, 0.7 and 0.8 m from crest plots to depression plots at sites 1, 2 and 3, respectively (Table 4.18). Slope gradients (G) were higher at the midslope positions relative to the crest or depression positions at all sites (Figures 4.17,

Table 4.18 Topographic attributes for all plots.

Plot ID	Easting -360000	Northing -5560000	E	G	K_v	K_h	H	K_a	ATD Zone
	m			°		m^{-1}		m^{-2}	
Site1									
Crest									
1C1	7368.9	5487.0	508.0	1.1	0.0288	0.0284	0.0286	0.000785	D
1C2	7365.0	5478.8	508.0	1.2	0.0389	0.0131	0.0260	0.000404	D
1C3	7369.8	5468.6	508.0	1.5	-0.0052	0.0218	0.0082	-0.000061	T
Midslope									
1M1	7343.3	5495.0	507.0	2.5	-0.0207	-0.0001	-0.0104	0.000167	A
1M2	7345.2	5484.2	507.2	2.7	0.0295	0.0031	0.0163	0.000168	D
1M3	7341.3	5475.5	507.1	2.3	0.0031	0.0150	0.0090	-0.000097	T
Depression									
1D1	7323.6	5496.8	506.4	1.5	-0.0453	-0.0430	-0.0442	0.001973	A
1D2	7313.4	5490.7	506.5	1.3	-0.0125	0.0151	0.0013	-0.000171	T
1D3	7320.3	5481.3	506.5	1.3	-0.0502	-0.0620	-0.0561	0.003257	A
Site 2									
Crest									
2C4	7864.0	5914.0	510.4	0.6	0.0098	0.0094	0.0096	-0.000002	T
Midslope									
2M4	7844.3	5925.1	509.9	1.8	-0.0103	-0.0083	-0.0093	0.000127	A
Depression									
2D4	7827.7	5930.5	509.7	0.5	-0.0050	-0.0179	-0.0115	0.000137	A
Site 3									
Crest									
3C5	7727.3	6134.8	511.0	0.6	-0.0072	0.0166	0.0047	-0.000166	T
Midslope									
3M5	7713.7	6152.3	510.6	2.3	0.0063	0.0164	0.0114	0.000087	D
Depression									
3D5	7710.2	6163.8	510.2	1.4	-0.0178	-0.0386	-0.0282	0.000899	A

4.18 & 4.19). Vertical curvature (*Kv*) values were generally positive at crest plots and negative at depression plots, indicating a deceleration of surface flows from the crest to the depression. Horizontal curvature (*Ka*) values were generally positive at the crest plots and negative at the depression plots, which demonstrate a divergence of surface flowpaths at the crest position and convergence of flow at the depression. Mean curvatures (*H*) were generally found to be positive at the crest and negative at the depression landscape position, indicating divergence and acceleration of flow at the crest and convergence and deceleration of flows at the depression. Accumulation curvatures were generally positive

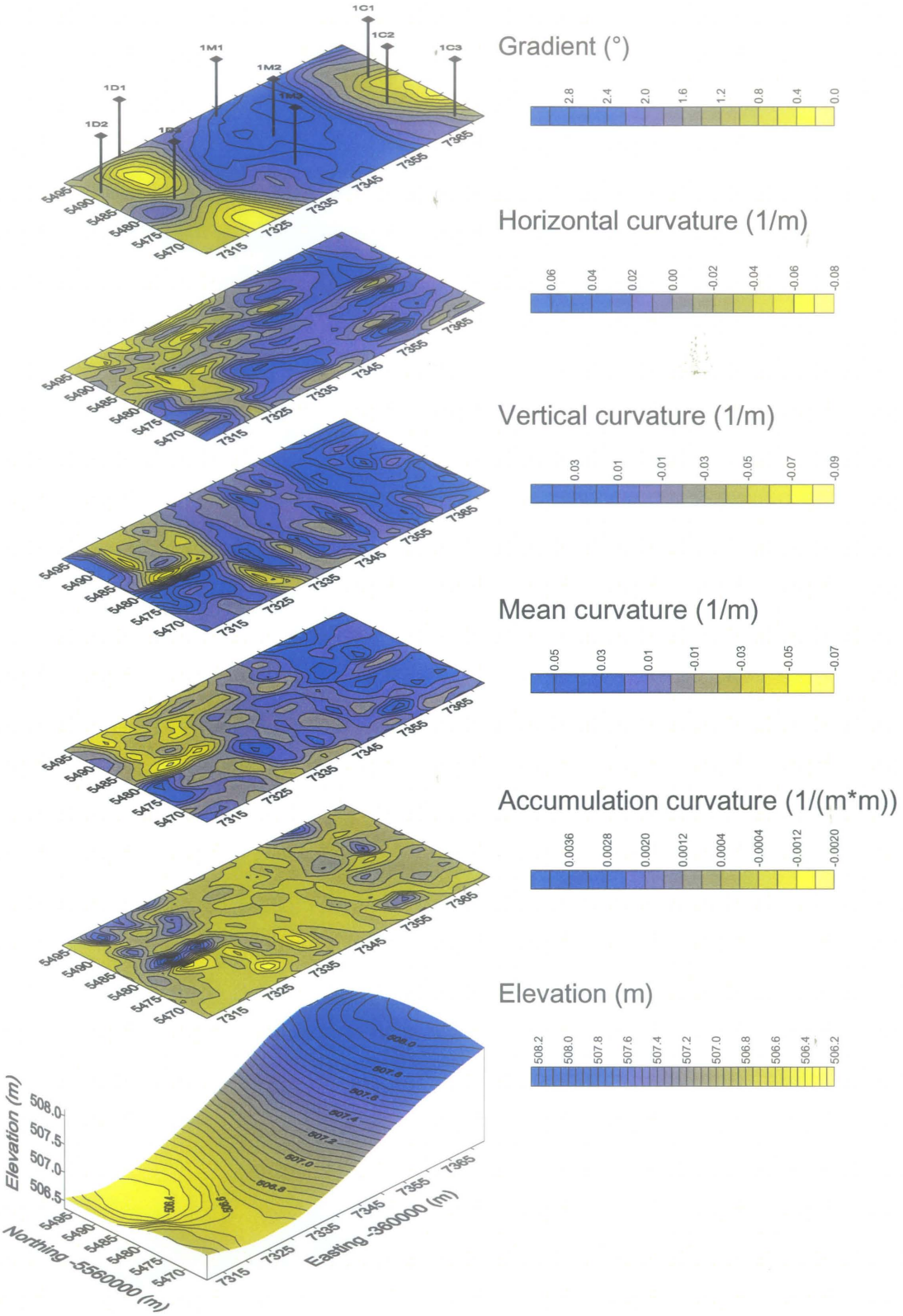


Figure 4.17 Digital terrain models for site 1.

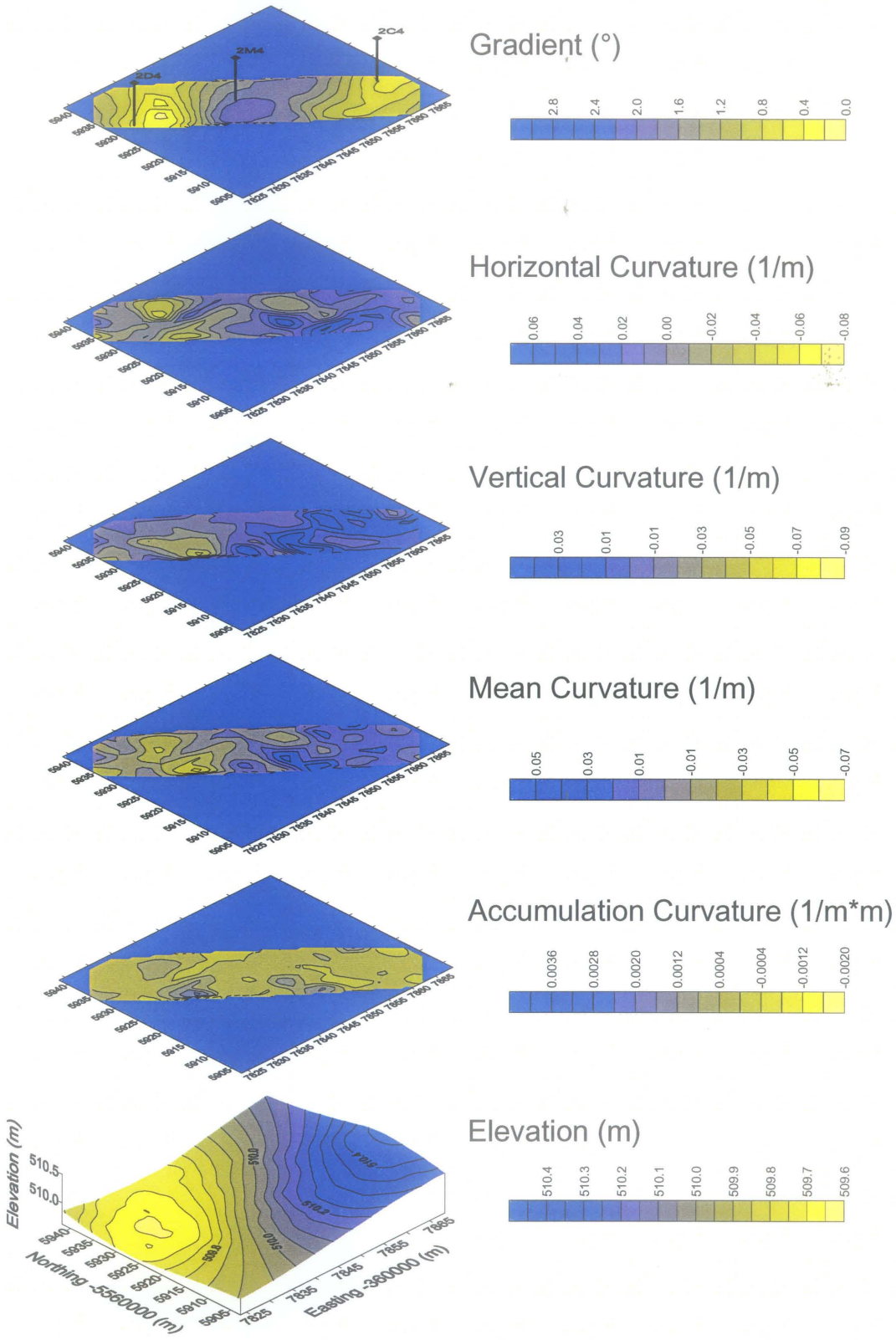


Figure 4.18 Digital terrain models for site 2.

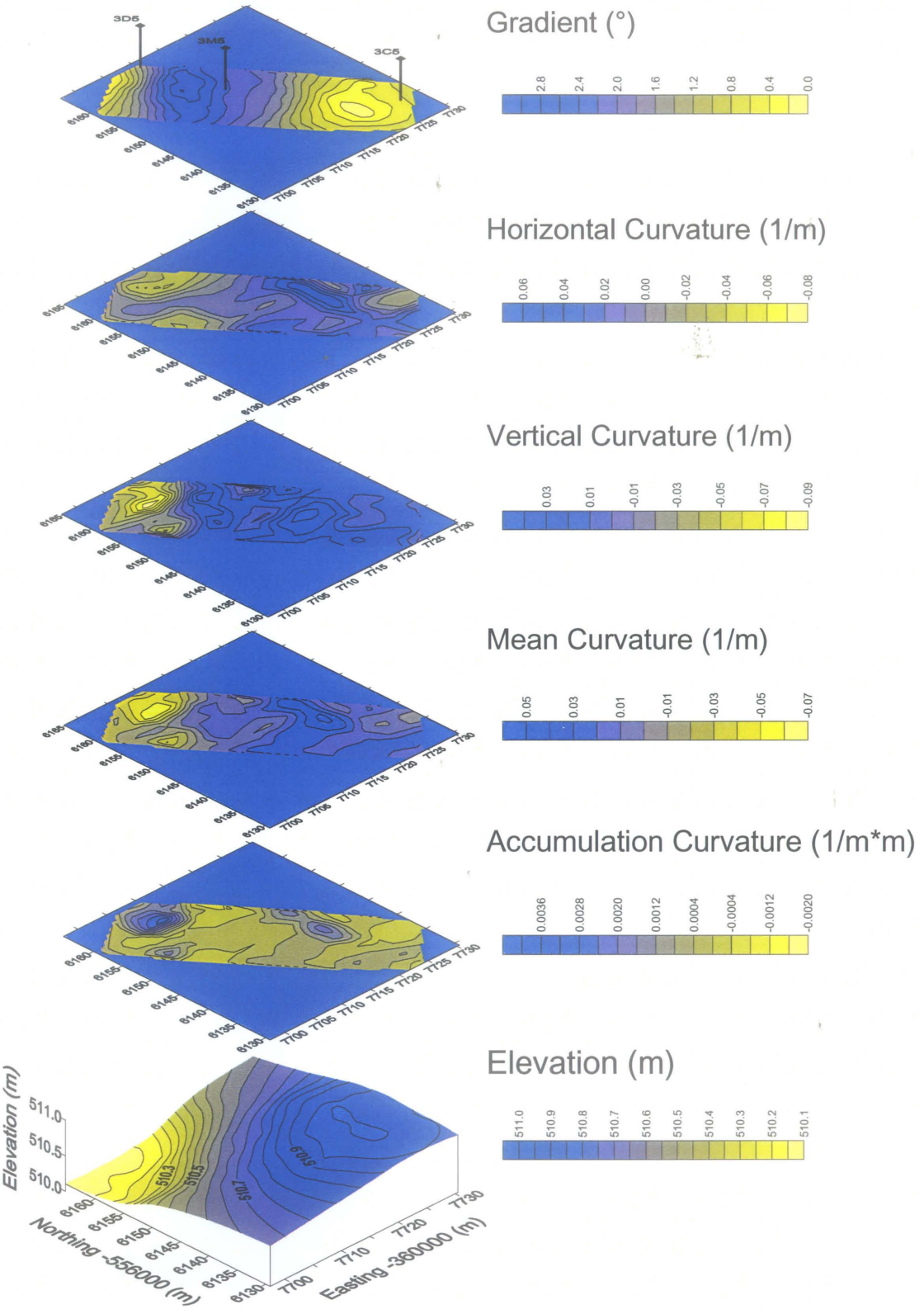


Figure 4.19 Digital terrain models for site 3.

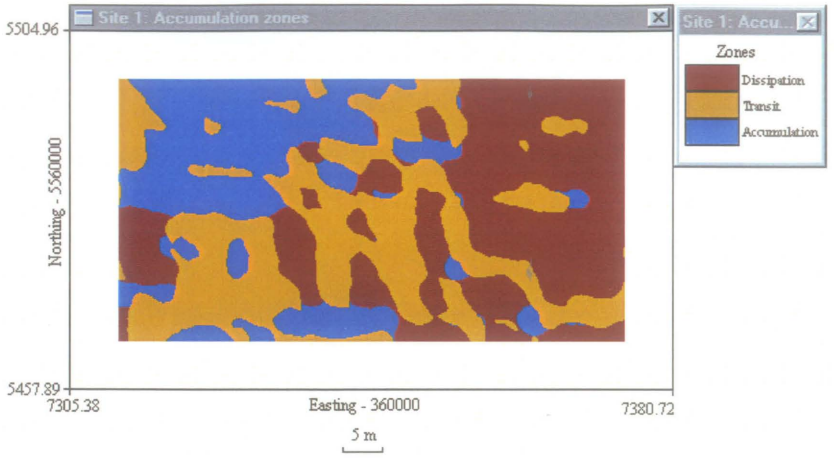
at depression plots, demonstrating that the degree of accumulation of water and material flows is highest at this location of the landscape. These results indicate that surface water flows diverge and accelerate from the crest position and converge and decelerate at the depression position. The midslope plots generally have properties intermediate to the crest and depression plots.

4.3.6.2 Dissipation, Transit and Accumulation Zones

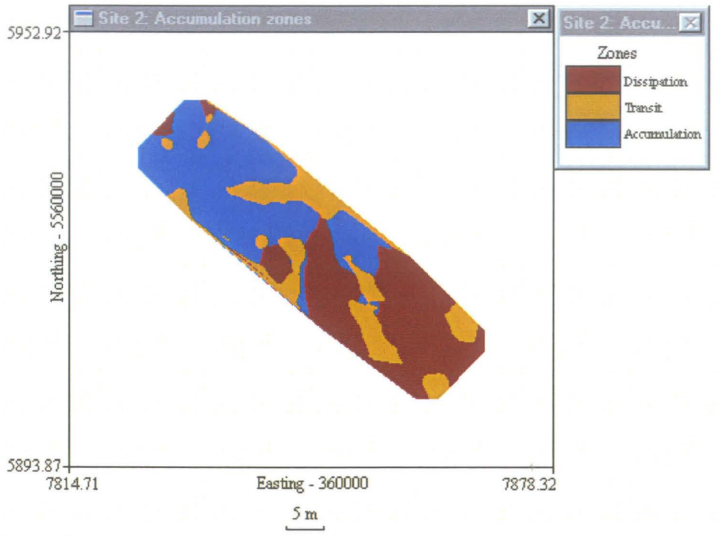
For all 3 sites, areas of crest, midslope and depression plots were dominated by dissipation, transit and accumulation zones (ATD zones), respectively (Figure 4.20). However, quantitative concepts did not consistently relate to their qualitative counterparts. For example, transit zones were found at 3 of 5 of the midslope plots, while dissipation zones were determined for 2 of 5 midslope plots (Table 4.18, Figure 4.20).

Pedologic indicators were found to be influenced by ATD zones. Depth to CO_3 (CO_3), A horizon thickness (A hor), solum thickness (solum) and profile development index (PDI) were all found to be significantly different between ATD zones (Table 4.19). In all cases, values were higher at accumulation zones, indicating that profile development was greater at accumulation zones relative to dissipation or transit zones.

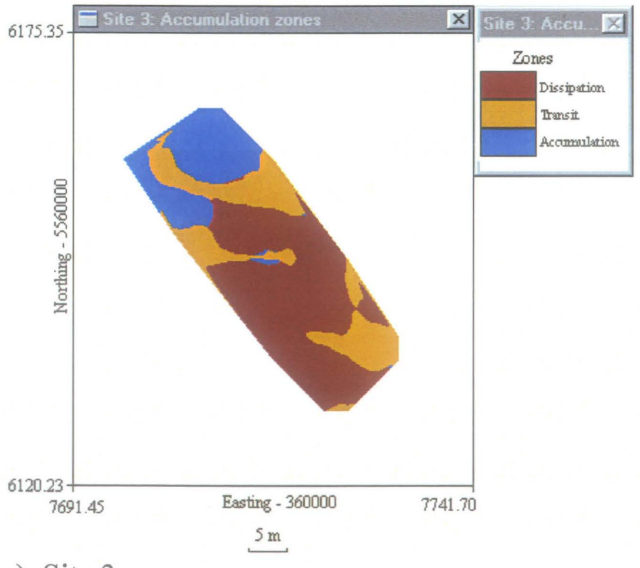
There was not much evidence found to suggest bromide redistribution parameters were significantly influenced by ATD zones. Only L_f and V_f/L_f values were found to be significantly different with ATD zones (Table 4.20). In May, lateral redistribution values



a) Site 1



b) Site 2



c) Site 3

Figure 4.20 Dissipation, transit and accumulation zones for all sites.

Table 4.19 Pedologic indicator median values and analysis of variance p-values for ATD zones.

Zone	Org C	CO_3	A hor	Solum	PDI
Dissipation	1.9	26.5 a[1]	13.5 a	39.5 a	1.78 a
Transit	2.5	26.0 a	10.0 a	42.0 a	1.66 a
Accumulation	2.6	56.5 b	26.0 b	73.5 b	2.58 b
p-value[2]	0.2291	0.0245**	0.0395**	0.0231**	0.0467**

[1] Median values followed by different letters were determined to be significantly different using a multiple comparison procedure at an experiment-wise error rate of α=0.15.
[2] Values followed by asterisks *, **, *** indicate statistical significance at α levels 0.10, 0.05 and 0.01, respectively.

Table 4.20 Bromide redistribution parameter median values and one-way analysis of variance p-values for ATD zones.

Zone	V_f	L_f	V_f/L_f	% Br	% Br_{30}	% Br_{60}	$Q50_0$	$Q50_{20}$
				May				
Dissipation	5586	1159 ab[1]	8.2 a	74.4	16.0	57.0	24.9	23.4
Transit	4592	830 a	10.1 a	76.2	28.0	59.6	21.0	18.7
Accumulation	4397	1689 b	5.2 b	56.2	27.0	46.9	21.8	18.8
p-value[2]	0.6002	0.0607*	0.0607*	0.2925	0.9227	0.2032	0.8353	0.8042
				October				
Dissipation	6673	1403	9.1	68.0	10.0	37.2	30.3	19.2
Transit	7260	1807	7.3	64.7	10.3	44.0	33.9	30.2
Acumulation	5973	1317	18.4	29.9	7.9	17.1	29.4	29.0
p-value	0.8353	0.9664	0.2392	0.0345**	0.6390	0.1690	0.8614	0.4256

[1] Median values followed by different letters were determined to be significantly different using a multiple comparison procedure at an experiment-wise error rate of α=0.15.
[2] Values followed by asterisks *, **, *** indicate statistical significance at α levels 0.10, 0.05 and 0.01, respectively.

were found to be significantly higher at accumulation zones than transit zones, while V_f/L_f values were found to be significantly lower at accumulation zones than dissipation or transit zones. These results are counter-intuitive and are not consistent with conclusions based examination of redistribution parameters with qualitative landscape positions. Trends reversed in October, indicating the importance of temporal variability in redistribution processes. It is apparent that examination of an entire hydrologic year was required to determine the net effect of ATD zones on bromide redistribution. However, no evidence was found to suggest significant differences between redistribution

parameters between ATD zones. The concept of ATD zones of the landscape did not appear to explain variability in solute redistribution in this study.

4.3.6.3 Bromide Recovery

Indicators of soil profile development were found to be predictors of bromide recovery. Temporal variability was an important influence on the ability of these indicators to predict recovery, as they were only effective at predicting recovery in October. Depth to carbonates (CO_3), A horizon thickness (A hor), solum thickness (solum) and profile development index (PDI) were all significantly correlated to total percent bromide recovery (% Br) and percent bromide recovery in the top 60 cm (% Br_{60}) in October (Table 4.21). These predictors demonstrate that as soil profile development increases, as indicated by increased CO_3, A hor, solum and PDI, there is less solute recovery over time. One can conclude from these relationships that, in this landscape, well developed soils have hydrologic conditions that favour rapid, deep leaching of soluble materials that remove solutes from the soil profile faster relative to more poorly developed soils. It is apparent from these results that an entire hydrologic season must be examined before agreement can be found between processes of solute redistribution and the pedologic footprint throughout the landscape.

Topographic variables of vertical curvature (*Kv*) and mean curvature (*H*) were found to be good predictors of % Br and % Br_{60}, while accumulation curvature (*Ka*) was found to be a good predictor of % Br only. Vertical and mean curvatures were positively correlated with % Br and % Br_{60}, while *Ka* was negatively correlated. As *Kv* and *H* decrease, surface flows decelerate and converge. It is intuitive that, as *Kv* decreases, surface water

Table 4.21 Spearman rank correlation coefficients for bromide redistribution parameters with some soil and topographic variables.

Parameter	Date	Org C	CO3	A hor	Solum	PDI	*G*	*Kh*	*Kv*	*H*	*Ka*	*E*
% Br	May	-0.01	-0.37	-0.28	-0.29	-0.26	-0.10	0.20	0.46	0.25	-0.14	0.08
	October	-0.12	-0.59**[1]	-0.63**	-0.46*	-0.55**	0.31	0.42	0.69***	0.57**	-0.54**	0.18
% Br_{30}	May	0.43	-0.10	-0.17	-0.14	0.03	0.06	-0.30	0.01	-0.14	0.03	0.12
	October	-0.26	-0.19	-0.37	-0.12	-0.29	0.64**	0.12	0.20	0.26	-0.22	0.15
% Br_{60}	May	0.11	-0.43	-0.40	-0.40	-0.34	0.16	0.04	0.44*	0.22	-0.19	-0.03
	October	-0.05	-0.60**	-0.69***	-0.50*	-0.51*	0.35	0.32	0.50*	0.50*	-0.39	0.29
V_f	May	-0.46*	-0.03	0.10	0.02	-0.15	-0.18	0.39	0.19	0.25	0.02	-0.12
	October	0.31	0.09	0.22	0.09	0.15	-0.56**	-0.09	-0.03	-0.19	0.02	-0.30
L_f	May	-0.04**	0.56	0.34	0.56**	0.44*	0.54**	-0.31	-0.34	-0.34	0.22	0.06
	October	-0.05	0.21	-0.05	0.14	0.23	0.03	0.01	0.13	0.02	-0.22	0.55**
V_f / L_f	May	-0.11	-0.43	-0.31	-0.41	-0.36	-0.52**	0.45*	0.35	0.38	-0.39	0.05
	October	-0.07	0.38	0.60**	0.34	0.29	-0.20	-0.21	-0.53**	-0.36	0.58**	-0.55**
$Q50_0$	May	-0.63**	-0.004	0.07	0.06	-0.21	0.08	0.38	0.01	0.20	0.03	0.00
	October	0.25	0.11	0.20	0.11	0.22	-0.54**	-0.06	0.01	-0.15	-0.06	-0.13
$Q50_{20}$	May	-0.64**	0.11	0.25	0.14	-0.11	-0.13	0.34	0.08	0.18	0.14	-0.04
	October	0.24	0.28	0.38	0.26	0.36	-0.63**	-0.29	-0.05	-0.38	-0.004	-0.11

[1] Values followed by asterisks *, **, *** indicate statistical significance at α levels 0.10, 0.05 and 0.01, respectively.

runoff velocity will slow and infiltration will become more favourable. Further to this, as *H* decreases, convergence and deceleration of surface flows increase resulting in more water input from surface runoff as well as higher rates of infiltration. With more water input and higher rates of infiltration, increased moisture status of the profile will favour deeper leaching and lower bromide recovery rates. As well, as *Ka* increases, accumulation of water flow increases, so it is expected that less bromide will be recovered at higher levels of *Ka*.

4.3.6.4 Vertical and Lateral Redistribution Functions

The vertical redistribution function (V_f) was negatively correlated to organic carbon (Org C) in May and was negatively correlated to slope gradient (*G*) in October (Table 4.21). Organic carbon provides a measure of soil organic matter levels. Soil organic matter increases soil water holding capacity, so it follows that as soil Org C levels increase, water holding capacity increases resulting in less water being leached through the profile, hence less vertical bromide redistribution. Vertical redistribution was found to be more important at the crest and depression positions, where *G* and, therefore, surface flow velocities are lower. These results are in agreement with Afyuni et al. (1994), who found positive correlation between *G* and lateral flow (i.e. decreased importance of vertical flow where slope gradients were high).

The lateral redistribution function (L_f) was found to be negatively correlated to Org C in May and positively correlated to solum and PDI in October. Organic matter, and therefore Org C, improves soil moisture holding capacity and infiltration, resulting in less available surface water thus less surface runoff, and hence less lateral redistribution. More lateral

redistribution was found where solum and PDI were higher, likely due to the fact that there was little lateral flow at poorly developed crest soils and strong lateral flow at better developed midslope soils. Topographic variables were also found to be predictors of L_f values, with positive correlations found for *G* in May and *E* in October. Increased *G* values result in higher surface flow velocities, and therefore less infiltration, and lead to more lateral surface redistribution. Elevation was found to be a predictor of L_f values, likely in that relative decreases in *E* generally indicate increases in soil water input due to gravity-driven flow.

When the relationship between vertical and lateral redistribution functions were examined (i.e. V_f/L_f), a negative correlation was found for gradient, while a positive correlation was found for horizontal curvature (*Kh*) in May. As surface flows converge, as indicated by increased *Kh* values, more water input will result in more water available for vertical redistribution in relation to lateral redistribution, if soil hydraulic characteristics are favourable for such. In October, Org C was found to be a good predictor of V_f/L_f, with a negative correlation being found. Topographic variables were found to be predictors of V_f/L_f in October, with negative correlations found for vertical curvature (*Kv*) and elevation (*E*), and a positive correlation found for accumulation curvature (*Ka*). The negative correlation to *Kv* demonstrates that, as *Kv* increases, surface flows accelerate resulting in less infiltration and an increased importance of the lateral redistribution function relative to vertical redistribution function. The importance of vertical redistribution relative to lateral redistribution increases with *Ka*, due to the fact that increases in accumulation of surface flows result in higher levels of water available for infiltration as well as less dissipation of water flows.

4.3.6.5 Depth to Centre of Bromide Mass

There was little correlation found for depth to centre of bromide mass with soil and topographic variables, however, the patterns of correlation found were consistent. Organic carbon (Org C) and gradient (*G*) were found to be negatively correlated to Q50 values in May and October, respectively (Table 4.21). Both $Q50_0$ and $Q50_{20}$ values decreased with Org C, indicating Org C was a good predictor of depth to centre of bromide mass in May. Organic carbon is a measure of organic matter, and is an important factor in moisture retention. Soil profiles with higher A horizon Org C levels have higher organic matter content and, therefore, higher moisture holding capacities and less water available for leaching. Slope gradient was found to be a good predictor of Q50 values in October, demonstrating that higher *G* promote more rapid surface flows and less infiltration, promoting less vertical downward soil water movement.

4.4 Summary and Conclusions

Spatial variability in soil distribution and soil properties was found to be systematic in nature with qualitatively defined landscape positions. Less variability in soil properties was found among landscape positions than between them. In general, soil profile development increased in the order crest < midslope < depression, as indicated by soil subgroup, CO_3, A hor, solum and PDI. Abrupt changes in horizonation were found, and appeared to have influenced bromide redistribution. Illuvial processes increased in the order crest < midslope < depression, as indicated by the occurrence of finer-textured Bm and Bt horizons at midslope and depression positions, respectively. Well-developed, clay-

coated blocky Bt horizons with vertical cracking, underlying Ae horizons, in depression positions appeared to have favoured rapid, downward vertical redistribution, indicating that soil structure may have had a more important influence than texture on solute movement.

Particle size distributions and bulk density values were most consistent with depth at the crest plots, demonstrating that pedogenic and hydrologic processes were not as important at this position of the landscape. The consistency of soil physical properties with depth at the crest suggests that soil profiles at this position were the least anisotropic. This was supported by the fact that vertical redistribution was found to be more important than lateral redistribution at this position.

A combination of topographic and pedologic factors resulted in more lateral redistribution at the midslope position relative to crest and depression positions.

Bromide recovery rates indicated that most of recovered bromide remained in the top 60 cm of the soil profile following the spring melt and recharge period. In October, more bromide was recovered in the top 30 cm at the midslope than the other positions, demonstrating that vertical redistribution was not as important at that position of the landscape. In October, low bromide recovery rates in the top 60 cm at the depression indicated that most of the applied bromide had leached below that depth. The depression had the lowest total recovery rates (% Br) in May and October, indicating high solute removal from the soil profile. Examination of graphical bromide redistribution plots, Vf values and Q50 values confirmed this conclusion.

The relative importance of lateral redistribution at midslope positions and vertical redistribution at depression positions has obvious implications for water and associated soluble nutrient movement through this landscape. Depression-focused recharge, as described by other researchers in similar undulating glacial till landscapes (Lissey 1971; Schuh et al. 1993; Seelig and Richardson 1994), appears to be an important mechanism of solute redistribution in this landscape. As concluded by Schuh et al. (1993), there appears to be large sensitivity of site-specific recharge to small differences in relative surface elevation at this site.

The vertical extent of solute leaching has practical agronomic and environmental importance. Results from May indicated that reduced nutrient availability of fall-applied nutrients for early crop growth could be expected at crest and depression positions. Solute redistribution was more important during spring runoff than over the growing season at crest and midslope positions. Crop water demands and soil moisture deficits at upslope positions of the landscape result in limited water availability over the growing season (Stolte et al. 1992; Shaykewich, personal communication, University of Manitoba, Winnipeg, MB), and would have reduced the availability of moisture for solute redistribution. In other words, little net downward water movement would have occurred during this period. Redistribution was found to be important during spring recharge and over the growing season at the depression position. The relatively unlimited supply of water at this position of the landscape (Stolte et al. 1992; Shaykewich, personal communication, University of Manitoba, Winnipeg, MB) from the shallow water table and surface run-on from upslope positions would result in a net downward flow of water through the soil profile throughout the growing season. This is supported by the bromide

redistribution results. In May and October, graphical redistribution plots indicated solute movement below crop rooting depths and entry into shallow groundwater sources at depression positions. This has important environmental implications in that fall-applied nutrients may enter groundwater sources following spring recharge.

Topographic variables and soil properties had mixed ability to predict bromide redistribution parameters. Crest plots generally had positive *Kv*, *Ka* and *H* values, while depression plots generally had negative *Kv*, *Ka* and *H* values, demonstrating that surface flows diverge and accelerate at crest positions and converge and decelerate at depression positions. Intermediate values were generally found at the midslope, although *G* values were highest there. Soil profile development indicators, including CO_3, A hor, solum and PDI, were negatively correlated to % Br and % Br_{60}, indicating that increased profile development resulted in more redistribution and lower recovery rates. Slope gradient was found to be a good predictor of vertical redistribution, with vertical redistribution found to be least important at the midslope where *G* values were the highest. Vertical curvature values were found to predict less vertical relative to lateral redistribution where *Kv* values were higher, and hence surface flow velocities were higher. Accumulation curvature values were found to predict more vertical relative to lateral redistribution where *Ka* values, and therefore accumulation of surface flows, were high. Temporal variability in solute redistribution influenced the utility of soil and topographic variables in predicting redistribution.

Pedologic indicators were found to be significantly different between ATD zones, with CO_3, A hor, solum and PDI all significantly higher at accumulation zones relative to dissipation or transit zones, indicating that profile development was greatest at

accumulation zones. However, the concept of ATD zones did not appear to influence bromide redistribution parameters over the course of the study.

5. GENERAL DISCUSSION

The processes influencing the movement of water and associated solutes through the vadose zone have important agronomic, environmental and economic implications. The vertical and lateral movement of soluble nutrients within the soil profile influences the availability of nutrients required for crop growth, and the entry of nutrients into groundwater and surface water systems, both of which have associated costs. Much research has been conducted measuring and modeling these processes in controlled laboratory environments, however, the complexity of these processes in natural environments requires complementary detailed field investigations to be conducted. The objective of this study was to examine the relationship between solute redistribution and soil distribution in relation to landscape morphology. Specifically, the study was to examine the spatial and temporal variability of soil properties and soil hydrologic processes across the landscape, to determine if the distribution of soils in relation to landscape features result in recognizable, systematic patterns of solute redistribution. The study consisted of an examination of long-term solute redistribution across the landscape as well as the vertical and lateral movement of a soluble tracer over the short-term.

Significant findings of the study include:

- Soil profile morphology was found to be related to landscape morphology;
- Spatial variability of static soil properties was found to be systematically related to qualitatively-defined landscape positions;

- Quantitative topographic variables were found to be important predictors of static soil properties;

- Topographic variables were not found to be good predictors of dynamic soil properties within the rooting zone, while relationships were apparent when greater depths were examined;

- Systematic variability was found in bromide redistribution over a hydrologic season in relation to 3 soil-landscape complexes;

- Recognizable patterns in vertical and lateral bromide redistribution were found to be related to soil properties and topographic variables;

- Depression-focused recharge was found to be an important mechanism resulting in significant removal of bromide from the rooting zone following spring melt and over the growing season;

- The utility of Landscape Element Complexes (LECs) as a predictive tool for static and dynamic soil properties were limited by differing hydrologic regimes at lower positions of the landscape;

- The concept of Accumulation, Transit and Dissipation zones of the landscape were found to explain spatial variability in static soil properties;

- *A priori* knowledge of soil-landscape processes was found to be important in determining the nature of solute redistribution processes occurring throughout the landscape.

The relationship between between soils and their position in the landscape has long been recognized (Jenny 1941, 1961; Hugget 1975; McCaig 1984). Pennock et al. (1987) noted that this relationship can largely be explained by the influence of topography on patterns of water movement and distribution. The spatial and temporal variability of soil properties with depth in the profile and across landscape positions, in turn, result in diverse patterns of water and solute distribution over the landscape (Bathke et al. 1992; Afyuni et al. 1994).

Soil morphology was found to be related to the topography of the land surface throughout the study field. Spatial variability in soil distribution and soil properties that influence hydrologic processes was systematically related to qualitatively defined landscape positions. Less soil variability was found among landscape positions than between them. Based on qualitative geomorphic concepts, soil development generally increased from Crest to Midslope to Lower-Depressional slopes, as evidenced by soil properties indicative of progressive soil development, including increased A horizon depth (Ahor), increased solum depth (solum), increased depth to carbonates (CO_3) and increased organic carbon in the A horizon (OrgC). The profile development index (PDI) also increased in this order. However, soil distribution in relation to landscape morphology was also influenced by hydrologic regime in Lower-Depressional areas of the landscape. Shallow groundwater dynamics influenced the nature of soil profiles in that increased soil development was found in areas of the landscape characterized by recharge, or net downward flows, relative to areas of throughflow or discharge, or net upward flows. These findings are in agreement with Manning (1999), who found variable soil

development and hydrologic regimes within similar elements of the landscape depending on the nature of the hydrologic regime.

Quantitative topographic variables were found to be important predictors of static soil properties. Ahor, OrgC and CO_3 were all found to decrease with relative elevation (*RE*), an indicator of general drainage characteristic of the landscape. Horizontal curvature (*Kh*) and vertical curvature (*Kv*) values, indicators of the convergent or divergent character of the land surface, were found to be negatively correlated to Ahor and CO_3. Flow accumulation, as measured by catchment area (*CA*) and topographic index (*TI*) were found to be positively correlated to Ahor, solum and CO_3. These findings are in general agreement with Florinsky et al. (2002) who found *Kh*, *Kv*, *CA* and *TI* to be good predictors of soil properties at other locations in the study field.

Topographic variables were not found to be good predictors of more temporally variable, or dynamic, soil properties, including soil moisture, and solute redistribution parameters within the rooting zone. It appears the temporal variability overshadowed the influence of topography for the single sampling event. Examination of the dynamic soil properties over an entire hydrologic season may have yielded better relationships. Although Florinsky et al. (2002) found correlations between soil moisture and topographic variables, the strength of these relationships were highest at the soil surface, and decreased with depth within the rooting zone. They found that temporal variability of dynamic soil properties changed these relationships over time, and concluded the decreased topographic control with depth resulted in a shallow "effective soil layer" for prediction.

Results from this study indicate that relationships between solute redistribution parameters and topographic variables were apparent and of statistical importance when greater depths were considered. The best predictors of static properties were also found to be related to solute redistribution parameters below the rooting zone, however, the nature of these relationships was not as straightforward. *RE* was found to be a good predictor of solute parameters and was positively correlated to NO_3^- and SO_4^{2-} redistribution when the 0-300 cm and 120-300 cm depth intervals were examined. These relationships indicate that solute redistribution parameters, although dynamic in nature close to the soil surface, become more temporally stable with depth, and allow for recognizable patterns throughout the landscape.

The recognizable, systematic pattern of deep solute redistribution found along the transect was, at first glance, contour-intuitive. Higher amounts of solute were recovered below 120 cm at upper-crest slope positions, relative to lower-depressional positions, which were characterized as hydrologic throughflow areas. This may be attributed to greater crop uptake at lower slope positions where moisture is relatively unlimited for crop growth and/or higher solute removal at lower slopes, where there is greater accumulation of water, the influence of a near-surface water table and more lateral flow losses.

The occurrence of deeply leached soluble nutrients at high concentrations at crest positions is an important finding to consider. Leaching potential is typically considered to be relatively low in these portions of the landscape in semi-arid regions. It appeared that these areas of the landscape have been chronically fertilized above crop use potential, which is relatively low in these portions of the landscape due to moisture limitations. The net effect appears to be deep leaching of excess nutrient over time resulting in large

accumulations below the rooting zone. The risk associated with deeply leached soluble nutrients at this position of the landscape, in terms of entry into groundwater sources, is unknown.

When LECs were examined, Ahor, solum and CO_3 increased from UPS to MID to LOW. Similar to conclusions by Manning (1999), it is apparent that the utility of LECs as a predictive tool for static soil properties is limited by differing hydrologic regime and pedogenic processes occurring at lower slope positions, as a result of near-surface, dynamic water tables. The use of LECs as a predictive tool for dynamic soil properties within the rooting zone was found to be very limited, however, it was based on a single sampling event. Among LECs, NO_3^- in the 0-300 depth interval increased from LOW to MID to UPS.

Topographic variables and concepts of LECs appear to have some utility in determining spatial variability of deep solute percolation and determination of potential for groundwater impacts. However, a priori knowledge of soil-landscape relationships and associated pedogenic processes in the context of the hydrologic regime is required to achieve sensible results. In other words, topography of the land surface is an important factor affecting solute movement, but its influence in areas of the landscape impacted by near-surface water tables is affected by whether the area functions as a recharge, discharge or throughflow site.

Systematic variability in short-term bromide redistribution was found in relation to three distinct soil-landscape complexes, namely:

- Crest – Calcareous Black Chernozem (Cordova Series);

- Midslope – Orthic Black Chernozem (Newdale Series); and

- Depression – Gleyed Eluviated Black Chernozem (Angusville Series).

Recognizable patterns of vertical and lateral bromide movement were found to be related to soil and topographic variables.

The majority of the recovered bromide following the spring melt and recharge period was found in the top 60 cm across all soil-landscape complexes. This indicated that, although significant bromide redistribution had occurred, most soluble material remained within the rooting zone.

Anisotropy was found to be important in determining the relationship between vertical and lateral redistribution. Pedogenesis was found to be of least importance at the Crest position, as evidenced by more consistent particle size distribution and bulk density with depth, relative to Midslope and Depression positions. Theoretically, this should result in less lateral "deflection" of flows through the soil profile at the Crest position. Patterns of bromide redistribution supported this, as vertical redistribution was more important than lateral at this position in the landscape. At Midslope positions, where pedogenic processes have resulted in less uniform soil properties with depth, anisotropic processes were more important, as evidenced by significant lateral bromide redistribution.

In October, more bromide was recovered in the top 30 cm at the Midslope relative to the other landscape positions, indicating that vertical redistribution was less important relative to lateral redistribution compared with Crest and Depression positions.

Abrupt changes in horizonation were found and appeared to have influenced bromide redistribution. For example, well developed Bt horizons, with clay-lined ped faces and vertical structural character, found at Depression positions, appeared to have favoured rapid downward, vertical redistribution. It was concluded that structure may be more important than particle size redistribution for water movement within this landscape.

Significant bromide leaching was found below the rooting zone at the Depression position in the May and October sampling events. Most bromide was removed from the top 60 cm at the Depression position following the growing season. This, combined with the lowest total recovery rates of the three landscape positions over both sampling periods, indicate the rapid, vertical redistribution that occurred at the depressional areas of this landscape under annual crop production. Although of limited areal extent, the importance of small, isolated depressional areas for recharge flow in this landscape is obvious. This "depression-focused" recharge, described previously by a complement of researchers (Lissey 1971; Schuh et al. 1993; Seelig and Richardson 1994), has obvious implications for soluble nutrient movement through these landscapes.

Solute redistribution was found to be more important during the spring runoff and recharge period than over the growing season at Crest and Midslope positions, in this semi-arid region. Redistribution was found to be important at the Depressions over both hydrologic seasons. Ponded water was found at the Depressions briefly following spring melt, however, it quickly infiltrated as the water table receded. The continued drop in the water table over the growing season, as conditions approach a water deficit, would promote deep vertical redistribution of soluble materials. This has obvious agronomic and environmental implications. The agronomic implications of these findings include

reduced availability of fall applied nutrients, particularly for early crop growth. However, due to the limited areal extent of these small depressional areas, the practical agronomic importance of this is limited.

Crest plots were described by positive vertical (*Kv*), accumulation (*Ka*) and mean (*H*) curvatures, indicating surface flows could be characterized by divergence and acceleration of surface flows. Depression plots were characterized by negative *Kv*, *Ka* and *H* values, indicating surface flows could be characterized by convergence and acceleration of surface flows.

Vertical curvature was found to be negatively correlated to a ratio describing vertical relative to lateral bromide redistribution, indicating that where surface flows accelerate, there was less infiltration and vertical recharge. Accumulation curvature was found to be correlated to vertical relative to lateral flow, indicating that where surface flows accumulate, there was more infiltration and more water available for vertical redistribution.

Soil properties of CO_3, Ahor, solum and profile development index (PDI) were found to be negatively correlated to % total bromide recovery and % bromide recovery in the top 60 cm. These results indicated that static soil properties representing the degree of pedogenic development have utility in predicting water and solute redistribution in the short-term. In other words, temporally stable soil properties indicative of water movement through the soil profile may be used as indicators of dynamic processes of water and soluble nutrient movement.

The concept of Accumulation, Transit and Dissipation zones were found to explain spatial variability in static soil properties, including Ahor, solum, CO_3 and PDI. These indicators of progressive pedogenic processes were all found to be highest at Accumulation zones. This concept was not found to be a good predictor of bromide redistribution parameters over the course of the study.

Temporal variability in bromide redistribution influenced the utility of soil and topographic variables in predicting redistribution. More research is required to examine these processes over time to better determine relationships between temporally stable topographic variables and static soil properties and dynamic processes of water and soluble nutrient redistribution.

6. CONTRIBUTION TO KNOWLEDGE

The systematic variability of soil distribution in relation to landscape morphology in glacial till landscapes has long been recognized. Determining the relationship between this variability and the redistribution of water and associated solutes will provide a better understanding of how nutrients move through the vadose zone of agricultural field soils and enter into groundwater systems. The agronomic, economic and environmental implications of these processes are obvious.

Previous research on this field site near Miniota, Manitoba determined that there may be utility in using soil and topographic variables, as well as landscape element complexes, in site-specific management, namely variable rate fertilization (Manning, 1999; Manning et al. 2001a, 2001b). Specifically, Manning (1999) noted that convergent LECs would most likely benefit from increased rates of nitrogen fertilizer under typically moisture-deficient growing season conditions. He also noted that weather is the single largest source of variability in the relationship between crop production and underlying, systematic variability. Based on this research, and the finding of the current study, it is apparent that an increased N application in convergent portions of the landscape may result in higher rates of deep percolation and removal of N from the crop rooting zone, in areas of depression-focused recharge, when environmental conditions are favourable for such.

This study provides an indication of the importance of small, isolated depressional areas in the removal of water and associated soluble material from these glacial till landscapes in Western Canada.

While there appears to be utility in using topographic variables and static soil properties to predict patterns of dynamic solute redistribution, more research is necessary to adequately determine the nature of these relationships over time. It was found that the relationship between pedologic expression and solute redistribution is strongest when examined over an entire hydrologic year.

This study highlights the importance of *a priori* knowledge of the relationships between soil-landscape complexes and hydrologic regimes in understanding processes of solute redistribution occurring throughout the landscape.

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8. APPENDICES

I. Soil series descriptions

The soil series of the study site (SE32-14-25W) are described in alphabetical order and include a general description of the genetic profile type, CSSC taxonomic subgroup classification, texture, parent material, topography and drainage, as found in Fitzmaurice et al. (1999).

Angusville Series (ANL)

The Angusville series is characterized by a Gleyed Eluviated Black Chernozemic soil profile developed on moderately to strongly calcareous, slightly stony, fine loamy (L-CL) morainal till of limestone, granitic and shale bedrock origin. These soils are imperfectly drained and occur in lower to mid slope positions of undulating to hummocky landscapes, in close association with the well drained Newdale, Rufford and Cordova soils, the imperfectly drained Varcoe series, and the poorly drained Drokan and Penrith series. Surface runoff is slow to moderately slow; permeability is moderately slow to slow within the solum and moderately slow in the subsoil. Vegetation on noncultivated lands consists of grasses and trembling aspen.

The average thickness of the soil profile is 61 cm and varies from 45 to 85 cm. The A horizon has a mean thickness of 25 cm and ranges from 20 to 40 cm. The very dark gray to gray Ap horizon is 15 to 20 cm thick, and the dark gray to gray Ae (Ahe) horizon, 5 to 15 cm thick. The dark brown to dark yellowish brown Btgj is 25 to 35 cm thick. A lime enriched layer of 10 to 20 cm may be present. The C horizon is light olive brown with yellowish brown mottles.

The Angusville soil profile is thicker and more strongly developed and free of lime carbonate in comparison to the closely associated, shallower, carbonated Gleyed Rego Black Varcoe series. The strongly leached Angusville soils are sites of net surface water infiltration and are considered to be sites of local recharge to the groundwater table.

Cordova Series (CVA)

The Cordova series is characterized by a Calcareous Black solum on moderately to strongly calcareous, slightly to moderately stony, loamy (L-CL) morainal till of mixed limestone, granitic and shale rock origin. These soils are well to rapidly drained and occur in the upper slope and crest positions of undulating to hummocky landscapes, in close association with the well drained Rufford and Newdale series. Surface runoff is moderately rapid to rapid, depending upon slope. Permeability is moderately slow. Native vegetation consists of mixed tall prairie grasses and herbs.

The Cordova soil prfile has a thin, very dark gray Ap(k) horizon, 12 to 18 cm thick, a calcareous, yellowish brown to dark yellowish brown Bmk horizon, 5 to 15 cm thick, a thin transitional BC horizon and a light gray lime carbonate accumulation layer, 25 to 35 cm thick. Secondary carbonates may be found along vertical cracks within the underlying grayish brown (dry) or dark grayish brown (moist) Ck horizon. In many areas, these soils have been altered by wind and water erosion; the crest position have lost most of the A horizon and part of the B horizon has been cultivated. In a few areas, the Cca horizon has been incorporated into the plow layer, imparting a light gray surface colour.

In this project area, the A horizon is 22 cm thick and varies from 15 to 35 cm; the depth of solum is 41 cm and varies from 25 to 75 cm. The Cordova series differs from the Rufford series, a carbonated REgo Black in having a Bmk horizon. Both Cordova and Rufford series differ from the Newdale series, the former having free lime carbonate present in the solum, while the latter has an A and B horizon free of carbonates.

Drokan Series (DRO)

The Drokan series is characterized by a Rego Humic Gleysol (carbonated) solum, developed on moderately to strongly calcareous, loamy (L-CL) morainal till of limestone, granitic and shale rock origin. They are poorly to very poorly drained and occur in depressional positions of the undulating to hummocky morainal landscape. Surface runoff is negligible and the soils remain under ponded condition unless drainage has been artificially improved. Permeability is moderately slow to slow. In most landscapes, these soils are influenced by seepage from the slough, and may have a considerable content of soluble salts. Native vegetation consists of sedges, cattails, rushes and willows. These soils are of small localized extent and best retained in their natural state.

The Drokan soil profile has a moderately decomposed organic layer, 5 to 10 cm thick, a very dark gray Ah horizon, 10 to 18 cm thick, a mottled transitional AC horizon, 4 to 8 cm thick and a lime accumulation layer, 8 to 12 cm thick. The C horizon is olive gray to olive with yellowish brown mottles. In this study area, the average A horizon is 25 cm thick and varies from 10 to 50 cm; the average depth of its solum is 38 cm and varies from 20 to 60 cm.

It differs from the closely related Penrith soil series in being carbonated and having shallower, less distinct horizons.

Hamiota (HMI)

The Hamiota Series is the poorly drained, Orthic Humic Gleysol member of the Newdale association, developed on moderately to strongly calcareous, loamy (L-CL) morainal till of limestone, granitic and shale rock origin. They occur in depressional positions of the undulating to hummocky morainal landscape. Surface runoff is negligible; permeability is moderately slow to slow. Native vegetation consists of sedges, cattails, rushes and willows.

A typical Hamiota soil profile has a decomposed L-H horizon, 2.5 to 7 cm thick, a black Ah horizon, 15 to 25 cm thick, a gleyed gray brown Bg horizon, 15-25 cm thick; a

transitional BC horizon may occur but more commonly a 10 to 20 cm light gray Ccag horizon is present. An olive gray Ckg horizon typically identifies the parent material.

These soils usually occur as intermediates between the Rego Humic Gleysol, Drokan and the Humic Luvic Gleysol, Penrith.

Newdale Series (NDL)

The Newdale series is characterized by an Orthic Black Chernozemic solum developed on moderately to strongly calcareous, loamy (CL) morainal till of limestone, granitic rock and shale origin. These soils are well drained and occur in mid to upper slope positions of undulating to hummocky landscapes. Surface runoff is moderate to moderately rapid; permeability is moderately slow. Most of these soils are presently cultivated; they have formed under intermixed aspen grove and grassland vegetation.

The Newdale solum has a black to very dark gray Ah horizon, commonly 20 cm thick and ranging from 15 to 40 cm, a dark brown Bm horizon, 10 to 30 cm thick, and a transitional BC horizon, 3 to 15 cm thick. A lime carbonate horizon, 10 to 15 cm thick may be present in shallower soils but is not evident in deeper profiles. Its solum depth averages 40 cm and ranges from 25 to 60 cm. Minor amounts of well drained Eluviated Black soils occur within the Newdale mapping units. These eluviated soils range from 75 cm to greater than 1 m in depth. They have thick A (combined Ah, Ahe) horizons, 30 to 60 cm and Bt horizons that are 40 cm thick.

The Newdale soils in the study area differ from the very similar Rufford and Cordova soils in being more strongly leached, thicker and free of lime carbonate in the A and B horizons.

Penrith Series (PEN)

The Penrith series is characterized by a Humic Luvic Gleysol solum developed on moderately to strongly calcareous, loamy (L, CL) morainal till of limestone, granitic rock and shale origin. These soils are poorly drained and occur in depressional positions which commonly occur at slightly elevated portions of undulating to hummocky landscapes. These soils are subject to ephemeral ponding of variable short durations in spring and early summer but usually are free of water in the summer and fall, unless replenished by heavy rains and runoff. Permeability is very slow within the solum and moderately slow in the subsoil. Vegetation consists of sedge and ringed with willow.

The solum of the Penrith series commonly has a moderately to strongly decomposed organic surface layer, 4 to 8 cm thick, a dark gray to gray Ahe horizon, 6 to 10 cm thick, a light gray, platy structured Aeg horizon, 6 to 10 cm thick, a dark gray to gray Btg horizon, 35 to 45 cm thick, and a gray transitional BC horizon, 15 to 25 cm thick. In the study area, the A horizon thickness averages 35 cm and ranges from 15 to 45 cm; the average solum depth is 65 cm and ranges from 30 to 75 cm.

The Penrith soils differ from the Drokan soils in being more strongly leached and having more distinct and thicker horizons. Penrith soils usually occur at sites of local infiltration

where there is a net downward movement of water in the soil. These soils are affected by ponding of surface water for a shorter time than Drokan soils. Penrith soils are sometimes cultivated, but surface ponding after heavy rains may result in drown out of crops.

Varcoe Series (VRC)

The Varcoe series is characterized by a Gleyed Rego Black (carbonated) Chernozemic solum on moderately to strongly calcareous, loamy (L, CL) morainal till of limestone, granitic rock and shale origin. These soils are imperfectly drained and occur in the lower slope positions of undulating to hummocky landscapes in close association with Angusville soils. They receive runoff from the upper slopes, and in some landscapes, may be influenced by seepage from adjacent lower lying areas. Permeability is slow and may be restricted during periods of subsoil saturation. In areas where seepage waters contain soluble salts, there may be a risk of soil salinization.

Varcoe profiles average 42 cm in thickness and range from 20 to 60 cm. The A horizon is usually 25 cm thick and ranges from 20 to 50 cm; very dark gray in color and is underlain by a dark gray transitional AC horizon, 4 to 8 cm thick. A lime accumulation horizon may be present, but is often thin and discontinuous.

Sample Position	Subgroup	Series Name	Series Code	Land Use	Slope Position	Depth CO_3 (cm)	A Horizon Thickness (cm)	Solum Thickness (cm)	Drainage	PDI	A Org C (%)	Horizon No.	Horizon	Upper Limit (cm)	Lower Limit (cm)	Horizon Thickness (cm)
DS1	CA.BL	Cordova	CVA	Cropland	Crest	13	13	18	W	2.00	1.744	1	Ap	0	13	13
												2	Bmk	13	18	5
												3	Cca	18	27	9
												4	Ck	27	66	39
												5	Ckgj	66	115	49
DS2	O.BL	Newdale	NDL	Cropland	Middle	26	13	32	MW	2.41	1.541	1	Ap	0	13	13
												2	Bm	13	26	13
												3	Bmk	26	32	6
												4	Ck	32	87	55
												5	Ckgj	87	122	35
DS3	GLR.BL	Varcoe	VRC	Cropland	Lower-Toe	38	31	69	I	0.90	2.537	1	Ap	0	11	11
												2	Ah	11	31	20
												3	ACkgj1	31	51	20
												4	ACkgj2	51	69	18
												5	Ccagj	69	94	25
												6	Ckgj	94	114	20
DS4	O.HG	Hamiota	HMI	Fen	Depression	75	20	40	P	2.50	5.371	1	LFH	5	0	5
												2	Ah	0	20	20
												3	Bg	20	40	20
												4	BCg	40	75	35
												6	Ckg	75	120	45
DS5	O.BL	Newdale	NDL	Cropland	Middle	46	14	46	MW	3.11	2.498	1	Ap	0	14	14
												2	Bm	14	27	13
												3	Btjgj	27	46	19
												4	BCkgj	46	54	8
												5	Ccagj	54	74	20
												6	Ckgj	74	122	48
DS6	CA.BL	Cordova	CVA	Cropland	Crest	13	13	19	W	2.00	2.138	1	Ap	0	13	13
												2	Bmk	13	19	6
												3	BCk	19	25	6
												4	Cca	25	51	26
												5	Ckgj	51	121	70
DS7	GL.BL	Angusville	ANL	Cropland	Lower-Toe	48	16	48	I	3.10	2.285	1	Ap	0	16	16
												2	Bmgj	16	27	11
												3	Btgj	27	48	21
												4	BCkgj	48	64	16
												5	Ccagj	64	90	26
												6	II Ckgj	90	100	10
												7	III Ckgj	100	116	16

Sample Position	Horizon No.	Texture	Structure 1	Structure 2	Moisture	Efferv.	Calcar.	Consistence		Coarse Fragments		Colour	Mottles	Clay Films		
								Moist	Dry	Type	%			Freq.	Thick.	Locat.
DS1	1	L	M.MC.GR		M	N	N	FB		GR	5	10YR 2.5/1				
	2	CL	M.M.AB		M	V	W	FR		GR	5	10YR 4/3				
	3	CL	M.MC.AB		M	S	V	FR		GR	5	2.5Y 5/3				
	4	CL	M.F.PR	M.M.AB	M	S	S	FR		GR	5	2.5Y 5/3				
	5	CL	MA		M	S	S	VM		GR	10	2.5Y 4/3	C.F.D			
DS2	1	L	M.MC.GR		M	N	N	FB		GR	1	10YR 2/1				
	2	CL	M.M.AB		M	N	N	FB		GR	1	10YR 4/3				
	3	CL	M.M.AB		M	W	W	FB		GR	5	10YR 4/3				
	4	CL	M.F.PR	M.M.AB	M	S	S	FR		GR	5	10YR 5/3				
	5	CL	MA		M	M	M	FR		GR	5	10YR 5/4				
DS3	1	CL	M.M.GR		M	N	N	FB				10YR 2/1				
	2	CL	M.MC.GR		M	N	N	FB				10YR 2/1				
	3	CL	M.MC.AB		M	V	W	FB		GR	1	10YR 3/1.5	C.F.F			
	4	CL	M.MC.AB		M	W	M	FB		GR	1	2.5Y 3/2	C.M.F			
	5	SCL	M.F.PR	M.FM.AB	M	S	V	FB		GR	5	2.5Y 5/4	M.C.D			
	6	CL	MA		M	M	S	FR		GR	5	2.5Y 5/4	M.M.D			
DS4	1															
	2	CL			W	N	N					2.5Y 2.5/1				
	3	CL			W	N	N					2.5Y 3/1				
	4	CL			M	N	N					2.5Y 4/1				
	6	CL			M	S	S					2.5Y 4/3				
DS5	1	L	M.MC.GR		D	N	N		HD	GR	1	10YR 2/1				
	2	L	W.M.SB		M	N	N	FB				10YR 4/3				
	3	CL	M.M.SB		M	N	N	FR				10YR 4/3	C.M.F	F	TH	PF
	4	CL	W.M.SB		M	W	W	FR		GR	1	10YR 4/4	C.MC.F			
	5	CL	W.F.PR		M	S	V	FR		GR	5	10YR 5/4	C.M.F			
	6	CL	MA		M	M	M	FR		GR	5	2.5Y 4.5/4	F.F.F			
DS6	1	L	M.C.GR		M	N	N	FR				10YR 2/1				
	2	L	M.M.AB		M	W	W	FB		GR	1	10YR 4/3				
	3	CL	M.M.AB		M	M	M	FR		GR	5	10YR 5/3				
	4	CL	M.MC.AB		M	S	V	FR		GR	5	2.5Y 5/4				
	5	CL	MA		M	M	S	VM		GR	10	2.5Y 5/3	F.F.D			
DS7	1	L	M.M.GR		M	N	N	FB				10YR 2/1				
	2	CL	M.M.AB		M	N	N	FR		GR	1	10YR 4/3				
	3	C	M.M.AB		M	N	N	FB		GR	5	10YR 3/3		M	MT	PF
	4	CL	W.MC.AB		M	M	M	FR		GR	5	2.5Y 5/3	F.F.F			
	5	SiCL	M.MC.AB		M	S	V	FR		GR	5	2.5Y 6/4	C.M.D			
	6	SL	W.C.GR		M	M	S	FR		GR	5	2.5Y 5/4	C.F.D			
	7	CL	M.F.PR	M.M.SB	M	M	S	FR		GR	5	2.5Y 4/4	C.F.D			

Sample Position	Horizon No.	Kvert	Khor	Water Table Depth (cm)	Saturated Zone		Roots	Rooting Depth (cm)	Notes
					Least	Great			
DS1	1	H1	H1		L2		P.F.R.B	95	no compaction apparent; c.f. present throughout entire profile; no major colour change in subsurface 150-510cm 2.5Y 6/2d (4/3m)
	2	M3	M3				P.F.R.B		
	3	M2	M2				P.F.R.B		
	4	M2	M1				F.V.V.E		
	5	M1	L3				V.V.V.E		
DS2	1	H2	H2	>300	L2		P.F.R.B	91	no visibile compaction zone; c.f. throughout entire profile; no major colour change in subsurface 150-180cm 2.5Y 6/3d (4/3m), 330-360 2.5Y 6/3d (4/3m), 480-510 2.5Y 6/3d (4/3m)
	2	M3	M3				F.F.R.B		
	3	M3	M3				F.F.R.B		
	4	M2	M1				F.F.V.E		
	5	M2	M1				F.F.V.E		
DS3	1	H2	H2		M1		F.F.R.B	65	compaction zone b/t 100-114cm; profile relatively c.f. free - only very small C.F. (i.e. ~2mm) throughout profile; gypsum crystals present 31 cm; no major colour change in subsurface 150-180cm 2.5Y 7/3d (5/3m), 330-360 2.5Y 6/3d (4/3m), 360-390 2.5Y 6/3d (4/3m)
	2	H2	H2				F.F.R.B		
	3	M3	M2				V.F.V.E		
	4	M3	M2				V.F.V.E		
	5	M1	L3						
	6	M1	L3						
DS4	1			<100	H1				no core taken for lab analysis because too wet during sampling; soil pit description in field & bulk samples in lab; unoxidized till begins at approx. 300cm colour 150-240 2.5Y 6/4d (4/3m), 240-270 2.5Y 6/3d (4/3m), 270-300 2.5Y 6/2d (4/3m), 300-330 5Y 6/2d (4/1m), 330-480 5Y 6/1d (4/1m)
	2								
	3								
	4								
	6								
DS5	1	H2	H2	>200	L1		P.F.R.B	105	c.f. present throughout entire profile; no major colour change in subsurface 150-180 cm 2.5Y 6/3d (4/3m), 270-300 2.5Y 6/3d (4/3m)
	2	H2	H2				P.F.R.B		
	3	M3	M2				P.F.R.B		
	4	M3	M3				P.F.R.B		
	5	M2	M2				P.F.R.B		
DS6	1						P.F.V.E	95	c.f. present throughout entire profile; no major colour change in subsurface 180-210 cm 2.5Y 6/2d (4/3m), 210-240 2.5Y 6/2d (4/3m), 300-330 2.5Y 6/2d (4/3m), 480-510 cm 6/3d 2.5Y 6/2d (4/3m)
	2						P.F.R.B		
	3						P.F.R.B		
	4						P.F.R.B		
	5						F.F.R.B		
DS7	1	H2	H2	250	L1		F.F.R.B	82	Btgj starts at 27cm, but no Ae present, former ANL profile, with Ae lost to tillage; c.f. throughout entire profile; no major colour change in subsurface 150-180cm 2.5Y 6/4d (4/3m), 300-330 2.5Y 6/4d (4/3m)
	2	H2	H2				P.F.R.B		
	3	H2	H2				F.F.V.B		
	4	M3	M2				F.F.V.B		
	5	M3	M2				F.F.V.E		
	6	H1	H1				F.F.V.E		
	7	M1	L3						

III. Soil profile description terminology defined.

Soil profile terminology definitions based on those described by the Expert Committee on Soil Survey (1983). Please refer to ECSS (1983) for more detailed definitions of terminology.

Terminology	Definition
Subgroup	Soil subgroup classification.
Series Name	Soil series name.
Series Code	Three-letter soil series code.
Land Use	Present land use.
Slope Position	Qualitative description of slope position: Crest Upper Middle Lower Toe Depression
Depth to CO_3	Depth to carbonates, as indicated by effervescence on addition of dilute HCl , in cm.
A Hor Thickness	A Horizon Thickness: Thickness of all A horizons in cm.
Solum Thickness	Thickness of A and B horizons combined in cm.
Drainage	Drainage is described on the basis of actual moisture content in excess of field capacity and length of the saturation period within the plant root zone: R - Rapid W – Well MW – Moderately Well I - Imperfect P – Poor VP - Very Poor
PDI	Profile development index (Fuller, personal communication, AXYS Environmental Consulting Ltd.).
A Org C	Organic carbon % in surface Ah/Ap horizon.
Horizon No.	Numeric identifier for each horizon or layer.
Horizon	Designation of master layer or horizon and associated suffixes.
Upper Limit	Upper limit of horizon or layer in cm.
Lower Limit	Lower limit of horizon or layer in cm.
Horizon Thickness	Difference between Lower and Upper Limt.
Texture	Textural class: SL – Sandy Loam L – Loam SiL – Silty Loam SCL – Sandy Clay Loam SiCL – Silty Clay Loam CL – Clay Loam SC – Sandy Clay

Structure	Description of the primary aggregation of primary soil particles into compound particles, by: Grade SL – Structureless VW – Very Weak W – Weak WM – Weak to Moderate M – Moderate MS – Moderate to Strong S - Strong Class VF – Very Fine FF – Very Fine to Fine F – Fine FM – Fine to Medium M – Medium MC – Medium to Coarse C - Coarse VC – Very Coarse Kind PL – Platy PR – Prismatic AB – Angular Blocky SB – Subangular Blocky GR – Granular MA – Massive
Structure 2	Description of the secondary aggregation of primary soil particles into compound particles, as described above.
Moisture	Field moisture status of horizons: D – Dry M – Moist W - Wet
Efferv.	Effervescence: The degree of effervescence due to a chemical reaction (i.e. the bubbling, hissing of foaming) upon addition of 10% HCl: N – Non Effervescent V – Very Weak W – Weak M – Moderate S - Strong
Calcar.	Calcareousness: Approximation of the amount of carbonates present expressed as $CaCO_3$ equivalent, made by noting the effervescence obtained with 10% HCl: W – Weakly Calcareous (< 5%) M – Moderately Calcareous (5-15%) S – Strongly Calcareous (15-25%) VS – Very Strongly Calcareous (25-40%) E – Extremely Calcareous (>40%)

Consistence	The resistance of soil material to failure under stress, described under wet, moist or dry conditions: Wet N – Non Sticky S – Slightly Sticky T – Sticky V – Very Sticky Moist LO – Loose VF – Very Friable FB – Friable FR – Firm VF – Very Firm Dry LO – Loose SO – Soft SH – Slightly Hard HD – Hard VH – Very Hard EH – Extremely Hard RG – Rigid
Coarse Fragments	Kind and amount of rock fragments in a horizon: Type GR – Gravel % Volumetric percentage
Colour	Munsell colour notation of soil horizon, described by Hue, Value and Chroma.
Mottles	Spots or blotches of different color or shades of color interspersed with the dominant color, described by: Abundance F – Few (<2%) C – Common (2-20%) M – Many (>20%) Size F – Fine (<5mm) M – Medium (5-15mm) C – Coarse (>15mm) Contrast F – Faint D – Distinct P - Prominent

Clay Films	Clay film frequency (%), thickness (mm) and location: Frequency F - few (<2%) C – common (2-20%) M – many (20-80%) C – continuous (>80%) Thickness VT – very thin (<0.005mm) TH – thin (0.005-0.05mm) MT – moderately thick (0.05-0.5mm) TK – thick (0.5-1.0mm) VK – very thick (>1.0mm) Location VC – voids and channels PF – ped faces VP – some voids PV – all voids BR – visible bridges
Kvert	Estimated vertical hydraulic conductivity: H – High (>15cm/hr) H2 – Very Rapid (>50cm/hr) H3 – Rapid (15-50cm/hr) M – Medium (<0.5-15cm/hr) M3 – Moderate-Rapid (5.0-15cm/hr) M2 – Moderate (1.5-5.0cm/hr) M1 – Moderate-Slow (0.5-1.5cm/hr) L – Low (<0.5cm/hr) L3 – Slow (0.15-0.5cm/hr) L2 – Very Slow (0.015-0.15cm/hr) L1 – Extremely Slow (<0.015cm/hr)
Khor	Estimated horizontal hydraulic conductivity, as described above.
Water Table Depth	Estimated depth to the surface of the zone of water saturation in cm.
Saturated Zone	Average annual least depth and greatest depth of saturated zone estimated in cm.

Roots	Description of roots: Abundance V – Very Few F – Few P – Plentiful A – Abundant Size V – Very Fine (<1mm) F – Fine (1-2mm) M – Medium (2-5mm) C – Coarse (>5mm) Orientation V – Vertical H – Horizontal O – Oblique R - Random Distribution I – Inped E – Exped B - Both
Rooting Depth	Depth of maximum root penetration in cm.
Notes	General notes on soil profile.

IV. Analytical results for the long-term solute redistribution study.

Sample Position	Depth Sampled	pH	EC	Cl^-	Br^-	NO_3^-	SO_4^-	Gravimetric Water Content
	— cm —		- mS cm^{-1} -	———	ppm	———		— g g^{-1} —
DS1	0-30	7.91	0.86	6.3	1.8	0.4	49.2	0.15
	30-60	8.53	0.50	5.2	0.5	<0.3	19.1	0.14
	60-90	8.63	0.52	6.6	<0.3	10.8	17.5	0.13
	90-120	8.61	0.54	15.1	0.3	21.4	173.9	0.16
	120-150	8.63	0.54	9.5	0.2	11.1	24.1	0.17
	150-180	8.5	0.58	5.6	<0.3	8.8	34.7	0.16
	180-210	8.56	0.60	4.3	0.3	8.7	47.8	0.17
	210-240	8.47	0.68	14.0	<0.3	6.9	92.8	0.17
	240-270	8.01	2.54	7.3	0.3	14.7	1585.0	0.17
	270-300	7.77	5.16	6.9	0.3	17.1	6076.8	0.17
	300-330	7.75	4.98	6.4	<0.3	17.7	12123.1	0.18
	330-360	7.76	4.88	6.2	<0.3	16.8	10063.5	0.18
	360-390	7.71	5.08	6.6	<0.3	14.8	9113.0	0.18
	390-420	7.7	5.02	5.5	<0.3	13.7	6452.4	0.18
	420-450	7.68	4.84	7.6	<0.3	11.7	8539.0	0.18
	450-480	7.65	4.80	9.4	<0.3	10.1	6614.4	0.19
	480-510	7.66	4.80	8.4	<0.3	8.9	5640.6	0.17
DS2	0-30	7.99	0.88	4.8	0.8	<0.3	255.0	0.19
	30-60	8.44	0.50	4.0	0.5	<0.3	59.6	0.18
	60-90	8.54	0.48	5.7	0.3	<0.3	18.6	0.16
	90-120	8.6	0.48	9.0	<0.3	<0.3	15.7	0.17
	120-150	8.57	0.50	6.2	<0.3	<0.3	16.6	0.18
	150-180	8.57	0.50	7.1	<0.3	<0.3	23.5	0.17
	180-210	8.52	0.52	7.6	<0.3	1.1	26.5	0.18
	210-240	8.47	0.60	8.5	<0.3	2.9	45.0	0.18
	240-270	8.3	0.80	8.0	<0.3	5.7	170.0	0.19
	270-300	7.68	4.90	6.9	<0.3	6.8	5849.9	0.18
	300-330	7.67	4.70	4.9	<0.3	6.7	7057.2	0.19
	330-360	7.67	5.10	6.6	<0.3	7.0	6126.6	0.18
	360-390	7.67	5.06	5.0	<0.3	7.0	6338.7	0.17
	390-420	7.66	5.10	5.4	<0.3	6.7	5724.8	0.18
	420-450	7.63	4.94	8.5	<0.3	6.4	8999.0	0.17
	450-480	7.67	4.38	7.7	<0.3	4.4	5832.2	0.17
	480-510	7.66	4.82	7.0	<0.3	2.7	6003.8	0.18
DS3	0-30	7.59	1.08	5.0	0.9	0.6	191.7	0.29
	30-60	8.32	0.68	3.5	0.5	<0.3	61.4	0.20
	60-90	8.75	0.50	7.0	0.5	<0.3	58.6	0.19
	90-120	8.64	0.50	7.9	0.4	<0.3	30.3	0.22
	120-150	8.53	0.50	5.4	<0.3	<0.3	27.0	0.19
	150-180	8.59	0.42	4.8	<0.3	<0.3	23.3	0.19
	180-210	8.45	0.48	7.3	<0.3	<0.3	22.1	0.17
	210-240	8.37	0.58	8.0	<0.3	<0.3	38.1	0.22
	240-270	8.36	0.48	9.7	<0.3	<0.3	35.0	0.19
	270-300	8.36	0.50	9.6	<0.3	<0.3	30.9	0.19
	300-330	8.26	0.54	10.4	<0.3	<0.3	38.0	0.18
	330-360	8.21	0.60	7.0	<0.3	<0.3	71.8	0.19
	360-390	7.57	4.32	5.8	<0.3	0.7	6017.2	0.19
DS4	0-30	6.61	0.58	<0.3	<0.3	<0.3	260.0	0.64
	30-60	7.89	0.64	6.5	<0.3	<0.3	110.1	0.35
	60-90	8.17	0.60	7.5	<0.3	<0.3	81.3	0.31

Sample Position	Depth Sampled	pH	EC	Cl^-	Br^-	NO_3^-	SO_4^-	Gravimetric Water Content
	— cm —		– $mS\ cm^{-1}$ –			ppm		– $g\ g^{-1}$ –
	90-120	8.3	0.50	13.1	<0.3	<0.3	79.7	0.28
	120-150	8.34	0.46	9.3	<0.3	<0.3	43.1	0.23
	150-180	8.39	0.42	9.6	<0.3	<0.3	34.4	0.20
	180-210	8.4	0.40	8.7	<0.3	<0.3	34.1	0.20
	210-240	8.27	0.50	5.7	<0.3	<0.3	28.3	0.18
	240-270	8.4	0.42	6.4	<0.3	<0.3	37.5	0.17
	270-300	8.26	0.48	6.7	<0.3	<0.3	62.1	0.20
	300-330	8.05	0.90	6.7	<0.3	0.9	169.1	0.19
	330-360	7.86	1.50	8.7	<0.3	<0.3	624.0	0.19
	360-390	7.81	1.60	6.1	<0.3	1.1	-	0.19
	390-420	7.82	1.60	6.4	<0.3	0.8	740.4	0.18
	420-450	7.87	1.42	6.9	<0.3	0.8	715.6	0.17
	450-480	7.82	1.58	6.0	<0.3	0.8	710.5	0.19
	480-510	7.79	1.50	7.3	<0.3	<0.3	714.4	0.20
	510-540	7.82	1.48	6.6	<0.3	1.2	695.0	0.19
DS5	0-30	7.11	0.58	4.0	0.7	<0.3	89.8	0.19
	30-60	8.08	0.54	2.9	0.4	<0.3	41.7	0.16
	60-90	8.28	0.86	3.7	0.7	<0.3	266.5	0.19
	90-120	8.46	0.52	6.0	0.6	<0.3	61.2	0.18
	120-150	8.53	0.40	8.5	<0.3	<0.3	35.7	0.13
	150-180	8.37	0.50	6.1	<0.3	<0.3	45.0	0.15
	180-210	8.31	0.62	7.5	<0.3	3.8	90.0	0.18
	210-240	8.25	0.70	7.3	<0.3	2.1	107.5	0.18
	240-270	8.26	0.70	8.0	<0.3	5.3	125.4	0.17
	270-300	8.25	0.68	9.3	<0.3	1.7	106.7	0.18
DS6	0-30	7.4	1.04	-	<0.3	<0.3	87.0	0.21
	30-60	8.49	0.50	5.5	0.5	<0.3	31.2	0.17
	60-90	8.67	0.54	12.4	0.6	<0.3	21.0	0.17
	90-120	8.68	0.52	5.9	0.4	<0.3	20.5	0.16
	120-150	8.64	0.54	7.3	<0.3	5.2	20.5	0.17
	150-180	8.58	0.56	6.1	0.2	1.6	33.0	0.17
	180-210	8.51	0.56	6.5	0.3	<0.3	39.9	0.17
	210-240	8.11	0.58	7.4	0.2	6.9	50.2	0.18
	240-270	7.90	2.84	5.8	<0.3	9.6	339.3	0.18
	270-300	7.69	5.10	3.2	<0.3	9.3	10642.3	0.18
	300-330	7.7	5.44	3.4	<0.3	8.3	9142.3	0.18
	330-360	7.7	5.40	4.8	<0.3	8.2	6225.9	0.18
	360-390	7.72	5.08	6.0	0.3	7.7	6266.4	0.18
	390-420	7.72	4.88	4.3	<0.3	7.8	7920.3	0.18
	420-450	7.7	5.16	8.3	<0.3	8.4	6209.3	0.18
	450-480	7.76	3.88	5.9	0.3	8.5	3908.3	0.17
	480-510	7.68	5.06	8.0	<0.3	8.7	7981.5	0.18
DS7	0-30	7.37	0.62	8.5	0.8	<0.3	95.8	0.15
	30-60	8.3	0.44	12.1	0.5	<0.3	56.4	0.07
	60-90	8.34	0.48	6.5	0.3	<0.3	29.7	0.14
	90-120	8.39	0.40	6.5	<0.3	2.6	13.1	0.18
	120-150	8.39	0.42	7.2	<0.3	5.4	18.3	0.18
	150-180	8.41	0.42	6.4	<0.3	2.4	11.4	0.18
	180-210	8.42	0.42	8.4	<0.3	1.9	24.4	0.19
	210-240	8.43	0.42	6.6	<0.3	1.0	21.3	0.19
	240-270	8.41	0.44	7.8	<0.3	<0.3	16.3	0.19
	300-330	8.43	0.44	8.5	<0.3	1.4	22.0	0.18

V. Detailed soil profile descriptions for the bromide tracer study.

Plot	Soil Subgroup	Series Code	Horizon No.	Horizon	Upper Limit (cm)	Lower Limit (cm)	Horizon Thickness (cm)	Texture	Structure 1	Structure 2
1D1	CA.BL	CVA	1	Apk	0	13	13	L	M.MC.GR	
			2	Bmk	13	28	15	CL	M.MC.GR	
			3	Cca	28	54	26	CL	M.MC.AB	
			4	Ck	54	110	56	SCL	M.FM.SB	
1D2	CA.BL	CVA	1	Ap	0	12	12	L	M.MC.GR	
			2	Ah	12	18	6	L	M.MC.GR	
			3	Bm	18	33	15	CL	M.C.GR	
			4	Cca	33	44	11	CL	WM.M.SB	
			5	Ck	44	77	33	CL	M.MC.SB	
			6	Ck2	77	119	42	CL	MS.MC.SB	
1D3	O.BL	NDL	1	Apk	0	12	12	L	M.MC.GR	
			2	Ah	12	20	8	L	M.MC.GR	
			3	Bmk	20	32	12	CL	M.MC.GR	
			4	BCk	32	44	12	CL	M.MC.GR	
			5	Cca	44	66	22	CL	M.M.SB	
			6	Ck	66	104	38	SC	M.FM.PR	WM.MC.SB
			7	Ckgj	104	119	15	SCL	WM.M.SB	
1T1	O.BL	NDL	1	Ap	0	10	10	L	M.C.GR	
			2	Ah	10	23	13	L	M.MC.GR	
			3	Bm1	23	35	12	CL	M.M.GR	
			4	Bm2	35	44	9	CL	M.MC.GR	
			5	Bmk	44	56	12	CL	M.MC.GR	
			6	BCk	56	65	9	CL	M.M.AB	
			7	Cca	65	82	17	SC	M.F.PR	M.FM.SB
			8	Ckgj	82	119	37	SC	M.F.PR	M.M.SB
1T2	O.BL	NDL	1	Ap	0	10	10	L	M.MC.GR	W.C.PL
			2	Ah	10	14	4	L	W.C.PL	
			3	Bm1	14	24	10	CL	M.MC.GR	
			4	Bm2	24	36	12	CL	M.M.AB	
			5	BCk	36	49	13	SL	W.M.SB	
			6	Ck1	49	64	15	CL	M.MC.SB	
			7	Ck2	64	73	9	SCL	W.M.SB	
			8	Ck3	73	84	11	CL	M.F.PR	M.M.SB
			9	Ck4	84	91	7	SCL	W.M.SB	
			10	Ckgj	91	108	17	CL	M.F.PR	M.M.SB
1T3	O.BL	NDL	1	Ap	0	10	10	L	M.MC.GR	W.C.PL
			2	Bm1	10	21	11	CL	M.M.AB	
			3	Bm2	21	26	5	CL	M.M.AB	
			4	BCk	26	42	16	CL	M.M.SB	
			5	Ck	42	64	22	CL	M.M.AB	
			6	Ckgj	64	108	44	CL	M.F.PR	M.M.SB
1A1	GLE.BL	ANL	1	Ap	0	11	11	CL	M.FM.GR	
			2	Ahe	11	19	8	SiCL	W.F.PL	
			3	Ae	19	34	15	SiL	M.F.PL	
			4	AB	34	44	10	CL	WM.FM.SB	
			5	Btgj	44	63	19	SC	M.FM.SB	
			6	BCkgj	63	82	19	CL	M.F.PR	WM.FM.SB
			7	Ckgj	82	104	22	CL	M.F.PR	M.M.SB
			8	Ccagj	104	120	16	CL	M.F.PR	M.M.SB
1A2	GLE.BL	ANL	1	Ap	0	12	12	CL	M.FM.GR	
			2	Ahe	12	17	5	SiCL	W.F.PL	
			3	Ae	17	29	12	SiL	M.F.PL	
			4	AB	29	39	10	CL	WM.FM.SB	
			5	Bt	39	61	22	SC	M.FM.SB	
			6	BCkgj	61	74	13	CL	WM.FM.SB	
			7	Ckgj	74	92	18	CL	M.F.PR	M.M.SB
			8	Ccagj	92	105	13	CL	M.F.PR	M.M.SB
			9	Ckgj	105	119	14	CL	M.F.PR	M.M.SB

Plot	Soil Subgroup	Series Code	Horizon No.	Horizon	Upper Limit (cm)	Lower Limit (cm)	Horizon Thickness (cm)	Texture	Structure 1	Structure 2
1A3	GLE.BL	ANL	1	Ap	0	11	11	CL	M.FM.GR	
			2	Ahe	11	16	5	SiCL	W.F.PL	
			3	Ae	16	23	7	SiL	M.F.PL	
			4	AB	23	30	7	CL	WM.FM.SB	
			5	Bt	30	50	20	SC	M.FM.SB	
			6	BCkgj	50	61	11	CL	WM.FM.SB	
			7	Ccagj	61	105	44	CL	M.F.PR	M.M.SB
			8	Ckgj	105	116	11	CL	M.F.PR	M.M.SB
2D	O.BL	NDL	1	Ap	0	8	8	L	M.C.GR	
			2	Bm	8	22	14	CL	WM.M.SB	
			3	BCk	22	35	13	SCL	M.MC.SB	
			4	Ck	35	56	21	SCL	W.F.PR	M.M.SB
			5	Ckgj	56	120	64	SCL	M.F.PR	M.M.SB
2T	O.BL	NDL	1	Ap	0	7	7	L	M.M.GR	
			2	Ah	7	16	9	L	M.C.GR	
			3	Bm1	16	25	9	CL	M.C.GR	
			4	Bm2	25	40	15	CL	M.FM.SB	
			5	BCk	40	48	8	CL	M.FM.SB	
			6	Ck1	48	65	17	CL	M.F.PR	M.FM.AB
			7	Ck2	65	68	3	CL	M.FM.GR	
			8	Ckgj	68	120	52	CL	M.F.PR	M.M.AB
2A	GLE.BL	ANL	1	Ah	0	12	12	L	M.MC.PL	
			2	Ahe	12	17	5	SiCL	M.F.PL	
			3	Ae	17	29	12	SiL	M.FM.PL	
			4	Bt	29	47	18	SiL	M.F.SB	
			5	Btgj	47	69	22	SiL	M.FM.SB	
			6	BCk	69	86	17	CL	M.F.PR	M.F.AB
			7	Ckgj	86	120	34	CL	W.F.PR	M.F.AB
3D	CA.BL	CVA	1	Ap	0	10	10	L	M.M.GR	
			2	Bmk1	10	22	12	L	M.M.AB	
			3	Bmk2	22	35	13	L	M.MC.AB	
			4	Cca	35	75	40	SiCL	M.C.AB	
			5	Ckgj	75	112	37	CL	MA	
3T	O.BL	NDL	1	Ap	0	11	11	L	M.MC.GR	
			2	Btj	11	35	24	CL	M.F.SB	
			3	BCk	35	46	11	CL	W.FM.SB	
			4	Cca	46	59	13	SiCL	M.MC.AB	
			5	Ck	59	90	31	CL	M.F.PR	
			6	Ckgj	90	123	33	CL	MA	
3A	GLE.BL	ANL	1	Ap	0	5	5	L	M.FM.GR	
			2	Ahe	5	14	9	L	M.C.PL	
			3	Ae	14	30	16	SiL	W.M.PL	
			4	Btgj1	30	57	27	CL	M.F.PR	M.M.SB
			5	Btgj2	57	78	21	CL	M.F.SB	
			6	BCgj	78	92	14	CL	MA	
			7	Ckgj	92	117	25	CL	MA	

Plot	Horizon No.	Moisture	Efferv.	Calcar.	Consistence		Coarse Fragments		Colour	Mottles	Clay Films	Roots
					Moist	Dry	Type	%				
1D1	1	M	V	W					10YR 2.5/1			P.F.R.B
	2	M	W	W					10YR 3/3		F.TH.PF	P.F.R.B
	3	M	S	V					10YR 4.5/4			F.F.V.E
	4	M	M	M					10YR 4/4			F.F.V.E
1D2	1	M	N	N					10YR 2/1			P.F.R.B
	2	M	N	N					10YR 2.5/1.5			P.F.R.B
	3	M	W	W			GR	2	10YR 4/4			P.F.R.B
	4	M	S	S			GR	10	10YR 5/3.5			F.F.R.B
	5	M	M	M			GR	5	10YR 4.5/3.5			F.F.V.E
	6	M	M	M			GR	5	10YR 4/3.5			V.V.V.E
1D3	1	M	N	N					10YR 2/1			P.F.R.B
	2	M	N	N					10YR 2.5/1.5			P.F.R.B
	3	M	N	N					10YR 3/3			P.F.R.B
	4	M	M	M					10YR 5/4			P.F.R.B
	5	M	S	V			GR	2	10YR 5.5/3.5			F.F.R.B
	6	M	M	M			GR	2	10YR 4.5/4			F.V.V.E
	7	M	M	M			GR	2	10YR 5/4	F.F.F		
1T1	1	M	N	N					10YR 2/1			P.F.R.B
	2	M	N	N					10YR 2/1			P.F.R.B
	3	M	N	N					10YR 3/2			P.F.R.B
	4	M	N	N					10YR 4/5			P.F.R.B
	5	M	N	W					10YR 3/4			P.F.R.B
	6	M	N	W			GR	2	10YR 4/4			F.F.R.B
	7	M	N	V			GR	5	10YR 5.5/3			F.F.R.B
	8	M	N	S			GR	5	2.5Y 4.5/4	F.F.F		F.V.V.E
1T2	1	M	N	N					10YR 2/1			P.F.R.B
	2	M	N	N					10YR 2.5/1.5			P.F.R.B
	3	M	N	N					10YR 3/4			F.F.R.B
	4	M	N	N					10YR 4/4			F.F.R.B
	5	M	M	M					10YR 5/4			F.F.R.B
	6	M	M	M					2.5Y 4/4			F.F.R.B
	7	M	M	M					2.5Y 4.5/4			F.F.R.B
	8	M	M	S			GR	5	2.5Y 5/3			F.F.V.E
	9	M	M	S			GR	5	2.5Y 5/4			F.F.V.B
	10	M	M	M			GR	5	2.5Y 4/3.5	F.F.F		F.F.V.E
1T3	1	M	N	N					10YR 2/1			P.F.R.B
	2	M	N	N					10YR 4/4			P.F.R.B
	3	M	N	N					10YR 3/3.5			P.F.R.B
	4	M	M	M					10YR 5/3			P.F.R.B
	5	M	S	S			GR	5	2.5Y 5/4			F.F.R.B
	6	M	M	M			GR	5	2.5Y 4.5/4	F.F.F		F.F.V.E
1A1	1	M	N	N					10YR 2.5/1			P.V.R.B
	2	M	N	N					10YR 3/1			P.V.R.B
	3	M	N	N					10YR 5.5/1			P.V.R.B
	4	M	N	N					-		F.TH.PF	P.V.R.B
	5	M	N	N					10YR 3/2	F.F.F	M.TK.PF	P.V.R.B
	6	M	W	W			GR	5	-	F.F.F	C.MT.PF	P.V.R.B
	7	M	M	M			GR	5	2.5Y 4.5/4	C.F.F		F.V.V.E
	8	M	S	V			GR	10	-	C.F.F		V.V.V.E
1A2	1	M	N	N					10YR 2.5/1			P.F.R.B
	2	M	N	N					10YR 3/1			P.V.R.B
	3	M	N	N					10YR 5.5/1			P.V.R.B
	4	M	N	N					10YR 3/2		F.TH.PF	P.V.R.B
	5	M	N	N					10YR 3/2		M.TK.PF	P.V.R.B
	6	M	W	W			GR	5	10YR 3/3	F.F.F	F.TH.PF	P.V.R.E
	7	M	M	M			GR	5	2.5Y 4.5/4	C.F.F		V.V.V.E
	8	M	S	V			GR	5	10YR 5/2	C.F.F		V.V.V.E
	9	M	M	M			GR	5	2.5Y 4.5/4	C.F.F		

Plot	Horizon No.	Moisture	Efferv.	Calcar.	Consistence		Coarse Fragments		Colour	Mottles	Clay Films	Roots
					Moist	Dry	Type	%				
1A3	1	M	N	N					10YR 2.5/1			P.F.R.B
	2	M	N	N					10YR 3/1			P.V.R.B
	3	M	N	N					10YR 4/2			P.V.R.B
	4	M	N	N					10YR 3/2		F.TH.PF	P.V.R.B
	5	M	N	N					10YR 3.5/3		M.TK.PF	P.V.R.B
	6	M	W	W			GR	5	10YR 3/3	F.F.F	C.TH.PF	F.V.R.B
	7	M	S	V			GR	5	2.5Y 4.5/3	C.F.F		F.V.V.E
	8	M	M	M			GR	5	2.5Y 4.5/4	C.F.F		
2D	1	M	N	N					10YR 2/1			P.F.R.B
	2	M	N	N					10YR 3/3.5			P.F.R.B
	3	M	M	M			GR	2	2.5Y 4.5/2		C.TH.PF	P.F.R.B
	4	M	S	S			GR	5	2.5Y 4.5/3			F.F.R.B
	5	M	M	M			GR	5	2.5Y 4/3.5	F.F.F		F.F.R.E
2T	1	M	N	N					10YR 2/1		M.MT.PF	P.F.R.B
	2	M	N	N					10YR 2/1			P.F.R.B
	3	M	N	N					10YR 3.5/3			P.F.R.B
	4	M	N	N					10YR 3.5/3			F.F.R.B
	5	M	V	W			GR	1	10YR 4/4			F.F.R.B
	6	M	M	M			GR	1	2.5Y 4/3			F.F.R.E
	7	M	M	M			GR	1	10YR 5/8			F.F.V.E
	8	M	M	M			GR	1	2.5Y 4/4	F.F.F		F.F.V.E
2A	1	M	N	N	FB				10YR 2/1			P.F.R.B
	2	M	N	N	FB				10YR 4/2			P.F.R.B
	3	M	N	N	VF				10YR 6/2			P.F.R.B
	4	M	N	N	FB		GR	1	10YR 3/2		S.MT.PV	F.F.R.B
	5	M	N	N	FB		GR	1	10YR 3/3	F.F.F	S.MT.PF	F.F.R.B
	6	M	V	W	FR		GR	1	2.5Y 4/4	F.F.F	C.TH.PF	F.F.R.B
	7	W	M	M	FB		GR	5	2.5Y 4/4	C.F.F		F.F.V.E
3D	1	D	N	N		SO	GR	1	10YR 2/1			P.F.R.B
	2	D	V	W		SO	GR	1	10YR 3/2			P.F.R.B
	3	M	V	W	FB		GR	1	10YR 3/2			P.F.R.B
	4	M	S	V	FR		GR	5	10YR 6/4			P.F.R.B
	5	D	S	S		VH	GR	5	2.5Y 5/3	F.F.D		F.F.V.E
3T	1	M	N	N	FB		GR	1	10YR 2/1			P.F.R.B
	2	M	N	N	FB		GR	1	10YR 4/3		C.TH.PF	P.F.R.B
	3	M	M	M	FB		GR	5	10YR 5/4			P.F.R.B
	4	M	S	V	FR		GR	5	10YR 5/4			P.F.R.B
	5	M	S	S	FR		GR	5	2.5Y 4.5/3			F.F.V.E
	6	M	S	S	FR		GR	5	2.5Y 4.5/3	C.F.D		
3A	1	D	N	N					10YR 3/1			A.M.R.B
	2	D	N	N					10YR 3/1			P.M.R.B
	3	D	N	N					10YR 6/2			
	4	M	N	N					10YR 4.5/3	C.F.D	C.TH.PF	P.F.R.B
	5	M	N	N			GR	1	10YR 4/3	C.F.D	C.TH.PF	F.F.R.B
	6	M	N	N			GR	1	10YR 5/4	C.F.D		F.F.R.B
	7	M	M	M			GR	5	10YR 5/4	C.F.D		

Plot	Horizon No.	Rooting Depth (cm)	Kvert	Khor	Saturated Zone Least	Saturated Zone Great	Notes
1D1	1	95	H2	H2	L2	L2	compaction zone in core = 96-110cm; no stones present in profile
	2		H1	H1			
	3		M2	M3			
	4		M3	M3			
1D2	1	100	H2	H2			compaction zone in core = 117-119cm
	2		H1	H1			
	3		H1	H1			
	4		M2	M2			
	5		M1	M1			
	6		M1	L3			
1D3	1	105	H2	H2	L2	L2	no visible compaction in core
	2		H2	H2			
	3		H1	H1			
	4		H1	H1			
	5		M2	M2			
	6		M1	L3			
	7		M1	M2			
1T1	1	108	H2	H2	L1	L1	no visible compaction in core; Ccaj - CO3 found throughout entire matrix, Ckgj - CO3 found in voids, channels, root channels
	2		H2	H2			
	3		H1	H1			
	4		H1	H1			
	5		H1	H1			
	6		M2	M2			
	7		M2	M2			
	8		M1	M2			
1T2	1	100	H1	H1	L1	L1	compaction zone in core = 83-108cm
	2		H1	H1			
	3		H1	H1			
	4		H1	H1			
	5		H1	H1			
	6		M2	M2			
	7		M3	M3			
	8		M1	M1			
	9		M3	M3			
	10		M1	M1			
1T3	1	98	H1	H1	L1	L1	compaction zone in core = 94-108; few large stones present 72cm, 89-95cm; possible gopher hole bottom of BC 37-42cm indicated by darker colour 10YR
	2		H1	H1			
	3		M3	M3			
	4		M3	M3			
	5		M1	M2			
	6		M1	M1			
1A1	1	110	H1	H1	H1	M3	no visible compaction zone in core
	2						
	3						
	4						
	5		M2	M3			
	6						
	7		M1	M2			
	8		M1	M2			
1A2	1	95	H1	H1	H1	M3	no visible compaction in core
	2						
	3						
	4						
	5		M2	M3			
	6						
	7		M1	M2			
	8		M1	M2			
	9		M1	M2			

Plot	Horizon No.	Rooting Depth (cm)	Kvert	Khor	Saturated Zone Least	Saturated Zone Great	Notes
1A3	1		H1	H1	H1	M3	compaction zone 111cm+
	2	100					
	3						
	4						
	5		M2	M3			
	6						
	7		M1	M2			
	8		M1	M2			
2D	1		H2	H2	L1	L2	no visible compaction
	2	105	H1	H1			
	3		M2	M2			
	4		M3	M2			
	5		M1	M1			
2T	1		H1	H1	L1	L1	no visible compaction; presence of Fe concretions in
	2	100	H1	H1			Ck2; Bm close to Bt, no evidence of Ae
	3		H1	H1			
	4						
	5		M3	M3			
	6		M2	M2			
	7		M1	M1			
	8		M1	M1			
2A	1				H1	M3	no visible compaction
	2	115					
	3						
	4						
	5						
	6						
	7						
3D	1		H2	H2	L1	L2	stones throughout entire profile
	2	83	H2	H2			
	3		H2	H2			
	4		M3	M2			
	5		M1	L3			
3T	1		H2	H2	M3	L1	stones present throughout entire profile
	2	85	H2	H2			
	3		H1	H1			
	4		M3	M2			
	5		M2	M1			
	6		M2	M1			
3A	1		H2	H2	H1	M1	stoniness b/t 60 & 117 cm; stained (black) root
	2	85	M2	M3			channels present throughout entire profile indicated
	3						preferential flowpaths
	4		M3	M3			
	5		M2	M2			
	6		M2	M2			
	7						

VI. Analytical results for the bromide tracer study.

Plot	Depth	EC	pH	% Sand	% Clay	% Silt	Texture	Bulk Density
	— cm —	- mS cm^{-1} -						- g cm^{-3} -
1D1	0-15	0.5	7.6	35	19	46	L	1.11
	15-30	0.4	8.1	28	23	50	SiL	1.29
	30-60	0.5	8.4	20	23	58	SiL	1.30
	60-90	1.9	8.2	18	16	66	SiL	1.29
	90-120	1.3	8.3	15	15	70	SiL	1.32
1D2	0-15	1.3	7.4	38	20	43	L	1.11
	15-30	0.3	8.1	39	21	40	L	1.16
	30-60	0.4	8.3	33	23	45	L	1.37
	60-90	0.4	8.5	33	20	48	L	1.49
	90-120	0.7	8.6	38	19	44	L	1.47
1D3	0-15	0.4	7.8	39	23	39	L	1.19
	15-30	0.3	8.0	38	26	36	L	1.37
	30-60	0.4	8.4	25	18	58	SiL	1.28
	60-90	0.5	8.5	28	19	54	SiL	1.33
	90-120	0.6	8.8	29	23	49	L	1.46
1T1	0-15	0.5	7.6	43	18	40	L	1.32
	15-30	0.3	8.1	41	18	41	L	1.46
	30-60	0.3	8.3	36	23	41	L	1.32
	60-90	0.6	8.3	35	33	33	CL	1.59
	90-120	0.9	8.3	36	30	34	CL	2.02
1T2	0-15	0.5	7.3	48	18	35	L	1.22
	15-30	0.3	8.0	46	21	33	L	1.78
	30-60	0.5	8.4	36	29	35	CL	1.46
	60-90	0.5	8.6	40	28	33	CL	1.47
	90-120	0.5	8.6	36	25	39	L	1.62
1T3	0-15	0.5	7.4	53	19	29	SL	1.14
	15-30	0.3	8.1	58	20	23	SCL-SL	1.48
	30-60	0.6	8.5	34	36	30	CL	1.46
	60-90	0.6	8.7	34	34	33	CL	1.57
	90-120	0.6	8.6	36	31	33	CL	1.64
1A1	0-15	0.6	7.2	40	21	39	L	1.08
	15-30	0.3	7.8	41	15	44	L	1.18
	30-60	0.3	7.7	38	29	34	CL	1.41
	60-90	0.4	7.8	38	38	25	CL	1.48
	90-120	0.4	8.1	38	29	34	CL	1.58
1A2	0-15	0.5	6.5	34	24	43	L	1.10
	15-30	0.2	7.7	39	15	46	L	1.34
	30-60	0.5	7.8	41	31	28	CL	1.40
	60-90	0.4	8.1	39	34	28	CL	1.37
	90-120	0.4	8.1	43	29	29	CL	1.31
1A3	0-15	0.4	7.3	35	21	44	L	1.06
	15-30	0.2	7.8	41	16	43	L	1.29
	30-60	0.5	7.9	44	30	26	CL	1.53
	60-90	0.4	8.2	41	30	29	CL	1.41
	90-120	0.5	8.2	41	29	30	CL	1.67

Plot	Depth	EC	pH	% Sand	% Clay	% Silt	Texture	Bulk Density
	— cm —	- mS cm^{-1} -						- g cm^{-3} -
2D	0-15	0.6	6.2	38	33	30	CL	1.11
	15-30	0.5	8.0	36	36	28	CL	1.61
	30-60	0.6	8.1	33	35	33	CL	1.72
	60-90	0.6	8.1	33	36	31	CL	1.62
	90-120	0.6	8.3	34	34	33	CL	1.70
2T	0-15	0.3	6.6	38	28	35	CL-L	1.22
	15-30	0.3	7.5	35	30	35	CL	1.59
	30-60	0.5	8.0	31	36	33	CL	1.68
	60-90	0.7	8.2	33	38	30	CL	1.70
	90-120	0.7	8.2	33	35	33	CL	1.70
2A	0-15	0.6	5.8	30	25	45	L	1.08
	15-30	0.2	7.0	38	16	46	L	1.42
	30-60	0.2	6.9	30	41	29	C	1.56
	60-90	0.4	7.2	35	38	28	CL	1.51
	90-120	0.5	7.9	39	30	31	CL	1.55
3D	0-15	0.8	6.6	46	24	30	L	1.06
	15-30	0.5	7.9	40	26	34	L	1.36
	30-60	0.5	8.1	38	30	33	CL	1.50
	60-90	0.6	8.2	33	34	34	CL	1.49
	90-120	0.6	8.4	39	30	31	CL	1.80
3T	0-15	1.0	6.2	43	23	35	L	1.32
	15-30	0.3	7.2	39	34	28	CL	1.50
	30-60	1.3	7.1	40	29	31	CL	1.55
	60-90	0.6	8.0	35	35	30	CL	1.95
	90-120	0.6	8.0	35	33	33	CL	1.69
3A	0-15	0.3	6.4	43	19	39	L	1.21
	15-30	0.2	7.0	40	15	45	L	1.37
	30-60	0.1	7.0	41	10	49	L	1.36
	60-90	0.3	7.4	41	29	30	CL	1.51
	90-120	0.6	7.9	39	31	30	CL	1.51

VII. Water content and solute concentrations for the May sampling event.

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
		cm			%		ppm		
1D1	1	150	-40	0-15	20.3	22.5	0.2	1.9	58.2
1D1	1	150	-40	15-30	19.2	24.8	0.2	2.5	106.2
1D1	1	150	-40	30-60	18.4	24.0	0.4	3.2	24.7
1D1	2	150	-20	0-15	20.8	23.1	2.9	2.6	81.9
1D1	2	150	-20	15-30	19.5	25.2	19.5	3.1	77.5
1D1	2	150	-20	30-60	19.7	25.7	36.2	3.2	34.9
1D1	2	150	-20	60-90	19.4	25.2	20.2	3.5	6.2
1D1	2	150	-20	90-120	30.9	40.9	0.7	16.2	13.3
1D1	3	75	0	0-15	19.3	21.5	32.4	3.0	110.5
1D1	3	75	0	15-30	22.7	29.3	513.4	2.9	132.1
1D1	3	75	0	30-60	26.7	34.8	216.1	6.2	30.0
1D1	3	75	0	60-90	20.9	27.0	192.2	5.5	30.5
1D1	3	75	0	90-120	20.7	27.4	73.9	4.5	6.7
1D1	4	150	0	0-15	20.9	23.2	87.6	1.8	7.1
1D1	4	150	0	15-30	19.7	25.5	219.7	3.1	153.7
1D1	4	150	0	30-60	19.5	25.4	3.2	7.2	4.6
1D1	4	150	0	60-90	19.4	25.1	17.7	3.6	97.3
1D1	4	150	0	90-120	17.9	23.7	1.3	6.3	2.7
1D1	5	225	0	0-15	19.6	21.8	2.0	2.1	157.1
1D1	5	225	0	15-30	19.6	25.3	63.9	2.5	388.9
1D1	5	225	0	30-60	18.9	24.6	345.4	1.7	32.8
1D1	5	225	0	60-90	20.1	26.0	139.6	2.2	8.9
1D1	5	225	0	90-120	18.4	24.4	1.6	2.3	2.8
1D1	6	75	20	0-15	21.3	23.7	6.0	2.6	153.5
1D1	6	75	20	15-30	20.4	26.4	100.9	2.7	111.3
1D1	6	75	20	30-60	21.6	28.2	119.1	9.0	34.1
1D1	6	75	20	60-90	21.9	28.3	25.3	5.3	6.7
1D1	6	75	20	90-120	20.6	27.2	0.7	4.1	3.9
1D1	7	150	20	0-15	20.5	22.7	9.3	2.9	137.1
1D1	7	150	20	15-30	20.3	26.2	73.1	4.0	157.1
1D1	7	150	20	30-60	20.7	27.0	117.2	7.7	25.6
1D1	7	150	20	60-90	23.3	30.1	24.7	3.3	4.4
1D1	7	150	20	90-120	18.8	24.9	1.8	6.7	4.7
1D1	8	225	20	0-15	19.6	21.7	2.7	2.6	126.9
1D1	8	225	20	15-30	20.5	26.6	9.6	2.3	110.7
1D1	8	225	20	30-60	18.6	24.3	84.3	2.8	30.8
1D1	8	225	20	60-90	18.0	23.3	104.9	4.1	12.0
1D1	8	225	20	90-120	17.9	23.6	1.0	1.9	2.5
1D1	9	75	60	0-15	20.3	22.5	0.4	2.8	184.3
1D1	9	75	60	15-30	20.5	26.5	0.4	2.9	177.8
1D1	9	75	60	30-60	18.7	24.4	38.4	7.1	0.2
1D1	9	75	60	60-90	18.9	24.4	0.3	6.8	5.4
1D1	10	150	60	0-15	20.4	22.6	0.4	6.1	115.0
1D1	10	150	60	15-30	20.2	26.1	0.4	2.3	91.2
1D1	10	150	60	30-60	20.5	26.7	0.3	6.4	30.7
1D1	10	150	60	60-90	20.2	26.2	0.2	6.0	9.2
1D1	11	225	60	0-15	20.9	23.2	1.4	2.5	163.8
1D1	11	225	60	15-30	21.5	27.8	1.3	2.2	129.7
1D1	11	225	60	30-60	19.3	25.2	0.2	3.6	57.4
1D1	11	225	60	60-90	19.7	25.5	0.2	2.3	18.2
1D1	12	75	140	0-15	21.4	23.8	0.2	2.6	96.6
1D1	12	75	140	15-30	27.1	35.1	0.5	3.3	139.0
1D1	12	75	140	30-60	21.1	27.6	0.3	4.2	31.4
1D1	13	150	140	0-15	20.2	22.4	0.3	2.9	121.4
1D1	13	150	140	15-30	22.3	28.8	0.4	4.5	109.5
1D1	13	150	140	30-60	20.5	26.7	0.3	3.3	53.5
1D1	14	225	140	0-15	20.6	22.9	1.1	3.3	194.7
1D1	14	225	140	15-30	19.7	25.5	0.5	3.3	62.5
1D1	14	225	140	30-60	19.4	25.3	0.3	4.8	26.4
1D2	1	150	-40	0-15	20.5	22.7	0.3	1.0	114.4
1D2	1	150	-40	15-30	20.2	23.5	0.3	1.9	182.8
1D2	1	150	-40	30-60	19.6	26.9	4.5	2.1	181.3

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm		%			ppm	
1D2	2	135	-20	0-15	20.7	22.9	0.2	1.0	49.2
1D2	2	135	-20	15-30	20.8	24.2	26.7	1.1	121.8
1D2	2	135	-20	30-60	18.2	25.0	21.9	1.1	36.3
1D2	2	135	-20	60-90	20.8	31.0	3.9	1.3	3.9
1D2	2	135	-20	90-120	18.1	26.5	0.3	2.7	5.9
1D2	3	75	0	0-15	21.7	24.0	2.9	1.1	55.4
1D2	3	75	0	15-30	19.2	22.3	138.9	1.0	86.0
1D2	3	75	0	30-60	18.4	25.3	506.5	2.1	44.5
1D2	3	75	0	60-90	21.4	31.9	37.0	2.5	6.8
1D2	3	75	0	90-120	16.0	23.4	2.7	3.4	7.9
1D2	4	150	0	0-15	20.8	23.1	10.7	0.7	138.4
1D2	4	150	0	15-30	18.3	21.3	153.2	0.6	157.1
1D2	4	150	0	30-60	17.3	23.7	283.7	2.2	37.1
1D2	4	150	0	60-90	20.9	31.2	74.7	0.6	9.5
1D2	4	150	0	90-120	17.1	25.1	1.0	1.1	7.6
1D2	5	225	0	0-15	21.5	23.8	20.8	1.0	147.8
1D2	5	225	0	15-30	18.9	22.0	114.6	0.8	113.6
1D2	5	225	0	30-60	17.4	23.9	262.4	1.5	24.8
1D2	5	225	0	60-90	15.4	22.9	85.4	1.5	6.8
1D2	5	225	0	90-120	16.7	24.5	2.1	2.0	5.7
1D2	6	75	20	0-15	21.0	23.2	1.1	1.2	193.4
1D2	6	75	20	15-30	19.8	23.1	7.1	1.1	102.5
1D2	6	75	20	30-60	18.0	24.8	8.7	1.4	43.7
1D2	6	75	20	60-90	19.2	28.7	3.1	1.5	11.5
1D2	6	75	20	90-120	15.7	23.0	0.3	3.6	4.8
1D2	7	150	20	0-15	21.4	23.7	2.0	2.1	107.1
1D2	7	150	20	15-30	19.0	22.1	8.9	1.7	131.2
1D2	7	150	20	30-60	17.1	23.5	16.7	2.5	40.7
1D2	7	150	20	60-90	18.4	27.5	3.7	2.8	9.6
1D2	7	150	20	90-120	17.0	24.9	0.3	2.0	10.1
1D2	8	225	20	0-15	21.4	23.6	6.4	6.1	80.1
1D2	8	225	20	15-30	18.7	21.7	42.2	2.3	48.0
1D2	8	225	20	30-60	16.4	22.5	24.3	1.4	18.4
1D2	8	225	20	60-90	15.7	23.4	0.7	2.0	3.5
1D2	8	225	20	90-120	16.9	24.7	0.3	0.3	3.2
1D2	9	75	60	0-15	21.4	23.6	1.4	2.6	322.2
1D2	9	75	60	15-30	20.6	24.0	2.4	2.3	178.8
1D2	9	75	60	30-60	18.3	25.2	1.4	1.7	77.5
1D2	9	75	60	60-90	23.0	34.3	0.6	3.0	21.9
1D2	10	150	60	0-15	22.6	24.9	0.6	3.2	154.8
1D2	10	150	60	15-30	19.8	23.0	1.1	2.7	57.4
1D2	10	150	60	30-60		-	-	-	-
1D2	10	150	60	60-90		-	-	-	-
1D2	11	225	60	0-15	21.0	23.2	0.4	2.5	76.8
1D2	11	225	60	15-30	19.3	22.5	0.3	5.6	57.7
1D2	11	225	60	30-60	17.0	23.4	0.3	2.7	21.3
1D2	11	225	60	60-90	17.5	26.2	0.5	2.5	4.8
1D2	12	75	140	0-15	22.8	25.3	0.3	2.4	67.8
1D2	12	75	140	15-30	18.4	21.4	0.5	2.1	58.2
1D2	12	75	140	30-60	12.4	17.0	0.2	1.7	21.0
1D2	13	150	140	0-15	21.1	23.4	0.4	3.0	292.9
1D2	13	150	140	15-30	18.3	21.3	0.7	4.6	169.5
1D2	13	150	140	30-60	17.8	24.5	0.4	3.0	32.1
1D2	14	225	140	0-15	22.3	24.6	0.3	2.7	62.3
1D2	14	225	140	15-30	20.4	23.8	0.4	2.5	41.4
1D2	14	225	140	30-60	18.3	25.1	0.4	1.5	11.7
1D3	1	150	-40	0-15	20.1	23.9	1.4	1.2	192.2
1D3	1	150	-40	15-30	16.0	22.0	0.5	1.2	113.9
1D3	1	150	-40	30-60	16.9	21.6	0.4	2.9	41.8
1D3	2	150	-20	0-15	20.9	24.8	14.8	1.0	111.6
1D3	2	150	-20	15-30	17.8	24.4	44.6	2.5	68.1
1D3	2	150	-20	30-60	18.9	24.1	10.5	1.2	23.2
1D3	2	150	-20	60-90	19.6	26.0	4.0	0.7	4.8
1D3	2	150	-20	90-120	17.2	25.0	0.6	1.6	6.8
1D3	3	75	0	0-15	18.4	21.9	6.0	2.6	129.7
1D3	3	75	0	15-30	17.1	23.5	79.6	2.0	52.4

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
		cm			%		ppm		
1D3	3	75	0	30-60	16.0	20.4	180.8	2.0	32.9
1D3	3	75	0	60-90	24.2	32.1	63.2	0.6	10.9
1D3	3	75	0	90-120	16.5	24.0	0.8	1.3	4.8
1D3	4	150	0	0-15	20.6	24.5	23.8	2.4	150.2
1D3	4	150	0	15-30	18.0	24.7	135.2	2.2	72.1
1D3	4	150	0	30-60	19.0	24.3	216.6	0.9	17.6
1D3	4	150	0	60-90	18.1	24.0	6.4	0.7	2.9
1D3	4	150	0	90-120	15.1	22.0	0.8	1.8	6.3
1D3	5	225	0	0-15	21.4	25.4	99.6	2.9	277.0
1D3	5	225	0	15-30	17.5	24.1	337.8	2.2	166.4
1D3	5	225	0	30-60	19.0	24.3	217.4	1.9	25.6
1D3	5	225	0	60-90	21.3	28.2	3.3	2.4	3.8
1D3	5	225	0	90-120	17.1	24.8	1.1	1.0	4.8
1D3	6	75	20	0-15	19.8	23.5	14.5	2.6	168.1
1D3	6	75	20	15-30	18.3	25.1	38.5	2.2	85.6
1D3	6	75	20	30-60	16.2	20.7	79.0	0.7	44.4
1D3	6	75	20	60-90	16.6	22.0	7.3	0.9	7.8
1D3	6	75	20	90-120	16.1	23.5	0.3	1.1	3.9
1D3	7	150	20	0-15	20.2	24.0	26.6	2.8	149.1
1D3	7	150	20	15-30	17.6	24.2	102.2	2.4	157.3
1D3	7	150	20	30-60	19.0	24.2	251.5	1.6	35.3
1D3	7	150	20	60-90	19.7	26.2	41.0	0.3	5.1
1D3	7	150	20	90-120	16.3	23.7	1.3	2.9	6.8
1D3	8	225	20	0-15	19.6	23.3	196.3	3.0	141.8
1D3	8	225	20	15-30	18.2	25.0	400.2	2.5	101.7
1D3	8	225	20	30-60	16.4	20.9	91.3	2.3	9.7
1D3	8	225	20	60-90	16.0	21.3	3.9	0.7	3.1
1D3	8	225	20	90-120	17.0	24.8	0.6	3.0	6.6
1D3	9	75	60	0-15	18.6	22.1	1.8	3.1	126.4
1D3	9	75	60	15-30	19.1	26.3	-	-	-
1D3	9	75	60	30-60	15.7	20.0	0.9	1.9	35.4
1D3	9	75	60	60-90	13.6	18.1	0.5	0.9	5.5
1D3	10	150	60	0-15	19.9	23.7	1.5	3.0	116.2
1D3	10	150	60	15-30	17.2	23.6	3.4	3.2	27.2
1D3	10	150	60	30-60	27.2	34.8	0.7	3.5	18.0
1D3	10	150	60	60-90	15.8	20.9	7.4	2.9	11.9
1D3	11	225	60	0-15	20.1	23.8	10.9	3.6	113.6
1D3	11	225	60	15-30	17.9	24.6	4.5	2.2	14.3
1D3	11	225	60	30-60	14.1	18.0	0.7	0.5	3.7
1D3	11	225	60	60-90	13.9	18.4	0.3	2.9	178.5
1D3	12	75	140	0-15	20.5	24.3	0.3	2.6	97.6
1D3	12	75	140	15-30	17.7	24.3	0.3	2.5	106.7
1D3	12	75	140	30-60	15.7	20.0	0.2	3.3	26.4
1D3	13	150	140	0-15	19.5	23.2	0.2	3.1	51.3
1D3	13	150	140	15-30	16.6	22.8	0.3	2.9	115.4
1D3	13	150	140	30-60	16.3	20.8	0.5	2.3	109.8
1D3	14	225	140	0-15	20.4	24.3	0.7	2.8	228.2
1D3	14	225	140	15-30	17.7	24.3	0.8	3.3	118.8
1D3	14	225	140	30-60	16.3	20.8	0.3	3.5	17.6
1T1	1	150	-40	0-15	24.8	32.9	1.1	2.9	163.2
1T1	1	150	-40	15-30	21.4	31.2	0.8	3.5	68.5
1T1	1	150	-40	30-60	22.0	29.1	0.4	2.7	12.7
1T1	2	150	-20	0-15	26.1	34.6	1.9	1.0	28.6
1T1	2	150	-20	15-30	20.8	30.4	18.9	1.3	87.7
1T1	2	150	-20	30-60	19.6	25.9	13.3	2.3	11.0
1T1	2	150	-20	60-90	23.7	37.7	3.7	2.4	2.3
1T1	2	150	-20	90-120	20.3	41.1	0.3	3.1	1.5
1T1	3	75	0	0-15	26.1	34.5	17.4	2.6	78.5
1T1	3	75	0	15-30	21.3	31.1	118.3	2.4	135.4
1T1	3	75	0	30-60	22.6	30.0	127.9	2.6	143.9
1T1	3	75	0	60-90	26.2	41.5	15.7	3.2	3.4
1T1	3	75	0	90-120	20.6	41.7	1.7	2.3	2.4
1T1	4	150	0	0-15	25.1	33.2	34.6	2.8	176.4
1T1	4	150	0	15-30	21.5	31.4	1.3	0.8	2.9
1T1	4	150	0	30-60	21.7	28.7	205.4	3.2	59.9
1T1	4	150	0	60-90	22.4	35.5	37.4	2.7	4.4

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
		cm			%		ppm		
1T1	4	150	0	90-120	21.2	42.9	0.5	2.8	2.1
1T1	5	225	0	0-15	25.5	33.7	31.5	2.7	169.1
1T1	5	225	0	15-30	21.8	31.8	116.5	2.8	228.4
1T1	5	225	0	30-60	18.5	24.4	117.9	2.4	27.8
1T1	5	225	0	60-90	15.8	25.0	7.6	2.3	2.3
1T1	5	225	0	90-120	20.3	41.2	0.9	5.0	3.7
1T1	6	75	20	0-15	26.7	35.4	6.2	2.0	101.1
1T1	6	75	20	15-30	22.3	32.6	126.4	1.8	94.6
1T1	6	75	20	30-60	22.7	30.0	41.8	2.7	13.4
1T1	6	75	20	60-90	25.5	40.5	0.7	3.1	3.2
1T1	6	75	20	90-120	20.4	41.4	0.5	3.0	3.8
1T1	7	150	20	0-15	25.0	33.1	24.3	2.6	107.2
1T1	7	150	20	15-30	23.5	34.3	81.9	3.0	73.2
1T1	7	150	20	30-60	17.5	23.2	40.3	3.4	6.0
1T1	7	150	20	60-90	24.1	38.3	3.6	2.5	2.6
1T1	7	150	20	90-120	20.6	41.6	0.3	3.2	1.4
1T1	8	225	20	0-15	26.5	35.0	67.4	1.8	84.5
1T1	8	225	20	15-30	20.6	30.0	207.2	1.9	50.2
1T1	8	225	20	30-60	17.7	23.4	71.1	1.8	9.4
1T1	8	225	20	60-90	16.5	26.1	6.8	2.5	5.4
1T1	8	225	20	90-120	15.8	31.9	0.3	4.1	2.3
1T1	9	75	60	0-15	26.9	35.6	8.6	1.6	87.1
1T1	9	75	60	15-30	20.4	29.8	17.5	1.4	73.9
1T1	9	75	60	30-60	20.7	27.5	3.7	1.8	18.5
1T1	9	75	60	60-90	23.7	37.5	0.4	2.7	0.4
1T1	10	150	60	0-15	26.2	34.7	3.6	2.5	113.3
1T1	10	150	60	15-30	21.4	31.3	20.6	3.6	61.6
1T1	10	150	60	30-60	16.3	21.6	3.6	3.0	11.8
1T1	10	150	60	60-90	21.0	33.3	0.3	2.4	2.7
1T1	11	225	60	0-15	24.1	31.9	11.3	1.2	127.0
1T1	11	225	60	15-30	18.5	27.0	43.2	1.0	65.9
1T1	11	225	60	30-60	14.5	19.1	15.9	2.4	20.5
1T1	11	225	60	60-90	15.5	24.7	0.5	2.2	4.3
1T1	12	75	140	0-15	26.6	35.2	1.3	1.4	67.4
1T1	12	75	140	15-30	21.3	31.1	2.9	1.3	54.0
1T1	12	75	140	30-60	20.2	26.8	0.5	2.3	8.1
1T1	13	150	140	0-15	25.4	33.7	5.2	1.6	155.9
1T1	13	150	140	15-30	16.2	23.6	5.9	2.0	93.0
1T1	13	150	140	30-60	22.7	30.1	1.3	1.4	13.8
1T1	14	225	140	0-15	25.3	33.5	3.1	1.9	123.6
1T1	14	225	140	15-30	19.5	28.5	5.6	1.7	45.2
1T1	14	225	140	30-60	17.4	23.1	0.6	1.2	10.9
1T2	1	150	-40	0-15	21.6	26.3	0.2	4.3	82.9
1T2	1	150	-40	15-30	16.3	29.1	0.4	2.0	68.5
1T2	1	150	-40	30-60	10.9	15.9	8.7	2.6	20.6
1T2	2	150	-20	0-15	20.8	25.3	1.6	2.2	93.1
1T2	2	150	-20	15-30	16.1	28.7	17.2	1.3	73.5
1T2	2	150	-20	30-60	10.8	15.8	149.3	2.5	27.4
1T2	2	150	-20	60-90	19.4	28.6	56.1	2.0	6.9
1T2	2	150	-20	90-120	14.5	23.6	4.5	3.3	6.4
1T2	3	75	0	0-15	24.2	29.4	20.4	2.5	115.3
1T2	3	75	0	15-30	16.6	29.5	94.8	1.0	94.5
1T2	3	75	0	30-60	15.9	23.2	250.3	2.5	34.1
1T2	3	75	0	60-90	24.2	35.7	29.4	1.9	6.2
1T2	3	75	0	90-120	17.8	28.8	0.6	2.3	3.9
1T2	4	150	0	0-15	23.4	28.4	8.4	1.4	144.0
1T2	4	150	0	15-30	17.8	31.6	48.9	1.4	92.6
1T2	4	150	0	30-60	11.7	17.1	110.5	1.1	21.2
1T2	4	150	0	60-90	14.2	20.9	22.0	2.1	9.0
1T2	4	150	0	90-120	6.8	11.0	0.8	3.1	5.3
1T2	5	225	0	0-15	23.0	27.9	3.3	1.1	135.6
1T2	5	225	0	15-30	16.9	30.1	18.1	0.9	97.3
1T2	5	225	0	30-60	13.4	19.6	84.7	1.5	42.2
1T2	5	225	0	60-90	12.3	18.1	48.6	2.0	7.3
1T2	5	225	0	90-120	6.4	10.4	3.7	2.7	2.9
1T2	6	75	20	0-15	24.3	29.6	3.2	2.5	74.8

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
		cm			%		ppm		
1T2	6	75	20	15-30	18.4	32.8	13.4	2.4	44.3
1T2	6	75	20	30-60	17.6	25.6	53.9	2.0	21.5
1T2	6	75	20	60-90	17.4	25.7	7.6	1.6	4.7
1T2	6	75	20	90-120	17.4	28.3	0.5	2.3	3.4
1T2	7	150	20	0-15	21.1	25.7	31.2	1.2	116.2
1T2	7	150	20	15-30	16.7	29.6	78.3	1.1	65.6
1T2	7	150	20	30-60	15.4	22.5	90.2	0.8	24.2
1T2	7	150	20	60-90	11.7	17.2	15.5	2.8	6.7
1T2	7	150	20	90-120	14.5	23.5	0.5	3.8	10.7
1T2	8	225	20	0-15	21.3	25.9	3.4	1.1	95.0
1T2	8	225	20	15-30	16.3	29.0	15.6	0.9	51.0
1T2	8	225	20	30-60	16.4	23.9	32.0	1.1	20.8
1T2	8	225	20	60-90	8.2	12.0	1.7	2.4	3.0
1T2	8	225	20	90-120	6.8	11.1	0.2	4.0	6.0
1T2	9	75	60	0-15	22.5	27.4	6.0	1.8	57.7
1T2	9	75	60	15-30	18.8	33.5	15.8	1.2	47.0
1T2	9	75	60	30-60	21.1	30.8	2.8	2.5	15.8
1T2	9	75	60	60-90	21.1	31.1	0.6	1.6	3.5
1T2	10	150	60	0-15	23.6	28.7	4.8	2.0	63.1
1T2	10	150	60	15-30	18.8	33.4	17.4	1.4	44.5
1T2	10	150	60	30-60	17.1	25.0	43.3	1.6	27.1
1T2	10	150	60	60-90	16.4	24.2	5.2	2.1	4.7
1T2	11	225	60	0-15	22.2	27.0	4.8	1.8	121.3
1T2	11	225	60	15-30	18.2	32.4	10.9	1.2	71.9
1T2	11	225	60	30-60	14.5	21.1	5.4	1.0	26.6
1T2	11	225	60	60-90	11.0	16.2	0.3	2.5	4.9
1T2	12	75	140	0-15	20.8	25.3	3.4	3.2	99.6
1T2	12	75	140	15-30	17.9	31.8	2.2	1.4	45.4
1T2	12	75	140	30-60	14.7	21.4	0.8	2.1	16.5
1T2	13	150	140	0-15	22.9	27.9	2.2	1.9	74.4
1T2	13	150	140	15-30	16.2	28.9	3.9	1.4	41.8
1T2	13	150	140	30-60	14.5	21.2	3.6	1.6	20.1
1T2	14	225	140	0-15	22.6	27.5	0.6	2.0	28.3
1T2	14	225	140	15-30	16.8	29.9	0.8	1.5	26.2
1T2	14	225	140	30-60	11.1	16.2	0.4	0.9	17.7
1T3	1	150	-40	0-15	20.3	23.2	0.3	2.9	105.0
1T3	1	150	-40	15-30	16.1	23.7	3.9	1.8	102.5
1T3	1	150	-40	30-60	15.8	23.2	45.5	1.6	51.8
1T3	2	150	-20	0-15	20.8	23.8	0.4	1.6	67.3
1T3	2	150	-20	15-30	17.7	26.1	14.1	1.5	120.2
1T3	2	150	-20	30-60	14.9	21.9	120.2	1.7	56.5
1T3	2	150	-20	60-90	11.3	17.8	19.2	1.8	7.6
1T3	2	150	-20	90-120	10.1	16.6	0.5	1.6	3.7
1T3	3	75	0	0-15	21.1	24.1	2.7	1.9	62.0
1T3	3	75	0	15-30	17.8	26.2	49.3	1.3	69.6
1T3	3	75	0	30-60	13.5	19.7	191.1	1.0	23.8
1T3	3	75	0	60-90	9.8	15.3	55.5	1.7	7.5
1T3	3	75	0	90-120	8.4	13.8	2.5	1.5	4.3
1T3	4	150	0	0-15	21.2	24.1	2.0	1.8	54.0
1T3	4	150	0	15-30	15.7	23.2	26.5	1.5	50.7
1T3	4	150	0	30-60	14.1	20.7	181.2	1.7	31.0
1T3	4	150	0	60-90	14.9	23.4	5.1	-	3.5
1T3	4	150	0	90-120	8.3	13.6	88.8	1.4	16.7
1T3	5	225	0	0-15	20.1	22.9	12.7	1.7	115.3
1T3	5	225	0	15-30	17.3	25.4	101.4	1.5	149.4
1T3	5	225	0	30-60	16.9	24.7	257.0	1.6	33.2
1T3	5	225	0	60-90	18.8	29.5	133.6	1.5	12.6
1T3	5	225	0	90-120	13.6	22.3	8.3	1.6	5.3
1T3	6	75	20	0-15	21.2	24.2	4.1	1.6	141.5
1T3	6	75	20	15-30	17.2	25.4	37.0	1.6	93.9
1T3	6	75	20	30-60	14.6	21.4	95.0	1.2	37.9
1T3	6	75	20	60-90	17.1	26.9	55.3	1.4	14.4
1T3	6	75	20	90-120	16.5	27.1	25.8	2.2	8.7
1T3	7	150	20	0-15	19.5	22.2	2.6	1.4	48.3
1T3	7	150	20	15-30	19.3	28.5	43.9	1.5	81.8
1T3	7	150	20	30-60	16.7	24.4	99.7	1.6	30.1

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
1T3	7	150	20	60-90	17.0	26.7	34.4	1.8	12.2
1T3	7	150	20	90-120	11.5	18.8	0.4	1.3	3.0
1T3	8	225	20	0-15	21.6	24.7	8.8	2.0	167.7
1T3	8	225	20	15-30	15.5	22.8	30.6	1.4	59.4
1T3	8	225	20	30-60	16.8	24.6	42.7	1.7	25.9
1T3	8	225	20	60-90	12.4	19.5	4.4	1.7	9.6
1T3	8	225	20	90-120	14.3	23.4	2.1	1.3	3.5
1T3	9	75	60	0-15	19.8	22.6	1.4	1.6	154.8
1T3	9	75	60	15-30	16.9	24.9	6.4	1.2	111.4
1T3	9	75	60	30-60	17.0	24.9	7.9	1.7	72.5
1T3	9	75	60	60-90	16.3	25.5	0.5	1.8	20.5
1T3	10	150	60	0-15	20.2	23.0	0.9	2.1	140.2
1T3	10	150	60	15-30	15.8	23.3	5.8	2.0	42.9
1T3	10	150	60	30-60	15.7	23.0	2.4	2.1	32.8
1T3	10	150	60	60-90	15.8	24.8	0.2	1.7	12.2
1T3	11	225	60	0-15	20.7	23.6	0.5	2.3	50.3
1T3	11	225	60	15-30	18.4	27.2	1.3	1.8	32.7
1T3	11	225	60	30-60	14.2	20.8	0.4	1.9	24.5
1T3	11	225	60	60-90	12.3	19.3	0.2	1.9	5.7
1T3	12	75	140	0-15	20.4	23.2	0.3	1.8	75.6
1T3	12	75	140	15-30	17.0	25.1	0.6	1.5	44.3
1T3	12	75	140	30-60	13.1	19.1	1.6	1.6	24.1
1T3	13	150	140	0-15	18.7	21.3	0.2	2.0	60.2
1T3	13	150	140	15-30	14.4	21.3	0.4	1.5	52.7
1T3	13	150	140	30-60	12.4	18.1	0.7	1.6	66.2
1T3	14	225	140	0-15	20.6	23.5	0.3	1.9	115.9
1T3	14	225	140	15-30	17.3	25.5	0.6	1.5	115.2
1T3	14	225	140	30-60	16.6	24.2	0.2	1.6	49.4
1A1	1	150	-40	0-15	29.9	32.4	14.2	5.1	247.6
1A1	1	150	-40	15-30	31.1	36.8	6.4	4.3	182.0
1A1	1	150	-40	30-60	17.1	24.2	4.6	1.6	35.1
1A1	2	150	-20	0-15	30.3	32.9	23.6	4.6	173.7
1A1	2	150	-20	15-30	30.6	36.3	88.8	4.4	132.3
1A1	2	150	-20	30-60	18.9	26.6	47.0	1.9	33.5
1A1	2	150	-20	60-90	23.2	34.2	1.8	1.8	4.9
1A1	2	150	-20	90-120	23.0	36.4	3.0	4.4	8.9
1A1	3	75	0	0-15	30.6	33.2	48.6	4.0	207.4
1A1	3	75	0	15-30	13.7	16.2	281.9	3.8	196.0
1A1	3	75	0	30-60	19.5	27.4	188.5	1.9	23.1
1A1	3	75	0	60-90	23.8	35.0	7.5	1.8	4.3
1A1	3	75	0	90-120	21.9	34.7	1.2	3.5	6.2
1A1	4	150	0	0-15	29.1	31.6	113.5	4.4	250.0
1A1	4	150	0	15-30	32.9	39.0	334.7	3.5	137.9
1A1	4	150	0	30-60	20.3	28.6	248.1	2.7	37.0
1A1	4	150	0	60-90	23.9	35.3	16.6	1.4	5.4
1A1	4	150	0	90-120	23.0	36.5	4.4	3.0	9.4
1A1	5	225	0	0-15	32.2	34.9	80.9	4.0	279.1
1A1	5	225	0	15-30	34.4	40.6	220.2	3.3	392.9
1A1	5	225	0	30-60	19.6	27.7	271.1	2.0	68.4
1A1	5	225	0	60-90	25.5	37.6	91.2	1.7	16.1
1A1	5	225	0	90-120	21.8	34.6	2.8	2.6	8.9
1A1	6	75	20	0-15	31.3	34.0	21.6	5.5	314.6
1A1	6	75	20	15-30	30.6	36.2	95.2	3.2	147.0
1A1	6	75	20	30-60	18.3	25.8	66.9	1.5	22.8
1A1	6	75	20	60-90	23.7	35.0	3.8	1.7	2.7
1A1	6	75	20	90-120	20.8	32.9	0.8	3.6	6.2
1A1	7	150	20	0-15	30.6	33.2	41.8	3.5	252.5
1A1	7	150	20	15-30	31.0	36.6	173.2	3.5	107.5
1A1	7	150	20	30-60	20.2	28.5	85.9	2.4	24.5
1A1	7	150	20	60-90	26.4	39.0	4.7	2.7	3.6
1A1	7	150	20	90-120	22.0	34.8	3.5	3.5	9.0
1A1	8	225	20	0-15	33.3	36.1	12.9	5.7	320.2
1A1	8	225	20	15-30	33.5	39.6	112.4	6.2	301.0
1A1	8	225	20	30-60	22.2	31.2	112.5	1.8	32.9
1A1	8	225	20	60-90	23.9	35.3	13.4	1.1	6.4
1A1	8	225	20	90-120	21.8	34.4	8.2	3.4	11.9

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
		cm			%		ppm		
1A1	9	75	60	0-15	31.2	33.8	1.0	4.9	129.8
1A1	9	75	60	15-30	31.9	37.7	1.6	3.9	207.6
1A1	9	75	60	30-60	20.8	29.3	0.5	3.0	17.5
1A1	9	75	60	60-90	25.0	36.9	2.3	2.5	0.9
1A1	10	150	60	0-15	32.0	34.7	6.3	7.4	242.2
1A1	10	150	60	15-30	33.0	39.1	11.6	5.4	225.9
1A1	10	150	60	30-60	23.0	32.4	2.3	1.9	39.3
1A1	10	150	60	60-90	24.5	36.2	3.9	2.5	0.6
1A1	11	225	60	0-15	31.1	33.7	4.2	4.1	105.9
1A1	11	225	60	15-30	33.8	40.0	10.7	4.6	115.8
1A1	11	225	60	30-60	25.3	35.6	5.4	2.5	41.3
1A1	11	225	60	60-90	24.0	35.4	4.2	7.5	3.9
1A1	12	75	140	0-15	32.4	35.2	2.5	6.5	152.7
1A1	12	75	140	15-30	30.5	36.1	1.5	3.7	133.7
1A1	12	75	140	30-60	19.3	27.1	1.0	2.0	22.1
1A1	13	150	140	0-15	27.8	30.2	1.0	5.3	54.5
1A1	13	150	140	15-30	32.8	38.8	2.0	4.5	181.6
1A1	13	150	140	30-60		-	-	-	-
1A1	14	225	140	0-15	29.6	32.1	0.9	4.3	123.8
1A1	14	225	140	15-30	32.7	38.7	18.7	4.1	205.1
1A1	14	225	140	30-60	17.0	23.9	1.7	2.7	53.3
1A2	1	150	-40	0-15	27.7	30.5	31.0	8.9	212.9
1A2	1	150	-40	15-30	24.0	32.1	58.7	4.2	123.8
1A2	1	150	-40	30-60	20.8	29.1	56.1	2.6	50.1
1A2	2	150	-20	0-15	30.4	33.4	16.1	6.6	180.9
1A2	2	150	-20	15-30	23.9	32.0	80.1	3.7	118.5
1A2	2	150	-20	30-60	21.4	29.9	140.2	3.2	33.3
1A2	2	150	-20	60-90	21.8	30.0	16.3	2.4	7.8
1A2	2	150	-20	90-120	25.1	32.8	13.2	5.2	7.0
1A2	3	75	0	0-15	28.0	30.8	118.0	6.9	220.6
1A2	3	75	0	15-30	26.0	34.7	178.0	3.6	125.1
1A2	3	75	0	30-60	21.7	30.4	110.8	2.7	21.0
1A2	3	75	0	60-90	26.2	36.0	8.4	1.8	8.1
1A2	3	75	0	90-120	30.7	40.2	1.4	3.2	22.1
1A2	4	150	0	0-15	29.2	32.1	38.1	8.1	200.6
1A2	4	150	0	15-30	22.2	29.7	64.9	3.5	117.7
1A2	4	150	0	30-60	22.6	31.6	98.5	2.1	16.6
1A2	4	150	0	60-90	26.3	36.1	2.6	3.0	2.7
1A2	4	150	0	90-120	24.5	32.1	4.7	4.8	7.7
1A2	5	225	0	0-15	30.7	33.8	33.2	6.7	190.2
1A2	5	225	0	15-30	22.2	29.7	103.0	3.1	134.2
1A2	5	225	0	30-60	22.2	31.0	130.1	2.3	20.1
1A2	5	225	0	60-90	27.9	38.3	3.4	2.5	1.0
1A2	5	225	0	90-120	26.9	35.2	0.9	5.4	2.5
1A2	6	75	20	0-15	29.7	32.7	7.4	8.0	171.4
1A2	6	75	20	15-30	22.8	30.6	10.9	3.3	78.5
1A2	6	75	20	30-60	21.3	29.7	2.0	3.4	9.1
1A2	6	75	20	60-90	25.5	35.0	3.2	1.7	3.6
1A2	6	75	20	90-120	29.9	39.1	0.9	2.7	22.4
1A2	7	150	20	0-15	28.5	31.3	6.2	4.6	193.2
1A2	7	150	20	15-30	21.5	28.7	25.8	2.1	87.7
1A2	7	150	20	30-60	23.1	32.3	42.1	1.7	60.2
1A2	7	150	20	60-90	26.5	36.4	3.5	2.9	7.1
1A2	7	150	20	90-120	26.6	34.9	0.4	4.0	18.5
1A2	8	225	20	0-15	29.0	31.9	3.3	3.2	120.1
1A2	8	225	20	15-30	20.4	27.3	12.8	2.1	45.1
1A2	8	225	20	30-60	23.0	32.2	6.9	2.6	12.0
1A2	8	225	20	60-90	24.4	33.5	3.5	4.1	0.9
1A2	8	225	20	90-120	25.5	33.4	0.4	4.2	3.4
1A2	9	75	60	0-15	26.8	29.5	0.4	3.4	175.5
1A2	9	75	60	15-30	20.7	27.7	10.8	4.1	83.7
1A2	9	75	60	30-60	23.9	33.4	0.7	2.0	7.9
1A2	9	75	60	60-90	28.3	38.9	0.7	2.9	24.8
1A2	10	150	60	0-15	28.1	30.9	1.8	3.5	215.3
1A2	10	150	60	15-30	21.8	29.1	0.5	2.5	92.1
1A2	10	150	60	30-60	22.3	31.1	1.8	1.8	19.5

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
1A2	10	150	60	60-90	24.8	34.1	1.8	3.1	12.5
1A2	11	225	60	0-15	26.5	29.1	0.4	3.2	109.5
1A2	11	225	60	15-30	20.4	27.2	1.1	2.3	70.9
1A2	11	225	60	30-60	23.1	32.3	0.5	3.3	9.7
1A2	11	225	60	60-90	20.0	27.4	0.4	3.4	5.7
1A2	12	75	140	0-15	26.6	29.2	5.3	3.9	172.0
1A2	12	75	140	15-30	20.2	27.0	4.3	2.2	70.6
1A2	12	75	140	30-60	23.4	32.8	0.7	2.4	7.7
1A2	13	150	140	0-15	26.1	28.7	0.4	5.5	166.3
1A2	13	150	140	15-30	20.5	27.4	3.4	2.0	113.8
1A2	13	150	140	30-60	22.6	31.6	2.5	1.9	9.5
1A2	14	225	140	0-15	26.1	28.7	1.0	3.0	111.2
1A2	14	225	140	15-30	19.9	26.6	7.8	2.2	28.4
1A2	14	225	140	30-60	26.6	37.2	0.5	3.0	14.2
1A3	1	150	-40	0-15	31.4	33.3	2.8	7.1	143.0
1A3	1	150	-40	15-30	26.1	33.7	24.7	4.4	79.9
1A3	1	150	-40	30-60	19.0	29.0	23.7	2.8	21.2
1A3	2	150	-20	0-15	30.3	32.1	5.8	4.4	111.6
1A3	2	150	-20	15-30	27.2	35.2	74.0	3.6	142.0
1A3	2	150	-20	30-60	19.1	29.1	46.8	1.6	24.1
1A3	2	150	-20	60-90	18.7	26.3	9.5	1.8	5.0
1A3	2	150	-20	90-120	20.2	33.7	1.5	4.2	9.8
1A3	3	75	0	0-15	32.0	34.0	239.1	4.9	353.2
1A3	3	75	0	15-30	31.5	40.6	322.5	3.5	170.7
1A3	3	75	0	30-60	22.0	33.7	117.4	2.5	21.0
1A3	3	75	0	60-90	24.4	34.4	7.1	2.7	4.8
1A3	3	75	0	90-120	18.9	31.6	1.8	4.1	8.5
1A3	4	150	0	0-15	30.8	32.6	98.1	4.8	192.6
1A3	4	150	0	15-30	22.3	28.8	232.0	1.6	80.4
1A3	4	150	0	30-60	21.5	32.8	62.1	2.8	12.3
1A3	4	150	0	60-90	23.1	32.5	8.9	2.8	7.2
1A3	4	150	0	90-120	22.1	36.8	3.5	2.6	6.9
1A3	5	225	0	0-15	29.2	31.0	92.3	2.3	359.6
1A3	5	225	0	15-30	24.4	31.4	219.4	1.8	126.3
1A3	5	225	0	30-60	20.5	31.3	120.3	0.9	11.1
1A3	5	225	0	60-90	21.4	30.1	8.9	2.4	9.8
1A3	5	225	0	90-120	20.1	33.6	1.5	4.0	5.4
1A3	6	75	20	0-15	34.4	36.5	49.8	4.3	163.1
1A3	6	75	20	15-30	23.9	30.8	26.1	1.9	58.9
1A3	6	75	20	30-60	21.4	32.7	7.3	1.9	12.9
1A3	6	75	20	60-90	22.2	31.2	1.2	2.1	4.7
1A3	6	75	20	90-120	23.2	38.7	1.0	3.2	9.2
1A3	7	150	20	0-15	30.1	31.9	107.1	3.6	254.9
1A3	7	150	20	15-30	21.9	28.2	111.1	2.0	78.9
1A3	7	150	20	30-60	22.6	34.6	20.2	2.4	6.4
1A3	7	150	20	60-90	21.2	29.8	1.6	3.6	2.3
1A3	7	150	20	90-120	16.9	28.1	0.7	4.0	3.8
1A3	8	225	20	0-15	32.5	34.5	66.9	4.0	225.7
1A3	8	225	20	15-30	21.2	27.4	90.5	3.1	82.9
1A3	8	225	20	30-60	21.7	33.1	82.4	2.3	15.4
1A3	8	225	20	60-90	21.4	30.1	7.5	4.5	3.0
1A3	8	225	20	90-120	19.0	31.7	0.9	3.4	2.2
1A3	9	75	60	0-15	30.3	32.1	14.5	3.5	337.6
1A3	9	75	60	15-30	23.0	29.6	7.6	2.0	78.4
1A3	9	75	60	30-60	21.0	32.1	2.3	2.2	13.2
1A3	9	75	60	60-90	24.8	34.9	0.6	2.3	0.5
1A3	10	150	60	0-15	31.3	33.2	4.5	4.2	389.4
1A3	10	150	60	15-30	23.7	30.5	19.6	2.8	119.5
1A3	10	150	60	30-60	20.8	31.8	1.0	2.5	9.2
1A3	10	150	60	60-90	24.6	34.6	0.7	2.2	1.5
1A3	11	225	60	0-15	29.8	31.6	3.2	4.3	210.3
1A3	11	225	60	15-30	22.1	28.5	2.2	2.5	61.7
1A3	11	225	60	30-60	18.9	28.9	4.6	2.2	12.0
1A3	11	225	60	60-90	22.4	31.5	0.9	3.1	2.7
1A3	12	75	140	0-15	28.5	30.3	0.9	3.7	159.3
1A3	12	75	140	15-30	20.1	26.0	3.8	2.9	108.3

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
		cm			%		ppm		
1A3	12	75	140	30-60	21.3	32.6	0.4	2.4	15.4
1A3	13	150	140	0-15	31.0	32.9	2.9	3.6	169.7
1A3	13	150	140	15-30	21.2	27.4	3.9	2.8	78.5
1A3	13	150	140	30-60	23.6	36.0	1.1	2.3	20.7
1A3	14	225	140	0-15	30.0	31.8	2.2	3.2	138.6
1A3	14	225	140	15-30	21.3	27.5	1.4	2.2	84.1
1A3	14	225	140	30-60	20.8	31.9	0.6	1.9	14.8
2D	1	150	-40	0-15	27.3	30.4	29.5	-	39.7
2D	1	150	-40	15-30	21.3	34.3	34.8	3.8	65.4
2D	1	150	-40	30-60	20.8	35.7	8.4	2.9	8.1
2D	2	150	-20	0-15	25.5	28.3	42.0	5.4	33.2
2D	2	150	-20	15-30	21.5	34.7	137.0	4.1	1.0
2D	2	150	-20	30-60	20.1	34.6	16.7	2.4	3.9
2D	2	150	-20	60-90	18.3	29.7	0.5	1.8	2.0
2D	2	150	-20	90-120	17.0	28.8	0.3	2.2	2.7
2D	3	75	0	0-15	26.6	29.6	169.4	4.9	15.8
2D	3	75	0	15-30	21.7	35.0	438.3	3.0	90.1
2D	3	75	0	30-60	19.5	33.4	104.9	2.9	0.7
2D	3	75	0	60-90	18.0	29.1	4.4	2.3	2.9
2D	3	75	0	90-120	17.5	29.7	0.5	2.4	5.1
2D	4	150	0	0-15	26.4	29.4	142.9	4.8	136.8
2D	4	150	0	15-30	22.5	36.3	213.1	3.0	24.4
2D	4	150	0	30-60	19.0	32.5	106.2	2.3	5.7
2D	4	150	0	60-90	17.4	28.3	2.9	2.4	2.2
2D	4	150	0	90-120	16.0	27.2	0.7	2.2	3.1
2D	5	225	0	0-15	26.2	29.1	8.7	4.4	74.8
2D	5	225	0	15-30	21.7	35.1	106.5	3.3	107.8
2D	5	225	0	30-60	19.2	33.0	30.9	2.5	7.8
2D	5	225	0	60-90	16.9	27.4	0.8	1.9	2.7
2D	5	225	0	90-120	16.0	27.2	0.4	2.0	3.0
2D	6	75	20	0-15	24.6	27.4	42.6	4.4	82.2
2D	6	75	20	15-30	21.5	34.7	75.9	3.5	65.9
2D	6	75	20	30-60	21.1	36.2	7.9	2.5	14.8
2D	6	75	20	60-90	19.2	31.2	1.7	3.3	4.4
2D	6	75	20	90-120	17.4	29.5	1.8	2.7	12.8
2D	7	150	20	0-15	24.6	27.4	12.3	4.1	68.9
2D	7	150	20	15-30	22.4	36.1	35.7	3.4	42.9
2D	7	150	20	30-60	20.1	34.5	28.6	3.6	6.2
2D	7	150	20	60-90	18.1	29.4	2.0	2.4	0.6
2D	7	150	20	90-120	17.9	30.4	0.7	2.2	3.8
2D	8	225	20	0-15	24.0	26.6	3.7	5.7	0.9
2D	8	225	20	15-30	20.8	33.6	33.4	3.6	15.0
2D	8	225	20	30-60	19.8	34.0	11.4	2.6	2.2
2D	8	225	20	60-90	18.5	30.0	1.1	2.7	2.2
2D	8	225	20	90-120	16.8	28.5	0.4	1.9	3.8
2D	9	75	60	0-15	25.8	28.6	4.9	5.0	131.1
2D	9	75	60	15-30	21.5	34.6	5.8	3.0	98.4
2D	9	75	60	30-60	22.4	38.4	8.4	3.4	29.6
2D	9	75	60	60-90	20.3	33.0	24.8	4.1	19.4
2D	10	150	60	0-15	26.6	29.6	1.0	5.5	16.2
2D	10	150	60	15-30	23.1	37.3	1.6	4.6	33.2
2D	10	150	60	30-60	19.2	32.9	0.4	2.1	11.6
2D	10	150	60	60-90	17.3	28.0	0.5	2.1	3.3
2D	11	225	60	0-15	25.7	28.5	0.8	6.6	41.6
2D	11	225	60	15-30	20.9	33.8	1.1	4.1	20.3
2D	11	225	60	30-60	19.9	34.2	0.8	3.8	2.3
2D	11	225	60	60-90	17.2	27.8	0.4	2.0	2.6
2D	12	75	140	0-15	24.4	27.1	0.7	6.0	99.0
2D	12	75	140	15-30	21.3	34.4	0.7	9.0	102.1
2D	12	75	140	30-60	20.7	35.5	0.7	3.0	24.1
2D	13	150	140	0-15	21.9	24.3	0.9	5.3	16.3
2D	13	150	140	15-30	19.3	31.1	0.5	3.3	8.5
2D	13	150	140	30-60	19.0	32.6	0.7	2.6	0.8
2D	14	225	140	0-15	22.5	25.0	0.5	5.1	71.3
2D	14	225	140	15-30	18.9	30.4	0.5	2.5	31.6
2D	14	225	140	30-60	19.1	32.8	0.4	2.2	7.6

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
2T	1	150	-40	0-15	26.0	31.7	0.4	4.4	167.1
2T	1	150	-40	15-30	21.9	34.8	0.6	3.6	70.1
2T	1	150	-40	30-60	20.0	33.5	0.8	2.7	0.2
2T	2	150	-20	0-15	24.9	30.4	0.5	4.1	120.8
2T	2	150	-20	15-30	22.2	35.3	0.7	2.3	76.7
2T	2	150	-20	30-60	19.2	32.3	0.6	2.4	0.4
2T	2	150	-20	60-90	18.9	32.1	0.4	1.7	1.9
2T	2	150	-20	90-120	18.9	32.1	0.3	1.9	<0.1
2T	3	75	0	0-15	27.7	33.9	26.7	4.5	93.2
2T	3	75	0	15-30	24.2	38.4	183.9	3.9	147.7
2T	3	75	0	30-60	19.6	32.9	84.1	2.7	3.8
2T	3	75	0	60-90	19.9	33.7	2.4	2.1	7.1
2T	3	75	0	90-120	19.3	32.8	0.5	1.9	4.3
2T	4	150	0	0-15	26.9	32.8	5.9	4.4	0.6
2T	4	150	0	15-30	23.0	36.6	39.5	4.4	24.8
2T	4	150	0	30-60	21.0	35.3	86.9	3.2	32.8
2T	4	150	0	60-90	19.6	33.2	12.9	2.3	3.5
2T	4	150	0	90-120	19.1	32.5	0.7	2.1	3.4
2T	5	225	0	0-15	25.9	31.6	14.0	4.6	50.4
2T	5	225	0	15-30	21.6	34.2	48.8	2.7	40.4
2T	5	225	0	30-60	19.6	32.9	15.7	3.2	5.9
2T	5	225	0	60-90	19.2	32.6	0.7	2.0	0.6
2T	5	225	0	90-120	17.7	30.1	0.3	4.4	4.0
2T	6	75	20	0-15	28.7	35.1	40.2	4.7	104.4
2T	6	75	20	15-30	21.1	33.6	139.8	2.8	1.5
2T	6	75	20	30-60	19.8	33.2	60.9	2.4	25.7
2T	6	75	20	60-90	19.6	33.2	8.0	1.8	8.5
2T	6	75	20	90-120	18.5	31.5	0.4	2.0	9.2
2T	7	150	20	0-15	28.6	34.9	48.8	4.9	62.1
2T	7	150	20	15-30	23.0	36.6	111.7	2.9	47.8
2T	7	150	20	30-60	19.0	32.0	13.8	1.6	6.7
2T	7	150	20	60-90	18.8	31.9	5.7	2.2	6.2
2T	7	150	20	90-120	19.6	33.3	1.0	1.9	3.3
2T	8	225	20	0-15	25.9	31.6	95.9	2.4	0.6
2T	8	225	20	15-30	21.9	34.9	179.5	2.1	41.8
2T	8	225	20	30-60	19.6	32.9	22.5	1.5	7.0
2T	8	225	20	60-90	19.6	33.3	1.4	1.7	1.3
2T	8	225	20	90-120	18.6	31.6	0.5	2.4	4.4
2T	9	75	60	0-15	28.9	35.3	21.2	2.7	131.1
2T	9	75	60	15-30	22.2	35.3	31.9	1.8	98.3
2T	9	75	60	30-60	19.2	32.3	6.0	2.4	14.0
2T	9	75	60	60-90	19.2	32.5	0.4	1.6	5.0
2T	10	150	60	0-15	26.4	32.3	22.4	2.7	0.9
2T	10	150	60	15-30	22.7	36.0	32.7	1.5	77.1
2T	10	150	60	30-60	20.7	34.7	14.8	2.2	33.7
2T	10	150	60	60-90	19.3	32.7	1.6	1.9	5.6
2T	11	225	60	0-15	25.9	31.6	79.4	2.5	113.2
2T	11	225	60	15-30	22.2	35.2	40.9	1.2	78.4
2T	11	225	60	30-60	19.9	33.4	6.3	2.4	0.9
2T	11	225	60	60-90	19.8	33.6	1.5	1.7	4.8
2T	12	75	140	0-15	25.6	31.3	5.7	1.8	1.4
2T	12	75	140	15-30	19.5	31.0	4.1	2.4	23.5
2T	12	75	140	30-60	20.4	34.3	0.5	2.6	12.4
2T	13	150	140	0-15	23.4	28.6	6.6	3.6	0.2
2T	13	150	140	15-30	23.1	36.6	5.9	2.4	30.5
2T	13	150	140	30-60	20.4	34.2	1.0	2.5	0.8
2T	14	225	140	0-15	24.8	30.3	24.8	3.2	0.2
2T	14	225	140	15-30	20.7	32.9	15.1	1.4	52.5
2T	14	225	140	30-60	19.8	33.2	2.9	2.4	12.0
2A	1	150	-40	0-15	27.9	30.0	0.5	4.1	136.4
2A	1	150	-40	15-30	26.6	37.7	0.6	3.9	51.0
2A	1	150	-40	30-60	27.2	42.6	0.7	2.9	8.8
2A	2	150	-20	0-15	27.9	30.0	0.5	4.5	105.2
2A	2	150	-20	15-30	28.0	39.7	1.0	4.5	75.0
2A	2	150	-20	30-60	26.5	41.5	6.6	3.8	16.9
2A	2	150	-20	60-90	23.5	35.5	19.3	2.7	11.2

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm		%			ppm	
2A	2	150	-20	90-120	21.4	33.2	12.5	3.5	0.3
2A	3	75	0	0-15	30.4	32.6	4.8	4.2	180.5
2A	3	75	0	15-30	26.5	37.6	36.8	5.0	58.3
2A	3	75	0	30-60	26.1	40.8	131.7	4.0	13.9
2A	3	75	0	60-90	23.9	36.0	91.8	4.2	3.7
2A	3	75	0	90-120	20.3	31.5	82.8	4.3	<0.1
2A	4	150	0	0-15	30.7	33.0	8.9	5.0	178.8
2A	4	150	0	15-30	26.5	37.6	36.4	6.6	39.6
2A	4	150	0	30-60	26.4	41.3	71.3	5.6	22.5
2A	4	150	0	60-90	23.5	35.4	86.6	5.0	6.9
2A	4	150	0	90-120	19.4	30.0	61.4	3.6	1.5
2A	5	225	0	0-15	32.7	35.1	6.6	5.8	222.4
2A	5	225	0	15-30	26.3	37.3	24.4	6.3	0.5
2A	5	225	0	30-60	22.0	34.4	45.0	2.0	11.8
2A	5	225	0	60-90	25.2	38.0	110.9	2.4	11.9
2A	5	225	0	90-120	19.8	30.7	76.7	4.0	7.8
2A	6	75	20	0-15	30.5	32.8	2.4	3.9	141.6
2A	6	75	20	15-30	28.1	39.9	12.4	3.1	32.7
2A	6	75	20	30-60	26.7	41.7	42.4	2.7	25.7
2A	6	75	20	60-90	24.6	37.2	112.0	2.7	8.9
2A	6	75	20	90-120	18.3	28.4	84.5	3.0	8.8
2A	7	150	20	0-15	30.0	32.2	4.2	5.1	182.3
2A	7	150	20	15-30	26.6	37.7	10.5	3.7	0.5
2A	7	150	20	30-60	25.3	39.6	29.3	2.6	15.2
2A	7	150	20	60-90	21.3	32.0	99.8	2.6	12.6
2A	7	150	20	90-120	18.9	29.2	81.9	2.4	12.2
2A	8	225	20	0-15	29.7	31.9	3.1	3.1	68.4
2A	8	225	20	15-30	26.8	38.0	16.6	4.6	23.9
2A	8	225	20	30-60	23.1	36.2	56.4	3.5	20.6
2A	8	225	20	60-90	24.2	36.6	85.0	4.1	21.7
2A	8	225	20	90-120	19.8	30.7	46.4	4.7	2.5
2A	9	75	60	0-15	29.0	31.1	1.6	4.5	163.9
2A	9	75	60	15-30	28.2	40.0	0.6	3.3	3.0
2A	9	75	60	30-60	27.2	42.6	1.1	2.3	11.6
2A	9	75	60	60-90	23.8	35.9	10.7	3.4	18.5
2A	10	150	60	0-15	29.0	31.1	0.5	3.7	123.2
2A	10	150	60	15-30	27.4	38.8	0.3	2.8	39.2
2A	10	150	60	30-60	26.4	41.3	0.6	5.2	16.2
2A	10	150	60	60-90	23.9	36.1	7.4	2.3	14.3
2A	11	225	60	0-15	28.0	30.1	0.9	4.5	393.1
2A	11	225	60	15-30	25.1	35.7	0.5	6.2	0.5
2A	11	225	60	30-60	24.2	37.9	0.8	2.6	16.6
2A	11	225	60	60-90	24.0	36.1	1.9	2.3	13.7
2A	12	75	140	0-15	26.5	28.4	0.4	5.3	252.7
2A	12	75	140	15-30	27.3	38.7	0.2	5.5	91.4
2A	12	75	140	30-60	25.4	39.8	0.4	4.3	19.6
2A	13	150	140	0-15	26.9	29.0	0.3	3.6	135.5
2A	13	150	140	15-30	23.3	33.0	0.3	10.4	33.6
2A	13	150	140	30-60	24.0	37.6	0.4	4.1	8.4
2A	14	225	140	0-15	27.6	29.7	0.2	4.4	209.8
2A	14	225	140	15-30	23.6	33.5	0.2	2.6	41.5
2A	14	225	140	30-60	25.2	39.4	0.4	2.4	15.7
3D	1	150	-40	0-15	25.3	26.8	1.9	3.7	599.5
3D	1	150	-40	15-30	27.3	37.1	4.1	4.5	213.1
3D	1	150	-40	30-60	17.5	26.2	1.9	3.6	20.1
3D	2	150	-20	0-15	25.2	26.7	13.8	4.0	63.7
3D	2	150	-20	15-30	21.7	29.4	112.8	4.5	26.4
3D	2	150	-20	30-60	16.7	25.1	114.0	3.3	4.1
3D	2	150	-20	60-90	15.3	22.8	17.2	2.4	2.6
3D	2	150	-20	90-120	15.3	25.8	0.6	2.5	4.7
3D	3	75	0	0-15	28.0	29.7	17.2	3.9	7.2
3D	3	75	0	15-30	31.0	42.1	190.8	3.5	114.6
3D	3	75	0	30-60	21.0	31.4	439.7	3.0	18.3
3D	3	75	0	60-90	16.8	25.1	18.6	2.5	3.9
3D	3	75	0	90-120	16.0	26.9	0.6	2.3	4.5
3D	4	150	0	0-15	26.5	28.0	61.0	3.5	95.3

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
3D	4	150	0	15-30	22.0	29.8	324.3	3.3	60.5
3D	4	150	0	30-60	18.7	27.9	167.7	3.0	12.4
3D	4	150	0	60-90	15.2	22.7	7.0	2.8	3.6
3D	4	150	0	90-120	14.8	24.9	1.4	0.7	5.6
3D	5	225	0	0-15	25.6	27.1	109.5	3.7	132.8
3D	5	225	0	15-30	23.8	32.2	250.8	3.6	123.6
3D	5	225	0	30-60	19.6	29.4	285.5	3.7	3.1
3D	5	225	0	60-90	16.6	24.8	20.5	2.7	2.7
3D	5	225	0	90-120	16.0	27.0	0.7	2.0	5.2
3D	6	75	20	0-15	26.0	27.6	34.1	4.6	89.1
3D	6	75	20	15-30	21.6	29.3	58.2	3.2	56.9
3D	6	75	20	30-60	17.4	26.1	42.2	3.6	9.8
3D	6	75	20	60-90	17.0	25.4	1.0	2.5	2.2
3D	6	75	20	90-120	16.0	27.0	0.6	3.4	2.5
3D	7	150	20	0-15	24.7	26.1	10.6	5.0	21.1
3D	7	150	20	15-30	19.9	26.9	84.7	2.9	54.9
3D	7	150	20	30-60	19.8	29.6	64.3	3.6	21.3
3D	7	150	20	60-90	16.0	23.8	6.2	2.8	4.8
3D	7	150	20	90-120	17.0	28.7	0.5	2.5	5.6
3D	8	225	20	0-15	24.9	26.4	23.2	3.1	86.1
3D	8	225	20	15-30	24.1	32.7	73.5	2.5	117.7
3D	8	225	20	30-60	20.5	30.7	30.1	3.2	25.8
3D	8	225	20	60-90	17.2	25.7	2.9	2.5	3.8
3D	8	225	20	90-120	14.7	24.8	0.5	2.2	4.1
3D	9	75	60	0-15	26.5	28.1	0.3	3.1	116.3
3D	9	75	60	15-30	22.4	30.4	0.7	2.4	147.3
3D	9	75	60	30-60	18.4	27.6	0.5	2.4	55.2
3D	9	75	60	60-90	15.1	22.5	0.3	2.5	7.9
3D	10	150	60	0-15	25.1	26.6	0.5	3.6	81.5
3D	10	150	60	15-30	21.9	29.6	0.6	2.0	117.3
3D	10	150	60	30-60	19.9	29.8	0.5	2.2	27.4
3D	10	150	60	60-90	14.7	22.0	0.3	2.2	5.4
3D	11	225	60	0-15	26.3	27.9	0.6	4.2	6.5
3D	11	225	60	15-30	23.3	31.7	1.3	2.3	90.4
3D	11	225	60	30-60	20.0	29.9	1.1	1.9	57.8
3D	11	225	60	60-90	22.2	33.2	0.5	2.4	30.3
3D	12	75	140	0-15	23.7	25.1	0.3	3.8	0.5
3D	12	75	140	15-30	20.3	27.6	0.3	3.4	7.5
3D	12	75	140	30-60	15.4	23.0	0.2	2.5	28.7
3D	13	150	140	0-15	24.9	26.4	0.3	3.3	79.4
3D	13	150	140	15-30	22.6	30.7	0.3	2.6	90.5
3D	13	150	140	30-60	18.4	27.5	0.2	2.5	44.7
3D	14	225	140	0-15	22.3	23.6	0.3	3.3	59.0
3D	14	225	140	15-30	20.1	27.3	0.2	3.2	59.2
3D	14	225	140	30-60	23.9	35.7	0.3	2.7	41.2
3T	1	150	-40	0-15	24.9	33.0	2.6	5.1	0.3
3T	1	150	-40	15-30	24.0	36.1	3.1	2.7	111.8
3T	1	150	-40	30-60	29.6	49.2	1.0	2.7	20.8
3T	2	150	-20	0-15	23.7	31.3	5.8	3.7	70.4
3T	2	150	-20	15-30	19.5	29.4	17.3	2.7	19.6
3T	2	150	-20	30-60	22.0	36.5	15.1	3.1	2.0
3T	2	150	-20	60-90	33.6	57.9	1.4	3.3	0.0
3T	2	150	-20	90-120	20.8	35.1	0.4	2.7	10.7
3T	3	75	0	0-15	21.8	28.8	127.4	4.2	116.8
3T	3	75	0	15-30	19.0	28.6	163.6	3.2	18.4
3T	3	75	0	30-60	18.3	30.3	123.0	3.3	0.7
3T	3	75	0	60-90	23.2	39.9	11.3	3.6	0.4
3T	3	75	0	90-120	17.6	29.7	0.9	2.8	6.7
3T	4	150	0	0-15	21.4	28.4	90.0	3.7	89.9
3T	4	150	0	15-30	22.9	34.5	330.5	3.3	65.9
3T	4	150	0	30-60	26.8	44.6	115.2	3.8	3.1
3T	4	150	0	60-90	20.9	35.9	2.1	3.1	0.1
3T	4	150	0	90-120	19.7	33.3	1.4	2.7	8.6
3T	5	225	0	0-15	22.7	30.0	75.4	4.5	168.4
3T	5	225	0	15-30	22.7	34.2	189.7	3.9	87.5
3T	5	225	0	30-60	17.3	28.7	2.2	3.1	0.8

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
3T	5	225	0	60-90	24.2	41.6	2.2	3.3	0.8
3T	5	225	0	90-120	18.0	30.5	0.9	2.7	8.9
3T	6	75	20	0-15	21.0	27.8	168.9	4.2	71.8
3T	6	75	20	15-30	20.6	31.0	350.9	2.7	35.5
3T	6	75	20	30-60	20.8	34.6	134.2	3.3	1.6
3T	6	75	20	60-90	-	-	-	-	-
3T	6	75	20	90-120	-	-	-	-	-
3T	7	150	20	0-15	23.5	31.1	187.9	3.9	150.0
3T	7	150	20	15-30	23.7	35.7	167.4	2.6	22.4
3T	7	150	20	30-60	21.2	35.2	148.9	3.1	3.6
3T	7	150	20	60-90	22.3	38.3	14.6	3.3	3.7
3T	7	150	20	90-120	16.3	27.6	0.8	2.5	10.3
3T	8	225	20	0-15	22.6	30.0	34.5	3.1	55.7
3T	8	225	20	15-30	21.5	32.4	133.2	2.8	46.1
3T	8	225	20	30-60	21.6	35.8	65.3	3.6	5.1
3T	8	225	20	60-90	23.9	41.2	3.9	3.0	0.5
3T	8	225	20	90-120	25.8	43.7	1.1	0.8	11.8
3T	9	75	60	0-15	23.8	31.5	49.4	3.6	201.1
3T	9	75	60	15-30	19.4	29.1	35.0	2.2	98.2
3T	9	75	60	30-60	17.3	28.7	7.3	2.8	3.2
3T	9	75	60	60-90	7.9	13.7	1.1	2.6	8.1
3T	10	150	60	0-15	21.6	28.6	10.5	2.9	0.4
3T	10	150	60	15-30	19.5	29.4	23.0	2.1	30.5
3T	10	150	60	30-60	17.0	28.2	7.1	2.5	8.4
3T	10	150	60	60-90	19.6	33.8	1.4	1.9	3.8
3T	11	225	60	0-15	22.8	30.1	23.6	2.8	178.5
3T	11	225	60	15-30	18.8	28.3	32.7	3.1	31.1
3T	11	225	60	30-60	18.7	31.1	18.7	2.2	<0.1
3T	11	225	60	60-90	-	-	-	-	-
3T	12	75	140	0-15	19.9	26.3	2.8	3.2	109.4
3T	12	75	140	15-30	16.3	24.5	7.3	2.5	56.9
3T	12	75	140	30-60	14.6	24.2	2.5	2.1	17.6
3T	13	150	140	0-15	21.5	28.4	1.6	3.2	61.1
3T	13	150	140	15-30	17.8	26.8	3.1	2.2	19.5
3T	13	150	140	30-60	16.3	27.0	0.8	1.4	3.6
3T	14	225	140	0-15	21.0	27.8	2.0	2.8	122.6
3T	14	225	140	15-30	18.8	28.3	5.1	1.9	46.0
3T	14	225	140	30-60	15.7	26.1	1.4	1.8	3.4
3A	1	150	-40	0-15	24.6	29.8	13.4	4.2	81.8
3A	1	150	-40	15-30	18.8	25.8	41.8	1.9	21.5
3A	1	150	-40	30-60	14.5	19.7	49.8	3.3	19.6
3A	2	150	-20	0-15	24.4	29.6	14.9	3.7	113.0
3A	2	150	-20	15-30	18.3	25.1	42.8	2.1	66.0
3A	2	150	-20	30-60	14.1	19.1	115.4	2.3	71.0
3A	2	150	-20	60-90	-	-	-	-	-
3A	2	150	-20	90-120	-	-	-	-	-
3A	3	75	0	0-15	27.2	33.0	13.6	4.4	259.8
3A	3	75	0	15-30	17.7	24.3	53.5	2.1	116.1
3A	3	75	0	30-60	16.4	22.3	167.9	2.4	24.9
3A	3	75	0	60-90	23.0	34.8	54.2	2.5	9.1
3A	3	75	0	90-120	20.7	31.2	1.5	3.3	13.2
3A	4	150	0	0-15	24.5	29.7	45.7	3.0	130.8
3A	4	150	0	15-30	15.2	20.8	129.0	2.4	57.5
3A	4	150	0	30-60	-	-	-	-	-
3A	4	150	0	60-90	-	-	-	-	-
3A	4	150	0	90-120	-	-	0.9	1.6	0.6
3A	5	225	0	0-15	24.7	29.9	10.4	3.0	126.0
3A	5	225	0	15-30	14.5	19.9	35.9	2.7	69.2
3A	5	225	0	30-60	16.9	22.9	48.1	2.6	40.8
3A	5	225	0	60-90	22.6	34.1	7.4	1.4	16.5
3A	5	225	0	90-120	21.4	32.2	10.7	3.0	15.4
3A	6	75	20	0-15	24.4	29.6	9.4	4.6	190.8
3A	6	75	20	15-30	18.6	25.5	27.2	1.9	111.0
3A	6	75	20	30-60	18.2	24.7	108.6	1.8	24.0
3A	6	75	20	60-90	21.8	32.9	26.5	1.7	11.6
3A	6	75	20	90-120	23.0	34.7	8.0	2.0	22.8

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
3A	7	150	20	0-15	29.0	35.1	7.0	4.2	210.9
3A	7	150	20	15-30	27.7	37.9	12.8	7.4	84.3
3A	7	150	20	30-60	-	-	-	-	-
3A	7	150	20	60-90	-	-	-	-	-
3A	7	150	20	90-120	-	-	-	-	-
3A	8	225	20	0-15	24.0	29.1	3.3	2.5	101.1
3A	8	225	20	15-30	8.3	11.4	-	-	-
3A	8	225	20	30-60	18.2	24.7	21.8	1.5	20.9
3A	8	225	20	60-90	22.6	34.0	6.9	1.4	10.5
3A	8	225	20	90-120	22.4	33.8	0.8	2.2	11.5
3A	9	75	60	0-15	24.9	30.2	3.9	3.2	149.9
3A	9	75	60	15-30	16.7	22.9	10.7	1.5	70.1
3A	9	75	60	30-60	20.9	28.4	20.1	1.8	17.6
3A	9	75	60	60-90	23.3	35.1	1.2	1.4	15.9
3A	10	150	60	0-15	23.9	28.9	3.9	2.3	56.8
3A	10	150	60	15-30	18.9	25.9	2.2	2.3	150.8
3A	10	150	60	30-60	17.1	23.3	2.4	1.6	46.8
3A	10	150	60	60-90	20.9	31.5	1.8	1.6	20.5
3A	11	225	60	0-15	29.3	35.5	3.3	3.5	57.0
3A	11	225	60	15-30	19.0	26.1	4.2	1.7	107.0
3A	11	225	60	30-60	20.0	27.2	2.8	1.9	14.4
3A	11	225	60	60-90	24.4	36.8	1.5	1.5	13.4
3A	12	75	140	0-15	27.1	32.9	6.9	3.7	211.1
3A	12	75	140	15-30	18.6	25.5	7.6	1.4	78.4
3A	12	75	140	30-60	12.9	17.5	8.4	1.6	36.4
3A	13	150	140	0-15	25.9	31.4	11.2	4.6	19.7
3A	13	150	140	15-30	15.3	21.0	5.0	1.7	43.7
3A	13	150	140	30-60	24.4	33.2	0.8	1.5	16.4
3A	14	225	140	0-15	23.7	28.7	2.4	1.9	82.9
3A	14	225	140	15-30	13.9	19.0	2.4	1.8	44.0
3A	14	225	140	30-60	19.6	26.7	4.6	1.9	14.1

VIII. Water content and solute concentrations for the October sampling event.

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
1D1	1	165	-40	0-15	14.2	15.8	2.4	7.9	7.0
1D1	1	165	-40	15-30	15.0	19.4	1.4	5.0	4.2
1D1	1	165	-40	30-60	13.9	18.1	2.1	3.8	3.0
1D1	2	165	-20	0-15	16.6	18.4	3.9	6.3	8.4
1D1	2	165	-20	15-30	15.8	20.4	2.6	5.8	4.2
1D1	2	165	-20	30-60	15.4	20.1	23.4	5.1	2.1
1D1	2	165	-20	60-90	17.5	22.7	31.0	6.4	2.8
1D1	2	165	-20	90-120	18.8	24.9	5.3	9.7	4.7
1D1	3	90	0	0-15	15.0	16.6	10.6	7.0	7.1
1D1	3	90	0	15-30	16.6	21.5	28.3	5.0	2.9
1D1	3	90	0	30-60	19.7	25.7	118.8	7.3	3.0
1D1	3	90	0	60-90	17.4	22.5	75.4	6.4	1.4
1D1	3	90	0	90-120	16.6	22.0	11.7	7.5	4.0
1D1	4	165	0	0-15	16.5	18.3	9.1	7.1	8.1
1D1	4	165	0	15-30	16.5	21.3	23.6	4.6	5.2
1D1	4	165	0	30-60	17.0	22.2	86.8	5.9	5.2
1D1	4	165	0	60-90	18.5	23.9	85.0	5.1	4.7
1D1	4	165	0	90-120	17.0	22.5	28.9	5.8	3.6
1D1	5	240	0	0-15	15.5	17.2	4.2	8.6	9.2
1D1	5	240	0	15-30	16.7	21.6	12.7	4.3	2.9
1D1	5	240	0	30-60	17.1	22.3	96.7	5.8	4.2
1D1	5	240	0	60-90	19.2	24.9	83.5	4.6	5.8
1D1	5	240	0	90-120	18.2	24.1	45.3	4.5	6.1
1D1	6	90	20	0-15	15.2	16.8	19.9	7.4	8.7
1D1	6	90	20	15-30	17.3	22.3	21.0	7.9	3.4
1D1	6	90	20	30-60	18.5	24.2	176.2	6.9	3.2
1D1	6	90	20	60-90	20.5	26.5	95.3	6.1	2.6
1D1	6	90	20	90-120	19.8	26.2	49.7	5.4	3.4
1D1	7	165	20	0-15	16.6	18.4	7.7	3.4	8.2
1D1	7	165	20	15-30	18.6	24.0	53.5	4.5	3.2
1D1	7	165	20	30-60	17.4	22.7	92.4	6.0	2.8
1D1	7	165	20	60-90	18.5	23.9	69.6	4.1	3.2
1D1	7	165	20	90-120	20.1	26.6	21.8	5.3	6.3
1D1	8	240	20	0-15	15.6	17.3	7.9	2.9	9.2
1D1	8	240	20	15-30	17.6	22.8	8.4	2.8	6.1
1D1	8	240	20	30-60	16.5	21.5	31.8	3.3	3.4
1D1	8	240	20	60-90	17.3	22.4	78.3	<0.1	4.8
1D1	8	240	20	90-120	21.6	28.5	24.3	3.9	5.5
1D1	9	90	60	0-15	15.4	17.0	5.1	7.4	10.0
1D1	9	90	60	15-30	17.4	22.6	1.4	4.2	3.7
1D1	9	90	60	30-60	17.7	23.1	1.0	3.9	2.9
1D1	9	90	60	60-90	18.4	23.8	1.0	3.2	3.8
1D1	10	165	60	0-15	16.7	18.6	0.7	2.6	9.6
1D1	10	165	60	15-30	19.1	24.7	1.1	3.2	4.1
1D1	10	165	60	30-60	18.2	23.7	5.3	5.4	5.1
1D1	10	165	60	60-90	20.4	26.3	4.5	5.3	5.5
1D1	11	240	60	0-15	16.3	18.1	0.7	2.6	10.4
1D1	11	240	60	15-30	18.6	24.1	1.4	3.2	6.5
1D1	11	240	60	30-60	17.0	22.1	1.3	2.4	4.7
1D1	11	240	60	60-90	18.6	24.1	4.9	1.8	3.0
1D1	12	90	140	0-15	17.3	19.2	1.1	5.6	10.0
1D1	12	90	140	15-30	17.3	22.3	0.4	1.8	2.4
1D1	12	90	140	30-60	19.3	25.2	0.5	1.9	2.6
1D1	13	165	140	0-15	16.4	18.2	0.4	2.1	5.4
1D1	13	165	140	15-30	17.2	22.2	0.6	1.9	3.6
1D1	13	165	140	30-60	17.0	22.2	0.4	3.5	2.7
1D1	14	240	140	0-15	16.6	18.5	0.5	2.1	7.5
1D1	14	240	140	15-30	14.3	18.5	0.5	1.6	3.2
1D1	14	240	140	30-60	18.5	24.1	0.4	1.5	4.3
1D1	15	90	220	0-15	15.6	17.3	0.5	2.5	11.2
1D1	15	90	220	15-30	18.1	23.3	0.5	2.6	3.9
1D1	16	165	220	0-15	16.1	17.8	0.5	2.4	11.1
1D1	16	165	220	15-30	16.9	21.8	0.4	3.0	3.8
1D1	17	240	220	0-15	15.9	17.6	0.4	2.4	9.1

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
1D1	17	240	220	15-30	18.8	24.3	0.4	1.9	3.1
1D2	1	165	-40	0-15	13.7	15.2	4.8	5.4	4.9
1D2	1	165	-40	15-30	14.6	16.9	2.4	1.4	3.5
1D2	1	165	-40	30-60	13.7	18.8	0.5	1.5	1.7
1D2	2	165	-20	0-15	14.8	16.3	16.5	3.1	<0.1
1D2	2	165	-20	15-30	14.8	17.2	5.8	2.5	2.7
1D2	2	165	-20	30-60	13.6	18.6	53.2	1.9	1.7
1D2	2	165	-20	60-90	14.3	21.4	57.2	3.6	1.2
1D2	2	165	-20	90-120	15.8	23.2	4.0	3.2	1.4
1D2	3	90	0	0-15	15.9	17.6	5.7	2.0	3.2
1D2	3	90	0	15-30	13.2	15.3	3.6	3.0	2.4
1D2	3	90	0	30-60	13.6	18.7	199.6	3.3	2.6
1D2	3	90	0	60-90	18.1	27.0	127.1	3.7	2.3
1D2	3	90	0	90-120	-	-	-	<0.1	<0.1
1D2	4	165	0	0-15	18.7	20.7	7.8	4.7	6.5
1D2	4	165	0	15-30	21.7	25.3	17.5	2.8	24.4
1D2	4	165	0	30-60	14.9	20.5	44.4	3.8	7.0
1D2	4	165	0	60-90	15.6	23.2	114.2	1.7	2.5
1D2	4	165	0	90-120	17.5	25.7	6.7	3.7	5.6
1D2	5	240	0	0-15	14.4	16.0	22.2	2.0	6.2
1D2	5	240	0	15-30	15.0	17.5	33.9	1.8	2.9
1D2	5	240	0	30-60	14.4	19.8	152.5	1.4	1.9
1D2	5	240	0	60-90	11.8	17.6	91.8	1.9	1.4
1D2	5	240	0	90-120	15.8	23.1	22.8	2.9	1.8
1D2	6	90	20	0-15	15.4	17.0	5.1	2.0	3.0
1D2	6	90	20	15-30	11.7	13.6	3.3	2.2	1.6
1D2	6	90	20	30-60	9.4	12.9	14.6	1.5	1.8
1D2	6	90	20	60-90	14.0	20.9	7.6	2.0	2.0
1D2	6	90	20	90-120	15.3	22.5	1.9	3.8	3.0
1D2	7	165	20	0-15	17.2	19.1	3.1	4.7	7.4
1D2	7	165	20	15-30	16.6	19.4	5.7	3.9	1.7
1D2	7	165	20	30-60	12.1	16.6	5.1	5.6	4.0
1D2	7	165	20	60-90	17.5	26.1	4.1	3.8	2.8
1D2	7	165	20	90-120	16.0	23.5	0.4	3.2	4.9
1D2	8	240	20	0-15	16.0	17.7	11.5	2.2	5.0
1D2	8	240	20	15-30	13.5	15.7	9.4	1.5	1.5
1D2	8	240	20	30-60	12.0	16.5	5.6	5.7	1.7
1D2	8	240	20	60-90	12.1	18.0	4.5	5.2	1.9
1D2	8	240	20	90-120	16.3	23.9	2.0	4.2	1.4
1D2	9	90	60	0-15	14.9	16.4	0.8	2.0	5.6
1D2	9	90	60	15-30	13.2	15.4	0.5	1.7	3.2
1D2	9	90	60	30-60	8.9	12.2	0.4	1.7	1.8
1D2	9	90	60	60-90	12.4	18.4	0.5	4.5	2.6
1D2	10	165	60	0-15	14.9	16.4	1.1	1.9	1.0
1D2	10	165	60	15-30	12.9	15.0	0.4	4.6	2.6
1D2	10	165	60	30-60	12.0	16.4	0.3	3.4	1.3
1D2	10	165	60	60-90	15.9	23.7	0.4	2.9	2.2
1D2	11	240	60	0-15	14.1	15.6	0.5	2.0	1.5
1D2	11	240	60	15-30	13.0	15.1	0.4	2.3	3.0
1D2	11	240	60	30-60	13.2	18.1	0.3	3.6	2.8
1D2	11	240	60	60-90	10.1	15.1	0.3	3.3	2.1
1D2	12	90	140	0-15	15.0	16.6	0.7	2.3	5.8
1D2	12	90	140	15-30	15.3	17.8	0.3	1.7	2.0
1D2	12	90	140	30-60	10.7	14.7	0.0	3.5	2.9
1D2	13	165	140	0-15	14.3	15.8	0.4	2.4	0.3
1D2	13	165	140	15-30	12.5	14.5	0.3	1.7	2.4
1D2	13	165	140	30-60	11.7	16.0	0.3	1.9	2.1
1D2	14	240	140	0-15	15.1	16.7	0.9	2.4	0.5
1D2	14	240	140	15-30	13.7	16.0	0.4	1.8	0.8
1D2	14	240	140	30-60	10.0	13.7	0.8	5.4	3.3
1D2	15	90	220	0-15	16.7	18.5	1.0	6.9	4.9
1D2	15	90	220	15-30	16.4	19.1	0.3	4.8	2.7
1D2	16	165	220	0-15	14.7	16.3	0.3	2.1	8.8
1D2	16	165	220	15-30	14.3	16.6	0.2	2.5	4.0
1D2	17	240	220	0-15	16.2	17.9	0.3	1.9	7.3
1D2	17	240	220	15-30	14.4	16.8	0.3	1.9	2.6

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm		%			ppm	
1D3	1	165	-40	0-15	15.8	18.8	3.8	4.5	7.1
1D3	1	165	-40	15-30	15.1	20.7	2.8	1.3	4.6
1D3	1	165	-40	30-60	18.4	23.5	1.2	5.2	2.8
1D3	2	165	-20	0-15	16.2	19.3	4.0	2.8	4.5
1D3	2	165	-20	15-30	14.2	19.5	4.8	3.9	2.6
1D3	2	165	-20	30-60	18.7	23.9	5.6	4.0	2.5
1D3	2	165	-20	60-90	17.1	22.7	5.7	5.5	2.4
1D3	2	165	-20	90-120	17.3	25.2	4.4	5.1	5.8
1D3	3	90	0	0-15	14.7	17.5	40.8	4.0	11.9
1D3	3	90	0	15-30	14.2	19.5	26.2	1.9	6.9
1D3	3	90	0	30-60	13.2	16.9	171.4	4.9	5.3
1D3	3	90	0	60-90	14.6	19.4	125.2	5.7	8.7
1D3	3	90	0	90-120	19.4	28.3	35.7	5.9	6.4
1D3	4	165	0	0-15	17.1	20.3	24.1	3.9	10.1
1D3	4	165	0	15-30	16.3	22.3	41.7	2.2	4.5
1D3	4	165	0	30-60	18.4	23.5	119.2	4.6	3.1
1D3	4	165	0	60-90	17.2	22.9	12.8	2.3	2.5
1D3	4	165	0	90-120	15.8	22.9	0.9	3.1	5.5
1D3	5	240	0	0-15	14.2	16.8	55.9	3.8	7.1
1D3	5	240	0	15-30	14.5	19.9	108.1	3.6	3.9
1D3	5	240	0	30-60	15.4	19.7	143.2	4.7	3.9
1D3	5	240	0	60-90	19.1	25.3	18.2	2.7	3.3
1D3	5	240	0	90-120	15.2	22.1	3.8	3.1	6.0
1D3	6	90	20	0-15	15.0	17.9	5.4	2.9	7.8
1D3	6	90	20	15-30	14.1	19.4	6.2	2.0	3.3
1D3	6	90	20	30-60	12.7	16.3	70.8	3.4	3.2
1D3	6	90	20	60-90	17.0	22.5	81.5	4.4	3.5
1D3	6	90	20	90-120	18.3	26.6	5.5	3.6	3.2
1D3	7	165	20	0-15	14.7	17.5	18.3	4.0	8.4
1D3	7	165	20	15-30	15.2	20.9	15.7	4.9	7.3
1D3	7	165	20	30-60	16.9	21.6	160.4	7.2	4.1
1D3	7	165	20	60-90	17.9	23.7	152.7	4.0	3.3
1D3	7	165	20	90-120	-	-	-	-	-
1D3	8	240	20	0-15	16.1	19.1	33.8	4.9	6.5
1D3	8	240	20	15-30	15.4	21.1	64.3	3.1	4.2
1D3	8	240	20	30-60	13.0	16.6	140.1	6.0	6.5
1D3	8	240	20	60-90	13.9	18.4	31.6	4.0	5.2
1D3	8	240	20	90-120	16.9	24.6	4.5	3.6	4.5
1D3	9	90	60	0-15	14.8	17.5	2.9	3.6	4.6
1D3	9	90	60	15-30	15.0	20.5	3.5	2.2	4.1
1D3	9	90	60	30-60	12.4	15.8	1.7	3.9	3.3
1D3	9	90	60	60-90	18.6	24.7	2.3	3.6	2.0
1D3	10	165	60	0-15	15.9	18.9	28.5	5.8	13.7
1D3	10	165	60	15-30	15.7	21.6	18.6	5.0	8.4
1D3	10	165	60	30-60	22.9	29.2	51.7	4.5	4.2
1D3	10	165	60	60-90	17.1	22.6	8.2	3.3	2.0
1D3	11	240	60	0-15	15.2	18.0	10.1	4.6	8.0
1D3	11	240	60	15-30	13.3	18.3	3.5	2.1	3.0
1D3	11	240	60	30-60	9.6	12.3	11.6	5.2	5.3
1D3	11	240	60	60-90	9.4	12.5	10.7	5.2	3.7
1D3	12	90	140	0-15	13.8	16.4	0.8	5.3	5.7
1D3	12	90	140	15-30	11.2	15.5	0.5	3.2	3.0
1D3	12	90	140	30-60	14.1	18.0	0.5	1.6	2.0
1D3	13	165	140	0-15	16.2	19.3	2.0	3.8	8.5
1D3	13	165	140	15-30	14.1	19.3	1.7	2.2	5.8
1D3	13	165	140	30-60	12.3	15.7	0.0	2.2	4.4
1D3	14	240	140	0-15	14.9	17.7	9.9	3.9	12.7
1D3	14	240	140	15-30	14.4	19.8	1.4	1.3	4.3
1D3	14	240	140	30-60	12.8	16.4	1.2	1.2	3.3
1D3	15	90	220	0-15	16.0	19.0	0.4	1.3	6.9
1D3	15	90	220	15-30	13.4	18.5	0.3	5.1	2.6
1D3	16	165	220	0-15	16.3	19.4	0.3	2.0	10.7
1D3	16	165	220	15-30	14.5	19.9	0.3	3.1	4.0
1D3	17	240	220	0-15	15.5	18.4	0.0	1.3	7.4
1D3	17	240	220	15-30	14.6	20.0	1.4	1.2	5.0
1T1	1	165	-40	0-15	19.4	25.7	3.2	2.7	6.7

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm		%			ppm	
1T1	1	165	-40	15-30	16.5	24.1	9.7	3.6	11.0
1T1	1	165	-40	30-60	17.6	23.3	9.7	2.8	5.7
1T1	2	165	-20	0-15	20.0	26.5	12.8	3.8	16.3
1T1	2	165	-20	15-30	17.8	26.0	8.7	2.7	8.0
1T1	2	165	-20	30-60	18.1	24.0	47.5	4.2	4.0
1T1	2	165	-20	60-90	21.7	34.4	19.3	4.3	3.9
1T1	2	165	-20	90-120	20.0	40.4	2.6	4.5	6.4
1T1	3	90	0	0-15	20.7	27.4	92.9	3.8	6.6
1T1	3	90	0	15-30	17.6	25.6	132.0	2.6	3.1
1T1	3	90	0	30-60	20.3	26.9	137.4	3.9	3.3
1T1	3	90	0	60-90	25.0	39.7	161.7	3.6	2.1
1T1	3	90	0	90-120	19.3	38.9	1.6	3.1	2.6
1T1	4	165	0	0-15	19.8	26.3	87.4	3.4	28.9
1T1	4	165	0	15-30	17.1	24.9	179.6	2.1	5.3
1T1	4	165	0	30-60	17.3	22.9	178.7	2.9	4.7
1T1	4	165	0	60-90	20.8	32.9	34.1	2.4	4.0
1T1	4	165	0	90-120	13.1	26.5	1.2	3.0	3.5
1T1	5	240	0	0-15	19.6	25.9	12.0	3.7	7.4
1T1	5	240	0	15-30	18.4	26.8	48.0	3.2	4.5
1T1	5	240	0	30-60	15.1	19.9	113.7	2.5	4.2
1T1	5	240	0	60-90	16.4	26.1	35.5	2.4	6.0
1T1	5	240	0	90-120	17.5	35.4	2.1	3.2	6.2
1T1	6	90	20	0-15	20.0	26.5	52.5	9.6	10.0
1T1	6	90	20	15-30	18.5	27.0	103.6	2.5	5.6
1T1	6	90	20	30-60	20.3	26.9	54.0	2.6	2.6
1T1	6	90	20	60-90	25.4	40.3	5.9	2.9	2.7
1T1	6	90	20	90-120	21.5	43.6	1.0	3.6	4.1
1T1	7	165	20	0-15	21.4	28.3	64.3	3.6	17.8
1T1	7	165	20	15-30	18.3	26.7	69.7	3.4	7.9
1T1	7	165	20	30-60	14.1	18.6	30.2	3.0	3.3
1T1	7	165	20	60-90	21.1	33.5	3.8	3.4	3.3
1T1	7	165	20	90-120	23.6	47.8	1.7	3.8	5.6
1T1	8	240	20	0-15	21.5	28.5	15.2	4.5	8.0
1T1	8	240	20	15-30	17.0	24.9	15.5	3.1	5.0
1T1	8	240	20	30-60	15.2	20.1	41.9	2.7	3.8
1T1	8	240	20	60-90	15.5	24.7	10.0	2.9	4.4
1T1	8	240	20	90-120	18.5	37.4	0.4	4.0	7.0
1T1	9	90	60	0-15	19.7	26.1	17.5	3.5	5.9
1T1	9	90	60	15-30	18.4	26.9	15.6	2.6	4.0
1T1	9	90	60	30-60	20.1	26.6	3.7	2.5	0.3
1T1	9	90	60	60-90	27.2	43.2	1.0	2.9	1.5
1T1	10	165	60	0-15	20.8	27.6	10.3	2.7	4.2
1T1	10	165	60	15-30	18.7	27.3	14.0	2.6	2.7
1T1	10	165	60	30-60	18.6	24.7	16.7	2.2	3.2
1T1	10	165	60	60-90	18.9	30.0	0.8	3.1	2.9
1T1	11	240	60	0-15	20.5	27.2	4.3	2.5	10.5
1T1	11	240	60	15-30	17.7	25.9	3.9	2.3	4.5
1T1	11	240	60	30-60	15.8	21.0	1.4	2.1	3.0
1T1	11	240	60	60-90	15.7	24.8	0.9	2.4	3.2
1T1	12	90	140	0-15	20.2	26.7	1.2	4.0	7.3
1T1	12	90	140	15-30	17.2	25.1	1.4	3.7	4.8
1T1	12	90	140	30-60	19.1	25.2	0.7	3.5	4.1
1T1	13	165	140	0-15	21.9	28.9	5.1	2.7	47.8
1T1	13	165	140	15-30	20.0	29.2	3.0	2.9	10.6
1T1	13	165	140	30-60	22.8	30.2	1.6	2.3	10.5
1T1	14	240	140	0-15	21.7	28.7	0.8	2.7	11.5
1T1	14	240	140	15-30	16.1	23.5	0.7	3.4	5.6
1T1	14	240	140	30-60	19.4	25.7	0.6	2.9	5.4
1T1	15	90	220	0-15	20.4	27.0	1.8	2.9	14.6
1T1	15	90	220	15-30	18.3	26.7	1.4	2.4	6.7
1T1	16	165	220	0-15	21.5	28.4	0.9	3.1	13.4
1T1	16	165	220	15-30	17.2	25.1	0.5	2.9	4.4
1T1	17	240	220	0-15	21.3	28.2	0.6	3.2	12.8
1T1	17	240	220	15-30	16.1	23.5	0.3	4.0	5.4
1T2	1	165	-40	0-15	15.9	19.4	4.0	4.9	21.0
1T2	1	165	-40	15-30	12.7	22.6	3.1	2.9	5.0

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
1T2	1	165	-40	30-60	9.3	13.5	2.7	4.8	4.9
1T2	2	165	-20	0-15	16.8	20.4	12.8	6.7	19.7
1T2	2	165	-20	15-30	13.8	24.5	8.2	3.7	5.1
1T2	2	165	-20	30-60	9.7	14.1	92.2	4.0	2.9
1T2	2	165	-20	60-90	22.6	33.3	110.6	3.4	3.9
1T2	2	165	-20	90-120	8.6	14.0	19.1	5.1	5.8
1T2	3	90	0	0-15	17.7	21.6	92.7	7.9	49.4
1T2	3	90	0	15-30	12.9	22.9	30.7	3.9	8.6
1T2	3	90	0	30-60	12.1	17.6	138.8	3.6	4.3
1T2	3	90	0	60-90	18.6	27.4	95.7	3.1	4.0
1T2	3	90	0	90-120	18.4	29.9	4.7	2.8	7.1
1T2	4	165	0	0-15	16.5	20.0	49.0	4.9	16.6
1T2	4	165	0	15-30	13.9	24.8	21.4	2.7	5.4
1T2	4	165	0	30-60	10.8	15.7	99.6	2.8	4.3
1T2	4	165	0	60-90	16.6	24.4	98.6	4.2	4.9
1T2	4	165	0	90-120	8.6	13.9	23.6	2.9	4.7
1T2	5	240	0	0-15	15.3	18.6	23.8	2.6	7.7
1T2	5	240	0	15-30	13.3	23.6	29.2	2.8	5.1
1T2	5	240	0	30-60	10.8	15.8	121.9	3.1	4.0
1T2	5	240	0	60-90	18.3	27.0	92.5	3.1	2.8
1T2	5	240	0	90-120	14.7	23.8	25.3	4.4	7.6
1T2	6	90	20	0-15	17.4	21.2	79.0	8.5	47.9
1T2	6	90	20	15-30	14.8	26.3	6.1	3.3	5.0
1T2	6	90	20	30-60	14.4	21.0	29.9	2.8	5.4
1T2	6	90	20	60-90	19.0	28.1	9.9	2.7	4.9
1T2	6	90	20	90-120	18.0	29.2	3.6	2.7	7.0
1T2	7	165	20	0-15	16.1	19.6	59.1	6.8	19.2
1T2	7	165	20	15-30	13.9	24.7	17.4	3.2	4.5
1T2	7	165	20	30-60	12.3	17.9	45.7	1.8	3.0
1T2	7	165	20	60-90	11.0	16.3	41.2	3.8	4.8
1T2	7	165	20	90-120	-	-	-	-	-
1T2	8	240	20	0-15	15.2	18.5	23.8	3.6	5.2
1T2	8	240	20	15-30	13.7	24.3	12.3	6.3	2.3
1T2	8	240	20	30-60	11.0	16.1	17.2	3.0	2.8
1T2	8	240	20	60-90	12.4	18.3	38.8	3.0	2.4
1T2	8	240	20	90-120	3.4	5.5	3.0	2.0	1.7
1T2	9	90	60	0-15	17.0	20.6	52.8	4.5	18.0
1T2	9	90	60	15-30	17.1	30.4	6.3	2.9	7.3
1T2	9	90	60	30-60	17.3	25.3	3.9	4.5	3.6
1T2	9	90	60	60-90	17.8	26.2	3.2	3.6	3.0
1T2	10	165	60	0-15	18.3	22.2	64.5	3.9	26.4
1T2	10	165	60	15-30	13.7	24.3	18.9	2.5	4.6
1T2	10	165	60	30-60	9.3	13.6	9.1	3.8	2.4
1T2	10	165	60	60-90	8.7	12.8	13.4	2.8	6.5
1T2	11	240	60	0-15	15.2	18.4	6.5	4.8	5.4
1T2	11	240	60	15-30	15.0	26.8	2.9	3.1	2.2
1T2	11	240	60	30-60	9.4	13.8	1.3	0.6	1.7
1T2	11	240	60	60-90	4.8	7.1	0.9	3.7	2.6
1T2	12	90	140	0-15	17.2	20.9	3.4	8.6	32.1
1T2	12	90	140	15-30	16.5	29.3	1.3	4.7	5.0
1T2	12	90	140	30-60	18.6	27.2	0.7	2.7	3.4
1T2	13	165	140	0-15	16.4	20.0	20.2	5.6	31.8
1T2	13	165	140	15-30	13.4	23.9	1.9	3.3	4.5
1T2	13	165	140	30-60	8.2	11.9	1.0	2.2	3.8
1T2	14	240	140	0-15	16.5	20.0	0.6	3.0	6.8
1T2	14	240	140	15-30	13.1	23.3	0.4	3.5	2.1
1T2	14	240	140	30-60	11.6	16.9	0.4	0.7	1.9
1T2	15	90	220	0-15	16.7	20.3	1.0	6.9	26.4
1T2	15	90	220	15-30	17.1	30.5	0.5	3.1	4.5
1T2	16	165	220	0-15	18.0	21.9	8.9	5.6	37.1
1T2	16	165	220	15-30	15.2	27.1	0.7	2.7	5.7
1T2	17	240	220	0-15	17.9	21.8	0.8	2.8	9.9
1T2	17	240	220	15-30	16.9	30.1	0.3	3.3	4.2
1T3	1	165	-40	0-15	15.7	17.9	61.9	5.0	44.0
1T3	1	165	-40	15-30	12.8	18.9	6.5	3.4	8.5
1T3	1	165	-40	30-60	14.0	20.5	9.2	4.2	7.1

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
1T3	2	165	-20	0-15	16.5	18.8	43.7	4.6	18.6
1T3	2	165	-20	15-30	15.2	22.4	4.7	2.6	0.7
1T3	2	165	-20	30-60	11.7	17.2	6.9	3.5	5.4
1T3	2	165	-20	60-90	9.3	14.6	34.3	4.8	14.2
1T3	2	165	-20	90-120	10.3	16.8	28.9	4.1	7.8
1T3	3	90	0	0-15	16.7	19.0	15.6	5.0	28.4
1T3	3	90	0	15-30	15.6	23.0	10.1	3.1	9.9
1T3	3	90	0	30-60	9.9	14.5	11.3	3.0	4.4
1T3	3	90	0	60-90	8.5	13.4	92.6	4.6	3.7
1T3	3	90	0	90-120	11.2	18.3	12.7	3.6	5.9
1T3	4	165	0	0-15	16.6	18.9	102.7	5.9	27.8
1T3	4	165	0	15-30	15.4	22.7	17.3	3.5	7.9
1T3	4	165	0	30-60	14.1	20.6	35.4	3.8	5.8
1T3	4	165	0	60-90	18.3	28.7	235.8	4.0	14.6
1T3	4	165	0	90-120	11.6	18.9	73.2	4.7	10.9
1T3	5	240	0	0-15	14.9	16.9	12.9	2.8	7.6
1T3	5	240	0	15-30	13.6	20.0	11.9	3.8	7.6
1T3	5	240	0	30-60	13.4	19.6	253.8	3.8	4.2
1T3	5	240	0	60-90	11.3	17.7	66.1	4.4	3.6
1T3	5	240	0	90-120	13.5	22.2	26.0	4.1	5.6
1T3	6	90	20	0-15	17.4	19.9	6.0	3.3	28.8
1T3	6	90	20	15-30	14.6	21.6	4.8	0.6	7.3
1T3	6	90	20	30-60	12.2	17.8	43.6	1.1	5.6
1T3	6	90	20	60-90	11.2	17.6	85.4	3.8	5.2
1T3	6	90	20	90-120	8.8	14.4	15.8	4.8	6.4
1T3	7	165	20	0-15	15.7	17.9	63.2	4.0	21.7
1T3	7	165	20	15-30	14.0	20.7	17.3	2.7	7.3
1T3	7	165	20	30-60	13.9	20.4	75.6	4.6	7.3
1T3	7	165	20	60-90	16.2	25.4	89.2	3.4	3.4
1T3	7	165	20	90-120	8.2	13.4	6.0	5.9	3.9
1T3	8	240	20	0-15	13.7	15.6	14.3	5.6	5.7
1T3	8	240	20	15-30	10.3	15.3	12.5	3.5	5.1
1T3	8	240	20	30-60	12.3	18.0	79.8	3.4	3.3
1T3	8	240	20	60-90	7.8	12.2	19.4	4.3	2.5
1T3	8	240	20	90-120	10.9	17.8	7.3	4.4	2.4
1T3	9	90	60	0-15	15.0	17.1	2.4	7.2	27.8
1T3	9	90	60	15-30	13.8	20.3	2.2	3.8	5.7
1T3	9	90	60	30-60	14.1	20.6	1.9	3.4	5.0
1T3	9	90	60	60-90	14.2	22.2	0.5	3.9	3.3
1T3	10	165	60	0-15	14.7	16.8	26.4	5.9	23.1
1T3	10	165	60	15-30	12.0	17.6	4.5	3.3	3.9
1T3	10	165	60	30-60	13.6	20.0	11.6	3.7	3.3
1T3	10	165	60	60-90	9.9	15.6	9.9	3.9	2.3
1T3	11	240	60	0-15	13.5	15.4	2.0	2.5	7.4
1T3	11	240	60	15-30	12.0	17.7	0.7	0.4	0.7
1T3	11	240	60	30-60	10.3	15.1	0.5	3.3	2.9
1T3	11	240	60	60-90	16.5	25.9	0.9	4.8	1.4
1T3	12	90	140	0-15	14.6	16.7	0.8	8.2	60.0
1T3	12	90	140	15-30	13.2	19.5	0.0	3.9	8.2
1T3	12	90	140	30-60	11.4	16.7	0.0	3.7	9.5
1T3	13	165	140	0-15	14.1	16.1	5.8	4.4	32.2
1T3	13	165	140	15-30	12.2	18.0	0.5	1.9	5.5
1T3	13	165	140	30-60	11.8	17.3	0.4	0.9	5.5
1T3	14	240	140	0-15	13.8	15.8	0.0	1.5	10.5
1T3	14	240	140	15-30	12.3	18.2	0.3	0.1	3.3
1T3	14	240	140	30-60	10.8	15.8	0.0	0.1	3.0
1T3	15	90	220	0-15	17.9	20.4	0.6	4.3	44.8
1T3	15	90	220	15-30	15.4	22.7	0.4	3.9	9.8
1T3	16	165	220	0-15	14.7	16.7	0.3	1.6	16.2
1T3	16	165	220	15-30	13.2	19.5	0.0	2.1	5.9
1T3	17	240	220	0-15	13.5	15.4	0.2	0.3	8.4
1T3	17	240	220	15-30	11.6	17.1	0.2	1.7	3.9
1A1	1	165	-40	0-15	25.4	27.6	2.9	2.1	47.2
1A1	1	165	-40	15-30	29.5	34.9	27.0	2.0	57.3
1A1	1	165	-40	30-60	17.9	25.3	71.0	1.1	40.9
1A1	2	165	-20	0-15	29.3	31.8	18.8	2.1	42.6

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
1A1	2	165	-20	15-30	26.7	31.6	93.9	1.4	76.5
1A1	2	165	-20	30-60	16.6	23.3	88.4	1.0	45.9
1A1	2	165	-20	60-90	24.8	36.6	77.3	1.2	28.9
1A1	2	165	-20	90-120	23.3	36.9	24.3	2.0	14.6
1A1	3	90	0	0-15	29.3	31.8	40.4	2.4	94.5
1A1	3	90	0	15-30	26.2	31.0	37.6	1.7	82.4
1A1	3	90	0	30-60	21.3	30.0	7.4	1.3	42.5
1A1	3	90	0	60-90	22.7	33.4	13.0	1.1	20.7
1A1	3	90	0	90-120	21.6	34.2	9.8	3.6	42.7
1A1	4	165	0	0-15	27.8	30.2	31.5	2.5	67.0
1A1	4	165	0	15-30	27.4	32.5	71.4	3.0	108.2
1A1	4	165	0	30-60	18.4	25.9	16.9	1.6	48.7
1A1	4	165	0	60-90	23.4	34.5	20.3	1.3	32.4
1A1	4	165	0	90-120	21.9	34.6	7.1	2.7	16.4
1A1	5	240	0	0-15	31.1	33.7	5.1	2.3	58.4
1A1	5	240	0	15-30	29.9	35.3	4.3	1.7	33.6
1A1	5	240	0	30-60	17.1	24.1	6.6	1.5	19.3
1A1	5	240	0	60-90	25.2	37.1	57.7	2.2	30.3
1A1	5	240	0	90-120	25.1	39.7	68.2	2.7	31.7
1A1	6	90	20	0-15	28.3	30.7	4.4	2.4	51.2
1A1	6	90	20	15-30	27.6	32.7	2.8	2.3	57.6
1A1	6	90	20	30-60	18.3	25.8	1.1	1.2	50.0
1A1	6	90	20	60-90	23.7	35.0	1.7	8.2	18.5
1A1	6	90	20	90-120	24.2	38.3	1.2	2.5	17.6
1A1	7	165	20	0-15	29.5	32.0	4.0	3.9	49.1
1A1	7	165	20	15-30	28.0	33.1	6.5	2.4	58.1
1A1	7	165	20	30-60	14.5	20.4	3.6	2.3	43.5
1A1	7	165	20	60-90	24.3	35.8	3.4	1.8	35.6
1A1	7	165	20	90-120	22.4	35.5	2.1	2.7	20.6
1A1	8	240	20	0-15	30.8	33.5	4.0	3.8	82.3
1A1	8	240	20	15-30	30.7	36.3	4.1	2.4	57.4
1A1	8	240	20	30-60	18.4	25.9	3.3	2.6	34.6
1A1	8	240	20	60-90	24.7	36.5	15.9	1.8	42.1
1A1	8	240	20	90-120	29.1	46.1	8.9	2.0	34.1
1A1	9	90	60	0-15	27.9	30.3	2.1	2.6	23.9
1A1	9	90	60	15-30	26.7	31.5	0.5	2.7	61.3
1A1	9	90	60	30-60	22.2	31.3	0.3	2.1	44.4
1A1	9	90	60	60-90	23.4	34.5	0.3	2.4	28.3
1A1	10	165	60	0-15	28.8	31.3	2.8	3.1	80.3
1A1	10	165	60	15-30	28.9	34.1	1.2	2.4	56.7
1A1	10	165	60	30-60	19.0	26.8	1.0	1.7	33.9
1A1	10	165	60	60-90	25.2	37.2	0.9	1.5	42.0
1A1	11	240	60	0-15	28.8	31.2	2.0	3.5	34.5
1A1	11	240	60	15-30	28.5	33.8	0.8	2.6	27.5
1A1	11	240	60	30-60	19.2	27.1	0.6	1.8	11.2
1A1	11	240	60	60-90	25.0	36.8	0.8	2.4	17.8
1A1	12	90	140	0-15	27.6	30.0	0.5	4.0	74.7
1A1	12	90	140	15-30	26.7	31.5	0.4	3.1	59.6
1A1	12	90	140	30-60	19.4	27.4	0.3	1.9	45.5
1A1	13	165	140	0-15	28.3	30.7	0.5	2.9	59.2
1A1	13	165	140	15-30	26.6	31.5	0.3	2.9	61.1
1A1	13	165	140	30-60	18.6	26.2	0.3	2.0	41.9
1A1	14	240	140	0-15	31.0	33.7	0.6	3.5	65.8
1A1	14	240	140	15-30	29.4	34.8	0.5	2.2	33.6
1A1	14	240	140	30-60	19.2	27.0	0.4	2.5	5.9
1A1	15	90	220	0-15	29.7	32.3	0.5	4.8	73.8
1A1	15	90	220	15-30	27.1	32.1	0.4	3.2	61.2
1A1	16	165	220	0-15	28.7	31.2	0.6	4.5	69.3
1A1	16	165	220	15-30	29.0	34.3	0.4	3.2	26.1
1A1	17	240	220	0-15	31.3	33.9	0.5	5.7	32.8
1A1	17	240	220	15-30	31.4	37.2	0.5	3.2	24.5
1A2	1	165	-40	0-15	26.7	29.4	2.4	3.7	66.9
1A2	1	165	-40	15-30	19.2	25.7	2.7	1.7	24.1
1A2	1	165	-40	30-60	22.9	32.1	9.7	2.6	46.3
1A2	2	165	-20	0-15	25.7	28.3	4.1	2.4	49.8
1A2	2	165	-20	15-30	19.6	26.2	9.8	1.8	31.2

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
1A2	2	165	-20	30-60	20.7	28.9	31.8	1.7	493.3
1A2	2	165	-20	60-90	23.4	32.2	34.3	1.9	28.1
1A2	2	165	-20	90-120	26.7	34.9	7.0	4.7	20.9
1A2	3	90	0	0-15	26.2	28.8	4.7	8.0	10.3
1A2	3	90	0	15-30	21.7	29.0	8.2	2.0	13.0
1A2	3	90	0	30-60	19.0	26.6	43.9	1.9	29.0
1A2	3	90	0	60-90	26.6	36.6	116.5	1.5	56.6
1A2	3	90	0	90-120	29.1	38.1	66.3	2.4	54.5
1A2	4	165	0	0-15	25.3	27.8	4.8	2.7	28.6
1A2	4	165	0	15-30	18.3	24.4	5.1	1.9	18.1
1A2	4	165	0	30-60	22.0	30.8	44.7	2.2	40.2
1A2	4	165	0	60-90	26.7	36.7	138.4	6.3	50.0
1A2	4	165	0	90-120	26.9	35.2	26.2	8.4	19.0
1A2	5	240	0	0-15	25.2	27.7	16.7	3.4	9.7
1A2	5	240	0	15-30	17.1	22.8	33.3	1.5	15.9
1A2	5	240	0	30-60	21.0	29.4	45.0	3.0	18.0
1A2	5	240	0	60-90	26.1	35.8	54.7	2.7	20.0
1A2	5	240	0	90-120	27.7	36.2	7.0	6.4	13.2
1A2	6	90	20	0-15	22.9	25.2	2.3	3.3	8.0
1A2	6	90	20	15-30	19.5	26.0	7.2	1.7	4.1
1A2	6	90	20	30-60	19.6	27.5	14.3	2.2	12.0
1A2	6	90	20	60-90	24.9	34.2	24.0	3.5	20.4
1A2	6	90	20	90-120	29.3	38.4	35.0	2.2	29.4
1A2	7	165	20	0-15	24.7	27.2	2.1	3.4	5.5
1A2	7	165	20	15-30	18.4	24.7	3.6	2.5	6.0
1A2	7	165	20	30-60	23.6	32.9	20.6	3.1	40.0
1A2	7	165	20	60-90	27.6	37.8	87.6	3.7	45.2
1A2	7	165	20	90-120	25.9	33.9	21.1	6.2	17.6
1A2	8	240	20	0-15	23.2	25.6	6.8	4.9	8.0
1A2	8	240	20	15-30	17.1	22.9	17.3	2.8	4.1
1A2	8	240	20	30-60	22.0	30.7	34.0	3.4	10.4
1A2	8	240	20	60-90	26.8	36.7	71.3	3.1	29.8
1A2	8	240	20	90-120	26.9	35.2	17.8	17.2	10.7
1A2	9	90	60	0-15	22.8	25.1	2.6	5.3	10.1
1A2	9	90	60	15-30	16.8	22.5	3.0	3.2	6.2
1A2	9	90	60	30-60	22.4	31.3	3.1	2.0	7.3
1A2	9	90	60	60-90	27.8	38.1	12.2	3.1	32.7
1A2	10	165	60	0-15	19.6	21.5	1.9	4.6	6.7
1A2	10	165	60	15-30	22.1	29.5	3.6	2.6	3.4
1A2	10	165	60	30-60	25.8	36.0	18.4	2.4	11.5
1A2	10	165	60	60-90	27.8	38.2	81.7	3.3	34.3
1A2	11	240	60	0-15	19.8	21.8	3.2	4.5	9.6
1A2	11	240	60	15-30	18.2	24.3	3.0	3.0	4.1
1A2	11	240	60	30-60	21.9	30.6	4.5	3.1	4.1
1A2	11	240	60	60-90	23.7	32.6	15.1	2.4	11.0
1A2	12	90	140	0-15	21.3	23.4	1.4	6.5	10.1
1A2	12	90	140	15-30	16.2	21.6	0.9	2.8	3.1
1A2	12	90	140	30-60	23.9	33.4	0.5	2.9	4.4
1A2	13	165	140	0-15	20.5	22.5	1.0	4.7	8.7
1A2	13	165	140	15-30	16.8	22.5	0.4	3.6	1.7
1A2	13	165	140	30-60	24.4	34.1	0.6	2.8	2.1
1A2	14	240	140	0-15	19.6	21.6	1.0	6.6	6.6
1A2	14	240	140	15-30	17.6	23.5	0.5	11.6	2.4
1A2	14	240	140	30-60	23.5	32.8	0.7	8.8	2.1
1A2	15	90	220	0-15	20.4	22.4	0.9	3.8	9.0
1A2	15	90	220	15-30	16.2	21.6	0.5	3.5	2.0
1A2	16	165	220	0-15	19.0	20.9	0.8	3.9	11.0
1A2	16	165	220	15-30	15.7	21.0	0.4	1.7	3.0
1A2	17	240	220	0-15	20.0	22.0	0.8	5.2	10.7
1A2	17	240	220	15-30	15.2	20.3	0.4	2.3	2.6
1A3	1	165	-40	0-15	27.1	28.8	1.7	3.2	12.6
1A3	1	165	-40	15-30	23.2	29.9	1.4	2.3	4.5
1A3	1	165	-40	30-60	17.7	27.1	3.3	2.7	4.5
1A3	2	165	-20	0-15	25.7	27.3	3.1	3.6	8.5
1A3	2	165	-20	15-30	18.4	23.7	3.2	2.3	2.5
1A3	2	165	-20	30-60	17.5	26.8	7.4	2.5	3.2

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
		cm			%		ppm		
1A3	2	165	-20	60-90	15.8	22.3	9.6	2.1	8.0
1A3	2	165	-20	90-120	22.4	37.4	13.7	2.7	14.5
1A3	3	90	0	0-15	28.8	30.6	26.1	3.6	8.5
1A3	3	90	0	15-30	22.4	28.8	33.5	2.5	4.9
1A3	3	90	0	30-60	20.3	31.1	26.7	1.8	12.5
1A3	3	90	0	60-90	22.9	32.2	51.9	2.0	27.2
1A3	3	90	0	90-120	20.7	34.5	58.9	2.3	24.5
1A3	4	165	0	0-15	26.1	27.7	12.2	3.4	11.1
1A3	4	165	0	15-30	19.1	24.7	16.7	2.0	4.8
1A3	4	165	0	30-60	19.8	30.2	35.0	2.1	6.3
1A3	4	165	0	60-90	20.5	28.9	64.7	2.3	13.1
1A3	4	165	0	90-120	-	-	-	-	-
1A3	5	240	0	0-15	23.3	24.7	5.1	2.9	10.0
1A3	5	240	0	15-30	18.4	23.8	12.2	1.9	4.3
1A3	5	240	0	30-60	18.7	28.6	46.9	1.8	2.4
1A3	5	240	0	60-90	20.1	28.3	69.5	1.8	12.0
1A3	5	240	0	90-120	19.6	32.6	37.1	2.7	9.7
1A3	6	90	20	0-15	29.6	31.5	3.1	3.5	11.5
1A3	6	90	20	15-30	21.2	27.4	2.3	1.8	3.5
1A3	6	90	20	30-60	20.7	31.7	3.1	1.6	9.2
1A3	6	90	20	60-90	23.4	32.9	7.2	1.8	18.8
1A3	6	90	20	90-120	23.0	38.3	8.4	2.2	20.0
1A3	7	165	20	0-15	25.9	27.5	4.9	3.5	13.7
1A3	7	165	20	15-30	17.3	22.3	2.8	1.8	2.9
1A3	7	165	20	30-60	21.6	33.1	9.7	2.0	8.3
1A3	7	165	20	60-90	19.5	27.4	18.7	2.6	16.4
1A3	7	165	20	90-120	20.1	33.4	16.3	2.4	10.6
1A3	8	240	20	0-15	25.4	27.0	3.6	3.4	12.3
1A3	8	240	20	15-30	17.0	22.0	2.8	1.8	2.1
1A3	8	240	20	30-60	19.3	29.5	14.5	2.4	1.6
1A3	8	240	20	60-90	22.2	31.3	34.7	3.2	9.6
1A3	8	240	20	90-120	20.2	33.7	14.5	2.5	12.5
1A3	9	90	60	0-15	27.1	28.8	2.0	4.2	10.2
1A3	9	90	60	15-30	24.7	31.9	0.6	3.0	4.8
1A3	9	90	60	30-60	21.2	32.4	1.4	2.1	3.1
1A3	9	90	60	60-90	24.2	34.1	1.7	2.1	19.5
1A3	10	165	60	0-15	24.9	26.4	1.9	4.0	10.0
1A3	10	165	60	15-30	20.3	26.1	0.9	2.3	3.8
1A3	10	165	60	30-60	18.1	27.7	1.2	2.0	2.6
1A3	10	165	60	60-90	22.6	31.9	3.2	2.2	8.0
1A3	11	240	60	0-15	22.7	24.1	8.4	3.5	9.1
1A3	11	240	60	15-30	15.9	20.5	0.6	1.6	1.3
1A3	11	240	60	30-60	19.1	29.2	3.4	2.0	1.6
1A3	11	240	60	60-90	21.1	29.7	1.3	2.2	3.8
1A3	12	90	140	0-15	25.9	27.5	0.6	3.7	7.9
1A3	12	90	140	15-30	18.2	23.5	0.4	1.7	3.2
1A3	12	90	140	30-60	23.4	35.7	0.4	2.1	4.0
1A3	13	165	140	0-15	28.7	30.5	1.3	3.3	11.7
1A3	13	165	140	15-30	19.0	24.5	0.6	2.0	5.0
1A3	13	165	140	30-60	23.2	35.5	0.7	2.2	4.7
1A3	14	240	140	0-15	23.5	24.9	2.2	3.6	13.0
1A3	14	240	140	15-30	18.8	24.3	0.5	1.8	3.3
1A3	14	240	140	30-60	19.0	29.0	0.5	1.9	2.3
1A3	15	90	220	0-15	26.3	27.9	0.8	3.6	8.3
1A3	15	90	220	15-30	23.5	30.4	0.4	2.8	7.2
1A3	16	165	220	0-15	25.9	27.5	0.6	15.3	14.9
1A3	16	165	220	15-30	18.1	23.3	0.4	1.7	4.5
1A3	17	240	220	0-15	25.4	26.9	0.4	2.5	19.0
1A3	17	240	220	15-30	18.3	23.7	0.4	1.9	4.4
2D	1	165	-40	0-15	21.8	24.3	5.0	2.9	5.5
2D	1	165	-40	15-30	17.9	28.8	6.3	3.3	13.6
2D	1	165	-40	30-60	16.4	28.2	4.2	2.7	1.7
2D	2	165	-20	0-15	20.7	23.0	8.2	2.4	13.1
2D	2	165	-20	15-30	17.2	27.8	17.5	2.9	3.0
2D	2	165	-20	30-60	17.6	30.2	47.1	2.6	1.8
2D	2	165	-20	60-90	15.2	24.6	8.1	2.4	2.5

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
2D	2	165	-20	90-120	16.6	28.2	0.3	2.1	1.9
2D	3	90	0	0-15	20.0	22.3	60.5	3.2	9.2
2D	3	90	0	15-30	17.4	28.1	134.6	2.4	5.3
2D	3	90	0	30-60	17.1	29.3	205.3	2.4	1.9
2D	3	90	0	60-90	16.9	27.5	30.5	2.5	1.8
2D	3	90	0	90-120	16.8	28.4	3.0	2.1	3.1
2D	4	165	0	0-15	18.3	20.4	34.9	3.8	15.8
2D	4	165	0	15-30	18.8	30.4	34.7	3.1	6.6
2D	4	165	0	30-60	17.5	30.0	46.5	2.5	3.2
2D	4	165	0	60-90	18.2	29.5	1.1	2.2	2.9
2D	4	165	0	90-120	17.2	29.3	2.9	2.2	1.8
2D	5	240	0	0-15	20.1	22.3	29.3	3.6	12.5
2D	5	240	0	15-30	16.5	26.6	50.6	2.7	3.5
2D	5	240	0	30-60	18.1	31.0	161.6	2.0	2.1
2D	5	240	0	60-90	18.1	29.4	45.9	2.3	2.3
2D	5	240	0	90-120	17.4	29.5	28.4	2.4	3.7
2D	6	90	20	0-15	19.0	21.1	29.4	3.4	5.7
2D	6	90	20	15-30	18.0	29.0	50.9	2.5	3.6
2D	6	90	20	30-60	16.2	27.8	102.9	2.2	2.8
2D	6	90	20	60-90	16.2	26.3	18.7	2.0	1.4
2D	6	90	20	90-120	16.8	28.5	0.7	2.0	2.2
2D	7	165	20	0-15	19.1	21.2	10.7	2.9	8.0
2D	7	165	20	15-30	18.5	29.9	10.6	2.7	3.4
2D	7	165	20	30-60	15.8	27.1	65.5	2.4	2.3
2D	7	165	20	60-90	16.8	27.3	24.5	2.0	1.6
2D	7	165	20	90-120	17.7	30.0	1.3	1.9	2.9
2D	8	240	20	0-15	21.1	23.5	20.0	3.6	25.1
2D	8	240	20	15-30	17.5	28.2	5.5	3.6	6.5
2D	8	240	20	30-60	16.5	28.3	2.7	2.3	2.7
2D	8	240	20	60-90	16.4	26.5	5.0	2.4	4.8
2D	8	240	20	90-120	17.5	29.8	3.3	2.8	5.7
2D	9	90	60	0-15	20.6	22.8	5.2	3.8	8.8
2D	9	90	60	15-30	18.4	29.8	2.5	3.6	4.3
2D	9	90	60	30-60	13.5	23.1	0.5	2.1	1.7
2D	9	90	60	60-90	14.7	23.8	0.6	2.2	1.8
2D	10	165	60	0-15	15.9	17.7	2.2	4.5	10.0
2D	10	165	60	15-30	14.3	23.1	0.5	2.3	2.6
2D	10	165	60	30-60	15.8	27.1	0.7	2.4	2.6
2D	10	165	60	60-90	16.2	26.3	1.1	2.5	1.2
2D	11	240	60	0-15	22.6	25.2	44.3	4.9	34.0
2D	11	240	60	15-30	18.9	30.6	20.5	5.0	8.5
2D	11	240	60	30-60	16.7	28.7	3.2	3.2	4.0
2D	11	240	60	60-90	17.4	28.2	1.7	9.1	5.8
2D	12	90	140	0-15	17.3	19.2	22.8	4.2	26.0
2D	12	90	140	15-30	16.4	26.4	2.9	3.6	3.1
2D	12	90	140	30-60	17.1	29.3	5.7	2.8	5.1
2D	13	165	140	0-15	20.5	22.8	15.7	4.6	22.8
2D	13	165	140	15-30	17.3	27.9	6.5	2.9	5.0
2D	13	165	140	30-60	14.7	25.2	1.2	2.1	2.0
2D	14	240	140	0-15	19.4	21.5	0.6	4.1	16.1
2D	14	240	140	15-30	18.5	29.9	0.6	4.1	2.5
2D	14	240	140	30-60	16.1	27.7	0.4	2.7	4.1
2D	15	90	220	0-15	22.2	24.6	0.9	5.1	16.5
2D	15	90	220	15-30	18.6	30.0	0.4	2.5	4.7
2D	16	165	220	0-15	20.8	23.1	0.5	5.6	20.3
2D	16	165	220	15-30	18.7	30.2	0.4	3.2	5.0
2D	17	240	220	0-15	21.9	24.4	0.5	3.7	16.0
2D	17	240	220	15-30	20.9	33.8	0.5	3.6	3.6
2T	1	165	-40	0-15	21.6	26.4	0.4	3.2	22.7
2T	1	165	-40	15-30	19.4	30.9	0.6	2.1	4.1
2T	1	165	-40	30-60	18.1	30.3	0.3	2.4	2.0
2T	2	165	-20	0-15	19.4	23.6	3.2	2.3	9.2
2T	2	165	-20	15-30	19.9	31.6	2.8	1.6	4.0
2T	2	165	-20	30-60	18.3	30.7	4.4	2.5	2.3
2T	2	165	-20	60-90	18.2	30.9	0.5	2.3	1.3
2T	2	165	-20	90-120	18.8	32.1	0.5	2.2	1.9

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
2T	3	90	0	0-15	21.0	25.7	7.8	2.3	14.4
2T	3	90	0	15-30	21.7	34.4	23.8	2.3	6.4
2T	3	90	0	30-60	18.4	31.0	71.9	3.0	11.5
2T	3	90	0	60-90	17.1	29.0	34.8	2.1	3.5
2T	3	90	0	90-120	19.5	33.2	3.7	1.8	5.5
2T	4	165	0	0-15	20.2	24.7	12.3	2.5	11.5
2T	4	165	0	15-30	19.8	31.4	24.4	2.1	4.1
2T	4	165	0	30-60	18.8	31.5	67.3	1.8	2.6
2T	4	165	0	60-90	19.1	32.4	11.6	1.8	2.0
2T	4	165	0	90-120	19.0	32.3	0.9	1.9	2.5
2T	5	240	0	0-15	23.1	28.2	14.0	2.8	22.1
2T	5	240	0	15-30	21.2	33.7	23.7	2.1	5.4
2T	5	240	0	30-60	18.6	31.3	73.8	2.3	2.2
2T	5	240	0	60-90	19.2	32.5	13.2	2.5	1.8
2T	5	240	0	90-120	19.2	32.7	0.7	1.8	3.6
2T	6	90	20	0-15	20.7	25.3	7.2	3.1	11.8
2T	6	90	20	15-30	19.9	31.6	8.8	2.6	4.4
2T	6	90	20	30-60	19.1	32.1	45.9	2.0	3.0
2T	6	90	20	60-90	20.1	34.1	14.6	2.0	3.0
2T	6	90	20	90-120	19.4	33.1	0.6	2.5	1.0
2T	7	165	20	0-15	20.2	24.7	16.2	3.0	12.1
2T	7	165	20	15-30	20.6	32.7	7.7	1.8	3.7
2T	7	165	20	30-60	18.6	31.3	14.2	2.9	4.2
2T	7	165	20	60-90	45.7	77.4	3.7	2.1	2.2
2T	7	165	20	90-120	20.2	34.3	0.8	2.2	2.2
2T	8	240	20	0-15	22.7	27.7	20.7	3.2	16.6
2T	8	240	20	15-30	21.8	34.6	22.2	2.0	5.0
2T	8	240	20	30-60	17.8	29.9	49.6	2.4	3.0
2T	8	240	20	60-90	20.3	34.4	12.5	2.7	5.7
2T	8	240	20	90-120	18.4	31.2	-	1.1	<0.1
2T	9	90	60	0-15	19.4	23.7	11.6	3.0	10.7
2T	9	90	60	15-30	20.3	32.3	9.3	2.3	4.5
2T	9	90	60	30-60	18.8	31.5	4.8	2.4	3.3
2T	9	90	60	60-90	19.2	32.6	1.2	2.6	2.4
2T	10	165	60	0-15	21.2	25.8	9.3	3.5	7.0
2T	10	165	60	15-30	21.0	33.4	9.0	2.0	3.4
2T	10	165	60	30-60	18.4	30.9	4.4	2.6	3.2
2T	10	165	60	60-90	18.4	31.2	1.2	2.3	1.6
2T	11	240	60	0-15	23.0	28.0	11.9	3.9	22.7
2T	11	240	60	15-30	21.2	33.8	11.7	2.1	5.0
2T	11	240	60	30-60	18.4	30.9	12.6	2.4	2.8
2T	11	240	60	60-90	19.4	32.9	2.6	2.4	5.1
2T	12	90	140	0-15	21.2	25.9	1.3	3.0	23.7
2T	12	90	140	15-30	21.4	34.0	1.3	2.0	5.1
2T	12	90	140	30-60	19.0	31.9	0.5	2.5	3.5
2T	13	165	140	0-15	23.8	29.1	3.0	3.4	36.6
2T	13	165	140	15-30	19.8	31.5	1.4	2.3	6.3
2T	13	165	140	30-60	18.2	30.6	0.8	2.8	4.3
2T	14	240	140	0-15	20.2	24.7	5.1	3.0	26.7
2T	14	240	140	15-30	21.1	33.5	2.4	2.5	4.5
2T	14	240	140	30-60	18.3	30.7	0.9	3.1	4.1
2T	15	90	220	0-15	22.6	27.5	1.3	3.3	12.4
2T	15	90	220	15-30	20.6	32.7	1.2	1.9	4.2
2T	16	165	220	0-15	22.7	27.7	2.0	3.7	18.7
2T	16	165	220	15-30	22.1	35.2	2.3	2.4	4.9
2T	17	240	220	0-15	22.4	27.3	4.0	3.7	17.7
2T	17	240	220	15-30	19.4	30.8	3.7	2.3	3.8
2A	1	165	-40	0-15	23.2	25.0	0.4	3.9	4.3
2A	1	165	-40	15-30	23.3	33.0	0.5	2.9	3.4
2A	1	165	-40	30-60	25.5	39.9	0.6	2.4	2.6
2A	2	165	-20	0-15	24.6	26.4	2.5	4.6	17.0
2A	2	165	-20	15-30	21.6	30.6	1.3	2.5	16.6
2A	2	165	-20	30-60	25.8	40.3	0.6	2.7	7.9
2A	2	165	-20	60-90	22.7	34.2	5.6	2.7	13.7
2A	2	165	-20	90-120	19.4	30.1	20.4	2.9	17.3
2A	3	90	0	0-15	24.9	26.7	2.7	3.4	16.7

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
2A	3	90	0	15-30	22.5	31.9	3.0	3.1	9.7
2A	3	90	0	30-60	24.3	38.0	4.3	2.3	5.8
2A	3	90	0	60-90	22.7	34.3	25.9	2.7	11.0
2A	3	90	0	90-120	19.6	30.4	59.8	2.3	13.9
2A	4	165	0	0-15	24.7	26.5	6.6	4.3	43.0
2A	4	165	0	15-30	21.9	31.0	4.3	3.0	13.1
2A	4	165	0	30-60	26.3	41.2	8.7	2.5	8.6
2A	4	165	0	60-90	23.4	35.3	55.1	2.5	17.5
2A	4	165	0	90-120	19.2	29.8	75.1	2.8	19.9
2A	5	240	0	0-15	25.9	27.9	2.8	3.6	16.3
2A	5	240	0	15-30	17.9	25.4	2.5	2.3	10.5
2A	5	240	0	30-60	26.7	41.8	12.6	2.4	6.0
2A	5	240	0	60-90	23.5	35.5	53.9	2.6	13.6
2A	5	240	0	90-120	22.0	34.1	56.8	3.1	15.2
2A	6	90	20	0-15	25.0	26.9	1.9	6.0	9.7
2A	6	90	20	15-30	21.1	29.9	1.1	3.3	9.5
2A	6	90	20	30-60	26.4	41.3	5.2	3.3	4.2
2A	6	90	20	60-90	23.7	35.7	37.0	2.7	10.5
2A	6	90	20	90-120	19.6	30.3	59.7	2.7	14.0
2A	7	165	20	0-15	24.1	25.9	7.1	6.9	29.9
2A	7	165	20	15-30	22.0	31.2	2.7	3.4	14.0
2A	7	165	20	30-60	23.9	37.4	3.8	3.1	4.5
2A	7	165	20	60-90	23.0	34.7	20.0	3.0	4.9
2A	7	165	20	90-120	19.7	30.5	65.8	3.1	12.8
2A	8	240	20	0-15	25.4	27.3	2.8	5.9	13.1
2A	8	240	20	15-30	21.8	31.0	4.2	3.1	19.4
2A	8	240	20	30-60	22.1	34.6	2.3	2.9	0.5
2A	8	240	20	60-90	23.1	34.9	12.5	4.7	2.0
2A	8	240	20	90-120	20.6	31.9	36.0	3.6	8.7
2A	9	90	60	0-15	24.2	26.1	1.0	6.1	9.8
2A	9	90	60	15-30	23.9	33.9	0.4	3.9	7.9
2A	9	90	60	30-60	24.7	38.7	0.5	3.7	3.8
2A	9	90	60	60-90	23.0	34.7	1.4	3.5	2.6
2A	10	165	60	0-15	23.5	25.3	1.0	5.7	10.4
2A	10	165	60	15-30	21.2	30.0	1.1	4.8	3.4
2A	10	165	60	30-60	25.2	39.4	0.5	2.7	<0.1
2A	10	165	60	60-90	22.9	34.6	0.9	3.2	<0.1
2A	11	240	60	0-15	24.8	26.6	1.1	5.6	10.6
2A	11	240	60	15-30	20.7	29.3	0.8	3.7	5.0
2A	11	240	60	30-60	25.6	40.1	3.3	4.3	4.5
2A	11	240	60	60-90	22.9	34.6	0.9	3.4	0.1
2A	12	90	140	0-15	23.8	25.6	1.4	7.8	8.0
2A	12	90	140	15-30	23.6	33.5	0.4	3.7	11.3
2A	12	90	140	30-60	21.6	33.7	0.5	5.5	5.2
2A	13	165	140	0-15	23.8	25.6	0.4	4.4	6.9
2A	13	165	140	15-30	20.0	28.3	0.8	5.3	4.1
2A	13	165	140	30-60	23.7	37.1	0.4	2.7	<0.1
2A	14	240	140	0-15	23.3	25.0	0.5	4.7	9.2
2A	14	240	140	15-30	21.5	30.5	0.4	3.1	4.2
2A	14	240	140	30-60	22.3	34.8	0.4	3.2	2.5
2A	15	90	220	0-15	24.3	26.2	0.4	4.8	12.6
2A	15	90	220	15-30	18.5	26.3	0.2	2.7	4.7
2A	16	165	220	0-15	23.3	25.0	0.5	7.2	0.7
2A	16	165	220	15-30	17.3	24.5	0.5	2.5	<0.1
2A	17	240	220	0-15	24.5	26.3	0.4	4.0	9.9
2A	17	240	220	15-30	17.8	25.2	0.2	3.8	1.6
3D	1	165	-40	0-15	17.0	18.0	2.1	3.4	<0.1
3D	1	165	-40	15-30	18.0	24.4	0.7	2.3	<0.1
3D	1	165	-40	30-60	12.8	19.1	1.3	4.0	1.2
3D	2	165	-20	0-15	18.3	19.4	5.8	3.6	0.2
3D	2	165	-20	15-30	17.3	23.5	4.6	3.0	<0.1
3D	2	165	-20	30-60	15.4	23.1	110.8	3.7	<0.1
3D	2	165	-20	60-90	15.9	23.7	210.3	4.2	<0.1
3D	2	165	-20	90-120	14.0	23.7	46.3	5.6	2.7
3D	3	90	0	0-15	20.6	21.8	3.7	3.8	0.8
3D	3	90	0	15-30	18.5	25.1	1.8	2.9	0.2

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
3D	3	90	0	30-60	17.7	26.5	80.2	3.1	2.9
3D	3	90	0	60-90	16.2	24.2	203.1	4.3	4.6
3D	3	90	0	90-120	16.6	27.9	30.0	3.8	1.6
3D	4	165	0	0-15	18.6	19.7	14.8	3.3	1.4
3D	4	165	0	15-30	18.2	24.7	12.7	2.6	0.2
3D	4	165	0	30-60	18.1	27.1	166.1	2.8	0.3
3D	4	165	0	60-90	15.1	22.5	172.2	4.3	2.7
3D	4	165	0	90-120	15.8	26.7	28.5	5.4	1.6
3D	5	240	0	0-15	19.0	20.1	12.4	3.2	0.6
3D	5	240	0	15-30	17.9	24.3	42.0	3.0	<0.1
3D	5	240	0	30-60	16.2	24.2	115.5	3.1	0.4
3D	5	240	0	60-90	17.3	25.8	80.6	4.2	2.4
3D	5	240	0	90-120	14.6	24.6	13.4	4.6	1.5
3D	6	90	20	0-15	18.8	19.9	2.9	3.6	0.3
3D	6	90	20	15-30	17.2	23.3	1.9	2.5	0.4
3D	6	90	20	30-60	15.8	23.7	27.2	3.7	0.2
3D	6	90	20	60-90	16.2	24.1	99.9	3.8	0.6
3D	6	90	20	90-120	17.1	28.9	6.7	4.1	2.6
3D	7	165	20	0-15	18.9	20.0	8.0	3.2	0.3
3D	7	165	20	15-30	17.9	24.3	9.6	2.3	0.3
3D	7	165	20	30-60	13.0	19.5	76.5	5.0	0.2
3D	7	165	20	60-90	19.3	28.8	94.9	3.3	<0.1
3D	7	165	20	90-120	16.6	28.0	3.5	3.8	1.0
3D	8	240	20	0-15	18.1	19.2	14.9	3.4	0.3
3D	8	240	20	15-30	18.9	25.6	61.1	3.2	<0.1
3D	8	240	20	30-60	16.7	25.0	175.3	3.4	0.4
3D	8	240	20	60-90	14.8	22.1	59.7	3.6	0.2
3D	8	240	20	90-120	15.5	26.1	6.9	4.3	1.7
3D	9	90	60	0-15	20.2	21.4	3.0	4.3	<0.1
3D	9	90	60	15-30	17.9	24.3	2.5	2.5	0.3
3D	9	90	60	30-60	13.9	20.9	1.1	4.0	<0.1
3D	9	90	60	60-90	-	-	-	0.9	<0.1
3D	10	165	60	0-15	17.0	18.0	0.7	3.5	0.3
3D	10	165	60	15-30	16.3	22.2	0.9	2.5	0.3
3D	10	165	60	30-60	15.0	22.4	0.8	3.2	<0.1
3D	10	165	60	60-90	17.1	25.6	1.1	3.5	7.8
3D	11	240	60	0-15	17.9	18.9	0.9	4.1	0.5
3D	11	240	60	15-30	16.4	22.3	1.6	2.2	0.4
3D	11	240	60	30-60	10.8	16.2	0.6	2.6	0.2
3D	11	240	60	60-90	12.9	19.3	0.8	3.6	1.5
3D	12	90	140	0-15	19.6	20.7	0.3	5.7	0.3
3D	12	90	140	15-30	17.4	23.6	0.4	3.3	1.3
3D	12	90	140	30-60	13.9	20.8	1.1	4.1	6.7
3D	13	165	140	0-15	17.6	18.6	1.8	4.2	0.4
3D	13	165	140	15-30	15.8	21.5	2.6	3.4	<0.1
3D	13	165	140	30-60	18.2	27.2	1.6	3.4	<0.1
3D	14	240	140	0-15	16.7	17.6	1.1	3.6	4.8
3D	14	240	140	15-30	17.1	23.2	31.4	3.8	0.4
3D	14	240	140	30-60	14.1	21.1	1.0	3.6	<0.1
3D	15	90	220	0-15	18.6	19.7	0.4	3.8	0.3
3D	15	90	220	15-30	16.6	22.5	5.8	2.1	<0.1
3D	16	165	220	0-15	19.5	20.6	2.1	3.6	3.6
3D	16	165	220	15-30	18.3	24.9	3.8	2.8	0.9
3D	17	240	220	0-15	19.3	20.4	1.0	3.4	32.5
3D	17	240	220	15-30	19.1	25.9	0.8	2.7	<0.1
3T	1	165	-40	0-15	18.9	25.0	1.2	2.8	4.1
3T	1	165	-40	15-30	20.9	31.5	0.9	1.7	1.5
3T	1	165	-40	30-60	22.6	37.5	1.9	1.8	2.5
3T	2	165	-20	0-15	19.1	25.2	6.8	2.5	11.8
3T	2	165	-20	15-30	19.3	29.1	10.7	1.7	3.1
3T	2	165	-20	30-60	30.3	50.3	18.0	2.2	4.1
3T	2	165	-20	60-90	26.1	45.0	2.4	33.2	2.1
3T	2	165	-20	90-120	19.5	33.0	0.8	2.0	6.5
3T	3	90	0	0-15	17.1	22.6	63.7	2.7	19.9
3T	3	90	0	15-30	17.1	25.7	67.8	1.8	11.6
3T	3	90	0	30-60	18.9	31.4	109.7	2.3	13.4

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
3T	3	90	0	60-90	17.4	29.9	11.6	1.9	5.8
3T	3	90	0	90-120	19.2	32.5	16.7	2.3	8.6
3T	4	165	0	0-15	18.5	24.5	24.4	2.6	12.8
3T	4	165	0	15-30	17.5	26.3	42.5	1.4	3.5
3T	4	165	0	30-60	23.6	39.2	148.2	1.7	3.9
3T	4	165	0	60-90	22.8	39.2	42.6	2.1	5.9
3T	4	165	0	90-120	22.8	38.6	1.6	1.6	9.9
3T	5	240	0	0-15	19.9	26.4	88.5	3.0	32.5
3T	5	240	0	15-30	20.9	31.4	58.0	1.6	9.0
3T	5	240	0	30-60	18.0	29.9	85.6	2.3	15.2
3T	5	240	0	60-90	15.5	26.6	8.5	1.6	4.8
3T	5	240	0	90-120	18.5	31.3	2.3	1.8	6.8
3T	6	90	20	0-15	18.3	24.3	113.6	3.0	66.2
3T	6	90	20	15-30	18.6	28.0	119.8	1.9	18.0
3T	6	90	20	30-60	17.3	28.7	138.0	2.2	13.7
3T	6	90	20	60-90	16.5	28.3	52.9	1.7	9.3
3T	6	90	20	90-120	18.5	31.3	11.4	1.8	11.9
3T	7	165	20	0-15	17.7	23.4	24.2	3.1	14.2
3T	7	165	20	15-30	20.1	30.3	75.1	2.2	9.3
3T	7	165	20	30-60	21.3	35.4	155.6	2.9	21.3
3T	7	165	20	60-90	19.9	34.3	34.7	2.5	8.4
3T	7	165	20	90-120	24.9	42.1	1.7	1.9	12.0
3T	8	240	20	0-15	19.2	25.3	116.6	3.9	40.5
3T	8	240	20	15-30	20.5	30.9	72.5	2.4	6.7
3T	8	240	20	30-60	20.2	33.5	98.2	2.5	5.6
3T	8	240	20	60-90	20.0	34.4	5.8	2.2	4.4
3T	8	240	20	90-120	20.3	34.2	2.7	2.1	10.9
3T	9	90	60	0-15	16.9	22.3	21.0	1.7	2.6
3T	9	90	60	15-30	16.9	25.4	28.7	3.3	4.7
3T	9	90	60	30-60	16.0	26.5	5.9	2.4	0.9
3T	9	90	60	60-90	13.9	24.0	1.3	1.9	1.3
3T	10	165	60	0-15	18.9	25.0	15.0	3.9	33.9
3T	10	165	60	15-30	18.4	27.7	3.1	2.0	5.7
3T	10	165	60	30-60	16.3	27.1	8.1	2.5	12.8
3T	10	165	60	60-90	17.2	29.7	6.6	2.4	9.2
3T	11	240	60	0-15	16.7	22.1	34.7	4.1	22.9
3T	11	240	60	15-30	15.6	23.5	15.3	1.9	4.1
3T	11	240	60	30-60	13.0	21.6	37.3	3.2	15.6
3T	11	240	60	60-90	18.8	32.3	9.8	2.2	5.7
3T	12	90	140	0-15	16.8	22.2	3.6	4.5	21.0
3T	12	90	140	15-30	13.8	20.8	1.4	2.6	4.4
3T	12	90	140	30-60	13.9	23.0	1.7	2.4	5.8
3T	13	165	140	0-15	19.6	26.0	10.6	4.3	26.6
3T	13	165	140	15-30	16.1	24.3	1.1	2.3	13.0
3T	13	165	140	30-60	15.6	25.9	3.5	4.3	20.4
3T	14	240	140	0-15	20.0	26.5	2.2	6.2	48.8
3T	14	240	140	15-30	17.3	26.0	1.3	3.8	7.3
3T	14	240	140	30-60	13.9	23.0	0.7	3.0	6.6
3T	15	90	220	0-15	17.3	22.8	1.7	5.6	106.0
3T	15	90	220	15-30	11.6	17.5	0.5	2.9	14.0
3T	16	165	220	0-15	17.8	23.5	0.8	5.6	69.3
3T	16	165	220	15-30	14.6	21.9	0.4	4.6	9.4
3T	17	240	220	0-15	18.3	24.2	0.8	4.9	6.9
3T	17	240	220	15-30	13.7	20.7	1.3	4.0	4.4
3A	1	165	-40	0-15	20.4	24.7	52.6	5.8	2.2
3A	1	165	-40	15-30	14.6	20.1	14.8	1.8	1.4
3A	1	165	-40	30-60	14.2	19.3	16.3	3.1	13.9
3A	2	165	-20	0-15	19.7	23.9	86.6	7.7	9.5
3A	2	165	-20	15-30	15.9	21.8	11.8	3.0	3.8
3A	2	165	-20	30-60	-	-	-	-	-
3A	2	165	-20	60-90	-	-	-	-	-
3A	2	165	-20	90-120	-	-	-	-	-
3A	3	90	0	0-15	19.6	23.8	4.8	4.2	2.0
3A	3	90	0	15-30	12.7	17.4	2.8	2.0	3.7
3A	3	90	0	30-60	10.8	14.7	8.0	2.6	4.9
3A	3	90	0	60-90	17.4	26.3	35.3	4.0	12.4

Plot	Sample Position	DAP	DFP	Depth Sampled	Gravimetric Water Content	Volumetric Water Content	Br^-	Cl^-	NO_3^-
			cm			%		ppm	
3A	3	90	0	90-120	20.4	30.8	18.5	3.2	11.7
3A	4	165	0	0-15	18.7	22.7	5.9	3.3	1.5
3A	4	165	0	15-30	-	-	-	-	-
3A	4	165	0	30-60	-	-	-	-	-
3A	4	165	0	60-90	-	-	-	-	-
3A	4	165	0	90-120	-	-	-	-	-
3A	5	240	0	0-15	18.9	23.0	29.7	3.2	<0.1
3A	5	240	0	15-30	11.4	15.7	4.8	2.4	<0.1
3A	5	240	0	30-60	17.6	23.9	35.6	4.6	12.7
3A	5	240	0	60-90	22.8	34.4	24.6	2.0	11.1
3A	5	240	0	90-120	22.7	34.3	9.7	2.6	12.7
3A	6	90	20	0-15	24.0	29.1	3.4	6.6	1.1
3A	6	90	20	15-30	11.0	15.0	1.8	3.1	1.1
3A	6	90	20	30-60	17.6	24.0	13.6	2.4	8.9
3A	6	90	20	60-90	24.0	36.2	13.5	3.1	15.6
3A	6	90	20	90-120	21.6	32.5	4.3	2.8	12.1
3A	7	165	20	0-15	21.7	26.4	3.8	4.4	0.5
3A	7	165	20	15-30	16.1	22.1	0.9	2.3	2.2
3A	7	165	20	30-60	-	-	-	-	-
3A	7	165	20	60-90	-	-	-	-	-
3A	7	165	20	90-120	-	-	-	-	-
3A	8	240	20	0-15	18.7	22.6	4.5	3.3	<0.1
3A	8	240	20	15-30	13.6	18.6	1.5	2.5	<0.1
3A	8	240	20	30-60	19.2	26.2	4.8	3.3	4.4
3A	8	240	20	60-90	22.8	34.5	9.5	2.3	10.4
3A	8	240	20	90-120	23.9	36.0	6.8	3.4	11.0
3A	9	90	60	0-15	19.2	23.3	6.6	3.9	0.5
3A	9	90	60	15-30	13.2	18.1	2.6	2.7	<0.1
3A	9	90	60	30-60	15.2	20.7	6.2	2.9	3.4
3A	9	90	60	60-90	21.7	32.7	3.8	2.5	11.9
3A	10	165	60	0-15	21.7	26.3	1.8	4.1	0.6
3A	10	165	60	15-30	11.6	16.0	0.8	1.9	3.2
3A	10	165	60	30-60	18.7	25.4	12.8	1.8	4.9
3A	10	165	60	60-90	26.2	39.6	2.4	2.5	16.2
3A	11	240	60	0-15	19.7	23.9	2.5	3.6	0.5
3A	11	240	60	15-30	10.7	14.7	1.8	2.2	<0.1
3A	11	240	60	30-60	20.0	27.2	2.4	2.6	6.6
3A	11	240	60	60-90	24.0	36.3	3.3	2.8	10.4
3A	12	90	140	0-15	20.0	24.3	2.4	3.4	<0.1
3A	12	90	140	15-30	12.5	17.2	2.0	2.3	<0.1
3A	12	90	140	30-60	18.6	25.3	0.6	2.7	<0.1
3A	13	165	140	0-15	14.2	17.3	3.4	3.2	<0.1
3A	13	165	140	15-30	18.3	25.1	2.2	2.9	4.7
3A	13	165	140	30-60	23.9	32.6	2.3	2.8	6.5
3A	14	240	140	0-15	20.3	24.6	0.8	3.7	<0.1
3A	14	240	140	15-30	9.5	13.1	0.8	2.8	0.4
3A	14	240	140	30-60	22.3	30.4	2.2	2.7	7.6
3A	15	90	220	0-15	19.0	23.1	2.2	5.8	0.3
3A	15	90	220	15-30	13.7	18.7	0.7	2.7	<0.1
3A	16	165	220	0-15	21.2	25.7	1.8	3.2	<0.1
3A	16	165	220	15-30	10.0	13.7	1.9	3.2	<0.1
3A	17	240	220	0-15	22.1	26.8	1.7	3.2	<0.1
3A	17	240	220	15-30	20.9	28.7	1.1	3.1	<0.1