Soil suitability for on-site sewage treatment in the Flathead Valley, Montana : soil permeability, variability, and ground-water contamination
by Bruce John Bauman

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Crop and Soil Science
Montana State University

Abstract:
A field study of in situ soil hydraulic conductivity was conducted in the Flathead Valley of northwestern Montana. Of special interest was interpretation of soil properties in terms of suitability for on-site sewage treatment systems. Thirteen sites were selected, soil profiles described and sampled, and the gypsum crust method used to determine hydraulic conductivity at saturation and in the near-saturation range. Multivariate statistical techniques were employed for data analysis.

Results suggest that soil water movement is strongly influenced by the vertical variability (textural stratification) often noted in soil profiles in the study area. Complex glacial and proglacial depositional environments are responsible for this variability, which is. also strongly expressed horizontally as lateral variation across the landscape. Soils formed from similar parent materials (and/or with similar textural properties) generally exhibit similar hydraulic characteristics in the saturated and near-saturated range. Substantial variability within these groups is not uncommon. This variability requires that determination of site/soil suitability for septic systems include on-site observations of soil profile characteristics. The implications of textural stratification within the soil profile need to be considered for proper design and long-term operation of individual on-site sewage treatment systems. Multivariate statistical techniques were employed in analysis of the physical and chemical properties of the soil horizons studied. Principle component analysis was shown to be an effective tool for graphical expression of soil profile variability. Cluster analysis demonstrated the ability of such methods to group horizons with similar properties.

Aquifer assessment should be included as an integral component of the site evaluation process for on-site sewage treatment systems. A simple model has been proposed that is designed to assist local regulatory officials in their efforts to minimize the environmental impacts of sewage treatment from suburban and rural housing developments. The model demonstrates that it is important to estimate the nitrogen load to the receiving aquifer (including the potential for denitrification), evaluate the diluting capacity of the aquifer* and also assess the relative importance of the particular ground-water system.

SOIL SUITABILITY FOR ON-SITE SEWAGE TREATMENT IN THE FLATHEAD VALLEY, MONTANA: SOIL PERMEABILITY, VARIABILITY, AND GROUND-WATER CONTAMINATION

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

March 15, 1985
Date

William N. [illegible]
Chairperson, Graduate Committee

Approved for the Major Department

March 26, 1985
Date

Dwane G. Miller
Head, Major Department

Approved for the College of Graduate Studies

3-27-85
Date

M P Malone
Graduate Dean

STATEMENT OF PERMISSION TO USE

Signature Bruce J Bauman

Date March 20, 1985

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ABSTRACT

A field study of in situ soil hydraulic conductivity was conducted in the Flathead Valley of northwestern Montana. Of special interest was interpretation of soil properties in terms of suitability for on-site sewage treatment systems. Thirteen sites were selected, soil profiles described and sampled, and the gypsum crust method used to determine hydraulic conductivity at saturation and in the near-saturation range. Multivariate statistical techniques were employed for data analysis.

Results suggest that soil water movement is strongly influenced by the vertical variability (textural stratification) often noted in soil profiles in the study area. Complex glacial and proglacial depositional environments are responsible for this variability, which is also strongly expressed horizontally as lateral variation across the landscape. Soils formed from similar parent materials (and/or with similar textural properties) generally exhibit similar hydraulic characteristics in the saturated and near-saturated range. Substantial variability within these groups is not uncommon. This variability requires that determination of site/soil suitability for septic systems include on-site observations of soil profile characteristics. The implications of textural stratification within the soil profile need to be considered for proper design and long-term operation of individual on-site sewage treatment systems. Multivariate statistical techniques were employed in analysis of the physical and chemical properties of the soil horizons studied. Principle component analysis was shown to be an effective tool for graphical expression of soil profile variability. Cluster analysis demonstrated the ability of such methods to group horizons with similar properties.

Aquifer assessment should be included as an integral component of the site evaluation process for on-site sewage treatment systems. A simple model has been proposed that is designed to assist local regulatory officials in their efforts to minimize the environmental impacts of sewage treatment from suburban and rural housing developments. The model demonstrates that it is important to estimate the nitrogen load to the receiving aquifer (including the potential for denitrification), evaluate the diluting capacity of the aquifer, and also assess the relative importance of the particular ground-water system.

INTRODUCTION

Many Americans are attracted to the amenities provided by low-density housing developments in suburban and rural locales. Through the early part of this century, high-density development was the rule, but with the advent of modern transportation systems, rural electrification, and steadily rising disposable income, millions of families have taken up residence in non-urban, low-density developments. This segment of the population of the United States has been growing rapidly. Extension of municipal sewerage to such low-density housing areas is economically prohibitive, necessitating the use of on-site soil treatment methods for the purification and disposal of sewage (U.S. Environmental Protection Agency, 1977). As the number of households employing on-site methods of sewage treatment has increased over the years, concerns have been raised regarding the potential for pollution of both surface and ground-water sources (Woodward et al., 1961).

Generally, the national housing trends outlined above hold true for Montana (U.S. Census Bureau figures for increases in the number of septic systems in Montana counties for the period 1960-1980 are contained in Appendix 1). Specifically, a notable example is the Flathead Valley area in northwestern Montana, which has experienced rapid development in the last 15 years. In this area almost half of all homes employ septic systems as their means of wastewater treatment

(U.S. Bureau of the Census, 1980). Previous to the work described in this report, there has been no scientific examination of the soil properties of this region in relation to hydraulic conductivity and septic system operation.

The primary focus of this study was to evaluate the physical and chemical properties of a variety of soil series in the Flathead Valley, obtain some specific _in situ_ hydraulic conductivity data (saturated and unsaturated flow), and analyze this information in terms of septic system performance. The vastness and variability of the geographical area preclude a comprehensive, basin-wide characterization of soil water movement. However, this study does establish a data base of hydraulic conductivity values in this region of the state.

An underlying goal of this study was to employ multivariate statistical techniques to examine the similarities and differences between sites and horizons. Such methods as principle component analysis, cluster analysis, and discriminant analysis have been widely used as classification tools in the earth sciences, but have only rarely been used to analyze and classify data from soil profiles. The intent was to evaluate their utility in distinguishing groups of soil horizons.

In the past decade there has been increasing concern regarding the environmental consequences of septic sytems, especially in terms of their impact on ground-water quality. This problem is also addressed in this thesis through an examination of the interactions of septic systems, soils, and ground water. The findings of a number of research studies concerning soil treatment of septic tank effluent and ground-water nitrate contamination from septic systems have been evaluated. This information is used to develop a simple model that illustrates relative impact of different environmental parameters on resultant nitrate concentration of ground water. This discussion also demonstrates the importance of aquifer assessment as an integral part of the site evaluation process, and provides a list of factors to be considered for aquifer assessment.

During research into these topics, much was learned about the status of on-site sewage treatment systems in Montana. Summary information concerning the increase of septic systems in Montana counties over the last 20 years is presented in Appendix 1, along with a discussion of regulation of this form of sewage treatment, and suggestions for improvement in state regulation.

SOIL PERMEABILITY, VARIABILITY, AND SEPTIC SYSTEMS IN THE FLATHEAD VALLEY, MONTANA

INTRODUCTION

The typical on-site waste treatment method used in the United States is the septic system, consisting of a septic tank and soil absorption field. The tank serves as a settling basin, providing primary wastewater treatment. Effluent from the tank flows to the soil absorption field, where secondary treatment occurs as the effluent percolates through the soil and geologic strata to the water table (Figure 1). Several soil properties play important roles in determining the efficiency of treatment of septic system effluent. Perhaps the most important is hydraulic conductivity, the rate of water movement through the soil. Accurate assessment of the hydraulic properties of the soil is necessary for proper septic system design. Improper design increases the likelihood of system failure, potentially causing contamination of surface and ground-waters (Bouma, 1971).

In the spring of 1981, a field study was initiated in the Flathead Valley of northwestern Montana, whose focus was to characterize the physical, chemical, and hydraulic properties of a variety of soil series in the area. This information was to be interpreted in terms of suitability of these soils for on-site sewage treatment systems. The use of multivariate statistical analyses as a tool for interpretation of soil profile data was also investigated with this data set.

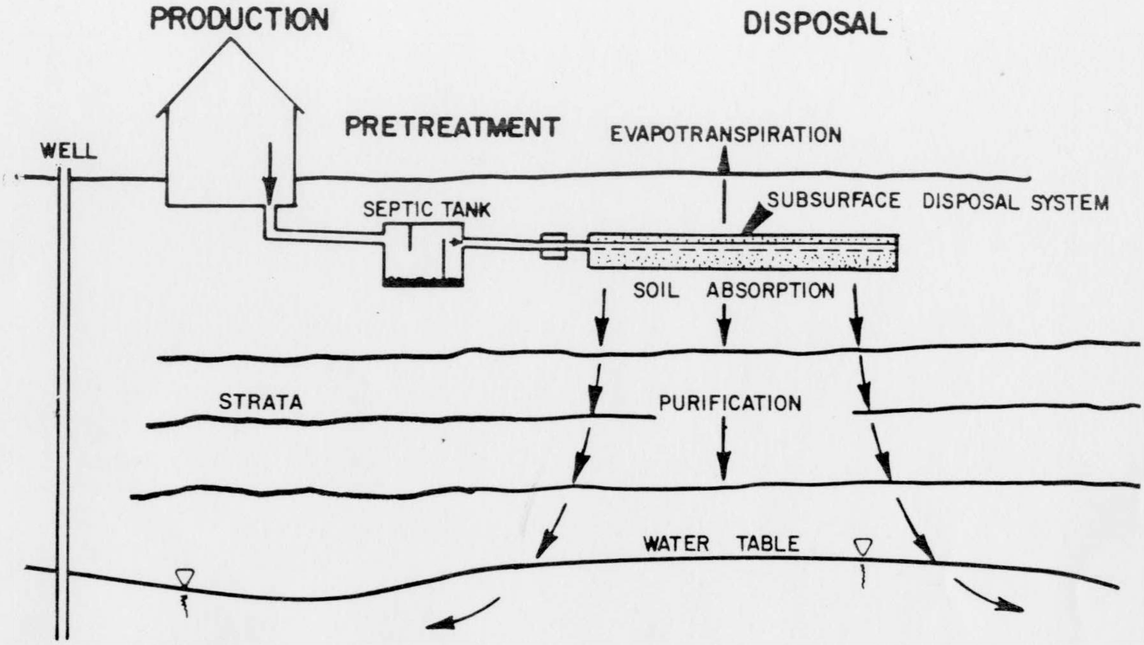


Figure 1. Soil treatment of wastewater by a typical septic system. (after U.S. Environmental Protection Agency, 1978).

LITERATURE REVIEW

Site Evaluation for On-Site Sewage Treatment

Soil Properties

The suitability of any particular parcel of land for on-site wastewater treatment is largely controlled by the physical properties of the soil at that location (Tyler et al., 1977). Successful operation of septic systems requires that two conditions must be fulfilled. First, the liquid effluent must move through the soil at a rate slow enough for it to be properly treated. Second, the soil must be capable of accepting the effluent at a rate that is greater than that at which it is produced by the household. If either of these two conditions are not met, the system is said to have failed. A failure of the first type is called a 'treatment' failure, and of the latter, an 'hydraulic' failure (U.S. Environmental Protection Agency, 1978).

Design criteria for determining the capability of an individual soil to properly accept and treat effluent are based both on external and internal properties of the soil (Baker, 1978). External factors have been well defined for a number of years, and have been incorporated into the standard procedures for determing site suitability. They include: depth to bedrock; depth to the seasonal water table; surface slope; and susceptibility to flooding (U.S. Public Health Service, 1967). While different states have required different criteria for these factors, general limitations are: 1) a minimum of one meter (three feet) between the bottom of the drainfield trench and ground water or bedrock; 2) maximum allowable slopes of 15-25 percent; 3) no sites permissible in floodplains (Parker et al., 1977).

Another important external factor is the relationship of the proposed drainfield site to the local surface hydrology. Sites on concave slopes or below slopes of poor permeability will receive additional water during precipitation and runoff events. This is especially true during periods (e.g. early spring) when the soil surrounding the frost-free drainfield may still be frozen (Mellon, 1967). Runoff of this nature increases the total hydraulic load the drainfield area would receive, potentially causing intermittent failures, and may lead to permanent hydraulic failure (Anderson, 1981).

Internal factors which influence site suitability for septic systems are those characteristics and properties of the soil that influence its ability to transmit water through its profile (i.e. the permeability or hydraulic conductivity of the soil). Morphological attributes of the soil that should be considered include: 1) soil texture or particle size distribution; 2) soil structure; 3) bulk density; 4) porosity; 5) pore size distribution; 6) stratification of different soil textures within the profile (Bouma, 1973; Anderson, 1977; Parker et al., 1977).

Soil texture, structure, and bulk density are characteristics that determine the porosity and pore size distribution of the soil matrix. Soils with higher fractions of silt and clay-sized particles will generally have lower permeabilities than soils containing abundant sand. Similarly, well-developed soil structure and low bulk densities generally result in higher porosity and large numbers of larger pores, promoting faster movement of water through the soil (Horn, 1971).

Textural stratification influences water movement in that both a coarser soil layer underlying a finer textured layer, or a fine-textured soil horizon below a coarser horizon, will retard the downward flow of water to varying degrees. In the former case (e.g. silt loam over sand), the matric tension of the sand material is initially not great enough to attract the water held relatively tightly by the silt loam soil above. Gradually, as water content increases in the fine-textured layer, matric tension will drop sufficiently to allow movement between layers (Miller, 1969). In the latter case, it is simply the lower hydraulic conductivity of the underlying horizon that inhibits water movement. Both types of stratification will result in decreased flow from a septic system drainfield.

In addition to these physical properties, soil morphological characteristics are used to evaluate site suitability for septic systems. Soil color patterns (mottles) and general soil color have been used as indicators of the general year-long moisture regime of a soil (Simonson and Boersma, 1972). Brighter, reddish colors suggest a well-drained soil that allows water to move through it freely. Dull, gray colors are indicative of poorly-drained soils that remain in a near-saturated condition for long periods of time (Soil Survey Staff, 1960). Septic systems installed in poorly-drained soils may be subject to premature hydraulic failure, and/or provide inadequate treatment of effluent (Wisconsin Bureau of Environmental Health, 1979).

The presence of mottles in a soil profile has also been used as an indicator of the upper boundary of a seasonal water table (Simonson and Boersma, 1972). As noted earlier, most states require that at least one meter (three feet) of separation between the bottom of the drainfield trench and the seasonal maximum high water table. However other researchers have found that mottles do not always occur in soils that are subject to saturation for even extended periods of time (Vepraskas and Wilding, 1983; Franzmeier et al., 1983; Pickering and Veneman, 1984), and sometimes they occur in soils that do not experience saturated conditions (Fredrickson, 1980).

Measurement of Hydraulic Characteristics

While there are many factors which influence site suitability for septic systems, traditionally the most important has been soil permeability as determined by the percolation test (Anderson et al., 1977). The results of this test have been used to determine both site suitability and the size of the drainfield required for the projected wastewater flow. The use of the percolation test (perc test) as a predictive tool for site suitability has its roots in the work performed by Henry Ryon in 1929. He developed a curve (later converted to tabular form) which used the perc test to determine the rate at which effluent should be applied to the soil (McGauhey and Krone, 1967). The relationships defined by Ryan were adopted by many public health officials and over a period of time became the standard for determining both the suitability of a site of waste disposal and for determining the size of the drainfield needed.

Slightly modified by subsequent research, the perc test has remained the most widely used tool for sizing septic tank drainfields throughout the U.S. This in spite of the fact that it has been widely critized by many researchers in the field of on-site waste disposal (Winneberger, 1967; Bouma, 1971; Anderson, 1973; Healy, 1973; Baker, 1977; U.S. Environmental Protection Agency, 1978). The focus of most of the criticism of the test is that results are inherently variable, and that it tends to underestimate the absorption field area required for some soils (especially coarse-textured soils with high perc rates).

Winneberger (1967) found that a series of percolation tests performed within a small area of uniform soil yielded perc rates varying from 9-33 minutes/cm (23-83 minutes/inch). In a study of 1500 perc tests on 250 Pennsylvania soils, Derr et al. (1969) reported an average coefficient of variation (CV = standard deviation/average) for the 4-8 tests performed at each site was 73 percent. Over 20 percent of the sites had a CV greater than 100 percent. Data from Bouma (1971) for six Wisconsin soils showed and average CV of 50 percent, and Barbarick et al. (1976) found a range of 7-48 percent for nine Arizona soils.

While this range of values demonstrates the variability of data obtained from the perc test, such values probably represent as accurate a determination as can be made with this method. In each case the perc test was conducted by scientists attempting to minimize any variation in procedure between successive tests. It has been argued that such care is rarely taken by those who routinely perform perc tests (Winneberger, 1974). Winneberger (1974) reported the results of a study in which fieldmen (employees who regularly performed perc tests) from three engineering firms were asked to perform perc tests at each of nine locations on a single 1/4 acre lot. The range in rates obtained in this experiment for all tests over the entire lot was 1-100 minutes/cm (2-259 minutes/inch), and for any one of the nine locations on the lot, 1.2-90 minutes/cm (3-229 minutes/inch). Allowing for some inherent error due to soil variability, he concluded that the values obtained from perc tests depended more on the procedures of the particular fieldman than on soil characteristics. Potential sources of variability in the perc test have been shown to be hole diameter and geometry, length of presoak period, amount of hydraulic head during the testing period, and soil anisotropy and heterogeneity (Healy and Laak, 1973; Barbarick, 1976).

Further criticism of the perc test comes from those who state that it is a measure of saturated flow through soil, while it is the process of unsaturated flow that actually occurs under mature septic tank drainfields. A study by the U.S. Public Health Service (1950) revealed that the equilibrium loading rate (the amount of effluent actually percolating into the soil) under the drainfields evaluated represented a 98 percent reduction in the flow rate compared to the saturated flow rate determined by the perc test. The study suggested that some sort of barrier to flow had developed in the soil.

Further research by Thomas et al. (1966), and McGauhey and Krone (1967), demonstrated that a hydraulically resistant layer forms at the bottom of the drainfield trench. Years earlier, (Allison, 1947) had shown in a laboratory study that soils kept saturated for extended periods of time developed a clogging zone at the infiltrative surface that was formed from the by-products of anaerobic bacterial activities. Other researchers (Jones and Taylor, 1965; de Vries, 1972; Kristiansen, 1981) have reported similar results. This clogging zone (also referred to as a mat, biomat, or crust) is a complex mixture of micro-organisms, the by-products of their metabolic processes (primarily polysaccharides, which adhere to the soil particles), and other organic matter from suspended solids filtered out of the septic tank effluent. The result of the formation of this biomat is a reduction in the effective porosity (and thus the permeability) of the soil infiltrative surface. This creates a limiting barrier to infiltration, reducing effluent flow from the drainfield trench. Importantly, it also creates conditions of unsaturated flow in the soil beneath the absorption field (Bouma et al., 1972).

Bouma et al. (1972) determined that such a mat usually develops during the first year of operation of a drainfield. Organic matter continues to accumulate and further reduce infiltration until an equilibrium situation is reached, where the rate of crust formation at the anaerobic soil infiltrative surface is matched by the rate of destruction in the aerobic zone several centimeters below the bottom of the drainfield trench. In an extensive evaluation of septic system operation in Wisconsin (Bouma et al., 1972), measurements were made of soil matric tensions existing under drainfields with clogging mats. Tensions were found to be in the range of 20 to 100 cm water, indicating unsaturated conditions in the soil below the mat.

Bouma (1971) proposed that measuring hydraulic conductivity over a range of moisture tensions was necessary for determining the capacity of a soil to absorb effluent under unsaturated conditions. He developed a test to measure this property on soils _in situ_, using crusts composed of gypsum and sand to simulate the biological crust found in drainfields (Bouma and Denning, 1972). Data from this test can be used to generate a graph for a particular soil showing the change in hydraulic conductivity (K) as soil moisture tension changes. The graph is called a K-curve. An example of K-curves for several soil textures is provided in Figure 2.

Hundreds of such tests were performed on the major soil series in Wisconsin (Baker, 1978). Analysis of these data showed that four major conductivity groups of soils could be distinguished, and that these groups were related to particular soil textures (Bouma, 1975). The cumulative results of these tests on Wisconsin soils are graphically displayed in Figure 2. This data was used to propose suggested maximum loading rates for septic system drainfield design (Table 1).

This methodology of evaluating soil hydraulic conductivity for interpretation for septic system design was selected as most appropriate for obtaining the type of information desired in this study based on the following criteria: it is not subject to the variability inherent in the perc test (especially in terms of hole size/geometry); it provides saturated and unsaturated data in the range of soil moisture tensions commonly found below septic systems; it can be performed in remote locations by a single technician; and it generally is not limited by stratified conditions in the soil profile.

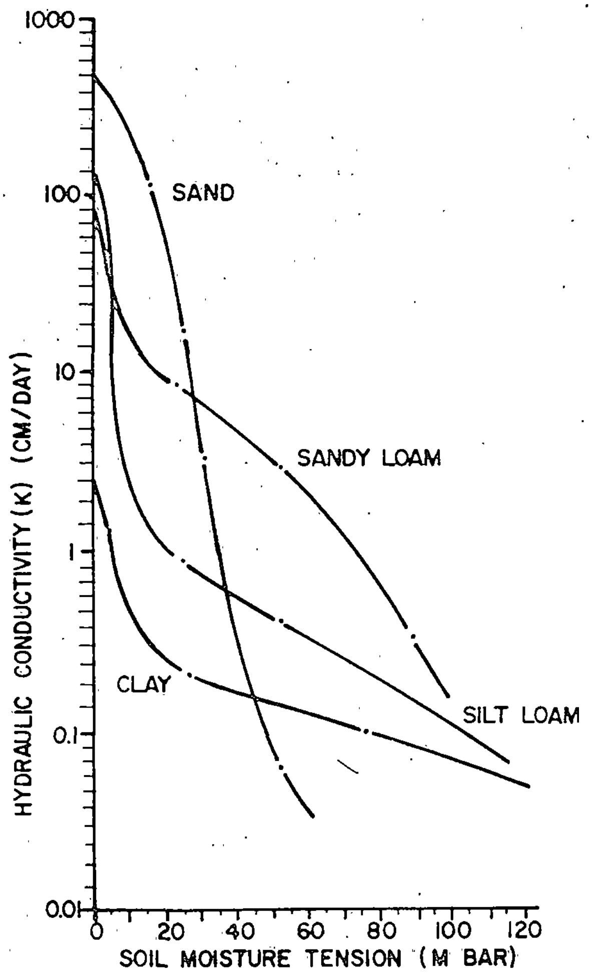


Figure 2. Relationship between hydraulic conductivity and soil matric tension for several soil textures (Bouma, 1975).

Table 1. Recommended loading rates for septic system drainfields based on <u>in situ</u> measurements (after Bouma, 1975).

SOIL TEXTURE	SANDS	SANDY LOAMS	LOAMS	SILT LOAMS	CLAYS
LOADING RATE (cm/day)	5	3	2	5[1]	1[1]

[1] Uniform distribution of effluent, 1 dose/day, shallow trenches only.

Multivariate Statistics

Multivariate statistical techniques have been widely used as classification tools in the earth sciences, but have only rarely been used to analyze and classify horizon data from soil profiles. A good discussion of their utility in exploring the statistical relationships between soil profiles and soil classification (numerical taxonomy) can be found in Webster (1977). In using such techniques, there is a basic assumption that while soil horizons possess dozens of measurable properties, most of the variability between horizons can be explained through the use of only a few soil properties (Norris, 1971). This assumption is based on the observation that all soil properties are not independent of one another, rather it is likely that change in one soil property (e.g. clay content) may be associated with changes in others, such as cation exchange capacity and permeability (Webster, 1977). As a result, it is possible to define variables that explain much of the difference between two or more horizons, and use them to classify the horizons into groups whose members are more similar to other members of the group than to members of another group.

Raynor (1966) employed such techniques to determine the similarities between 91 horizons, and to group them into a soil-similarity matrix. Principle component analysis was used by Norris (1971) to compare statistical classification of soil profiles with field classification. Similar groupings were obtained by both methods. A study by Henderson and Ragg (1980) showed that discriminant analysis was reasonably effective in separating soil taxonomic units for gley soils, and advocated the use of this technique for the design of soil taxonomies. Berg (1980) applied stepwise discriminant analysis to evaluate soil genesis in sand dune soils by determining which pedogenic variables were most useful in separating out soils of different ages. From this review of applications of multivariate statistics to soil profile data, the methods of principle component analysis, cluster analysis, and discriminant analysis were selected as the techniques that would best demonstrate the similarities and differences of the horizons from the study sites.

REGIONAL SETTING

Study Area Description

The study area was selected through discussion with members of the Soils Steering Committee of the Flathead River Basin Environmental Impact Study. The extent of the geographical area can be described as the Upper and Lower Flathead Valley, defined in this study as the area beteen the Whitefish and Galton Ranges to the north, the Jocko Range to the south, the Swan and Mission Ranges to the east, and Salish Range to the west (Figure 3).

Geology

Differences between soils can often be traced to the differences in the geologic deposits from which they form. This is particularly true in the Flathead Valley, an area whose complex glacial history has resulted in a soil landscape of equal complexity. The geology of the study area has been described in reports by Alden (1953), Konizeski et al. (1968), and Johns (1970), and the reader is referred to these reports for a more technical treatment of this information. The following discussion summarizes the complex nature of the surficial deposits found in the study area.

The dominant geological forces that have created the present landscape in the Flathead Valley include the tectonic activity that created the valley and surrounding mountains, the glacial processes

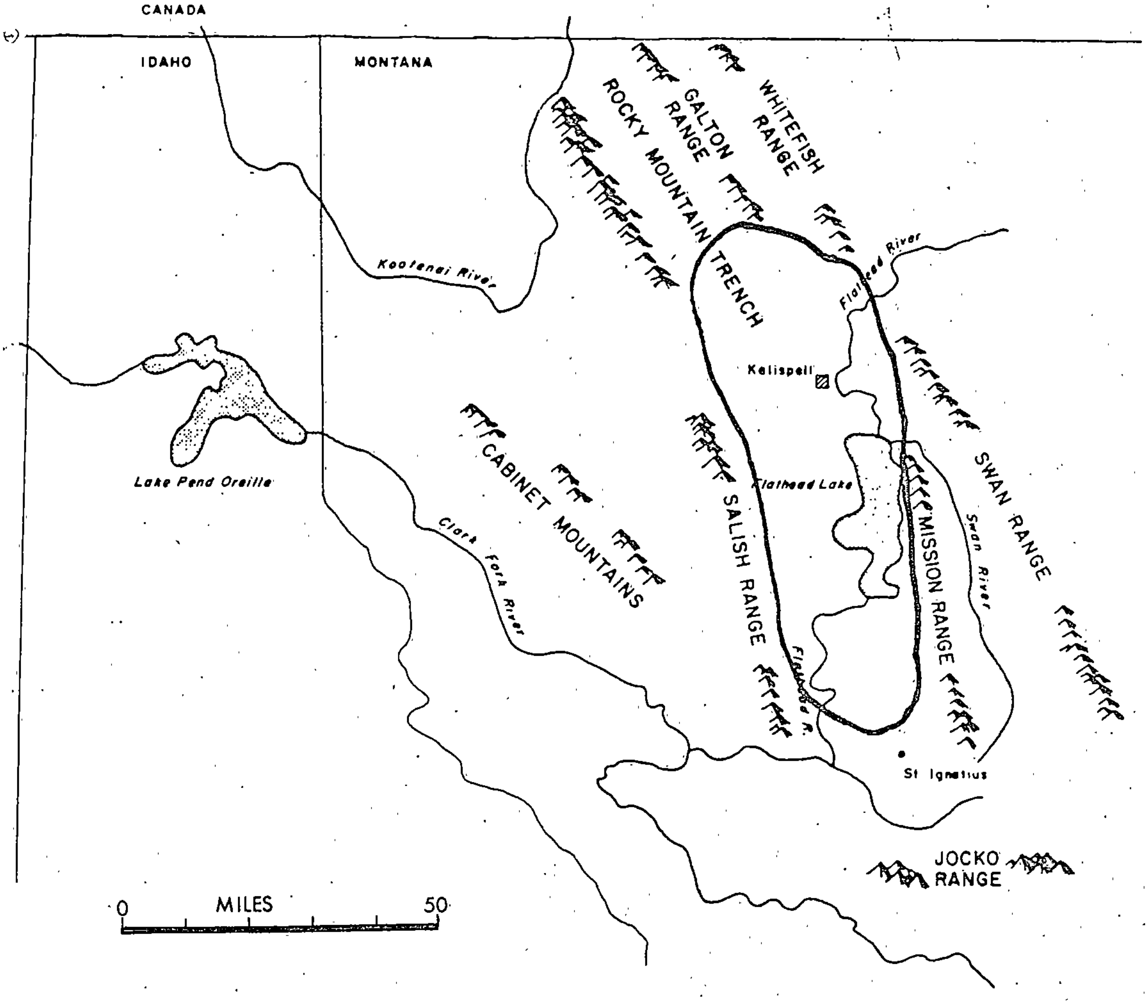


Figure 3. Map of northwestern Montana with the study area outlined (after Stoffel, 1980).

that are responsible for the deposition of much of the surficial materials found in the valley, and the reworking of these deposits by river action. Precambrian sedimentary argillite (an indurated silt- or claystone), quartzite, and dolomite (a magnesium limestone) from the Belt series form the mountains (the Mission, Swan, Whitefish, and Salish ranges) which border the study area (Figure 3). The valley itself was probably formed from normal faulting during the late Paleocene or Eocene, continued subsiding during the Tertiary, partially filling with erosional waste from the surrounding highlands (Konizeski et al., 1968).

As world climate cooled during the Pleistocene epoch, a massive lobe of the Cordilleran ice sheet advanced down the Rocky Mountain Trench, a topographic depression which includes the area between the Salish and Whitefish mountains, and into the Flathead Valley (Figure 3). A second mass of ice, (the result of ice accumulation in the mountains of Glacier National Park), entered the valley from the northeast, following the Flathead River valley. A third lobe of ice from the Swan River Valley may also have moved into the Flathead Valley (Konizeski et al., 1968). These three masses of ice coalesced in the upper Flathead Valley to form a single sheet of ice, the Flathead lobe, that at its maximum extent is estimated to have been 760 meters thick in the Kalispell area (Alden, 1953).

As this massive glacier moved southward, its erosive base scoured out the unconsolidated Tertiary deposits over which it travelled, and also picked away at the underlying bedrock wherever it was exposed, incorporating this material into the ice mass. The southernmost advance of the Flathead lobe terminated in the vicinity of Moiese, where much of the entrained material was deposited as the Mission moraine, thought to be of late Bull Lake (Weber, 1972), or early Pinedale age (Stoffel, 1980). With the world climate warming, subsequent moraines were deposited in the study area during the retreat of the Flathead lobe just south of Polson, and to the immediate north of present Kalispell (Alden, 1953).

In the period following deposition of the Mission moraine, and continuing at least until the deposition of the Kalispell moraine, the Flathead Valley was inundated a number of times by the waters of glacial Lake Missoula (Alden, 1953). This enormous glacial lake was formed by ice dams in the vicinity of present Lake Pend Oreille in northern Idaho. Weber (1972) noted nine cycles of this lake in the Bitterroot Valley, 50 miles south of the Flathead Valley, at elevations ranging from 1130 to 1260 meters. Richmond et al. (1965), and Konizeski et al. (1968), found evidence that Lake Missoula filled the Flathead Valley to an altitude of 1035 meters, and lacustrine beds of silt and clay interfinger with and overlap the Kalispell moraine at an elevation of 945 meters. However, these beds could have formed from ancestral Flathead Lake (Richmond et al., 1965).

During the final stages of the glacial retreat, the three separate masses of ice that originally formed the Flathead lobe regained their individual identities. The presence of three separate sources of ice, their meltwaters distributing the entrained glacial debris in a more or less random fashion as outwash deposits, added to the complex nature of the surface deposits of the study area. These alternating episodes of deposition by lacustrine, fluvial, and glacial sources resulted in a highly stratified surficial geology of interbedded tills, outwash, and lacustrine silts and clays. Much of this complex surface remains today, with part of it having been reworked in those areas close to the major streams and rivers of the valley (Konizeski et al., 1968).

Glacially-related deposits found in the Flathead Valley can be grouped into five main categories of glacial drift (Table 2). The processes of glacial deposition have arranged such materials in a rather complex fashion over much of the study area. From the experiences of this study, it is possible for all five types of deposits to occur within a short distance laterally, and to a lesser extent, vertically.

The surficial deposits of the Upper Flathead Valley have been mapped to a limited extent and scale as part of an investigation on the ground-water resources (Konizeski et al., 1968). Widespread deposits of till are found in the area extending about seven miles south of Whitefish, on the flanks of the Whitefish range between Whitefish and Columbia Falls, as well as on many upland positions in the valley, where the till was not exposed to considerable fluvial action. Till covers the slopes leading to Flathead Lake on both the east and west shores, and is found on the terminal moraine at Polson (Alden, 1953).

Perhaps the most extensive glacial deposits are the thinnly bedded silts, sands, and clays that were laid down during episodes of pro-glacial lakes. These lacustrine deposits are far-ranging at least in part due to glacial Lake Missoula. The enormous body of water filled most of the intermontane valleys from the Flathead west to the Idaho

Table 2. Definitions of some of the common terms used to describe categories of glacial-related sediments (adapted from Bloom, 1969, p. 396).

1. **TILL**--Nonsorted, nonstratified, deposited directly from ice without reworking by meltwater. Contains large range of particle sizes, from clays to boulders.
    - a. **Basal** till--compact, dense till deposited at the base of a wet-base glacier.
    - b. **Ablation** till--less consolidated than basal till, often lacking the finer grain sizes. Carried on the surface of the ice and "let down" as the ice melts out from underneath.
2. **Ice-contact stratified drift**--Material modified by meltwater during or after deposition. Considerable stratification and sorting is usual, as are chaotic structures and slumping.
3. **Outwash**--Alluvium deposited by meltwater not in close proximity to melting ice. Sorting and stratification are more regular that in ice-contact drift. Similar to coarse alluvium.
4. **Lacustrine sediment**--Lake-bottom deposits, usually fine-grained, formed in settling basins on or near melting ice. Often forms silt and clay plains of broad extent. Sometimes **varved,** or composed of rhythmic silt-clay couplets each representing an annual cycle of deposition.
5. **Eolian sediment**--Sand dunes, sand sheets, and loess derived from other types of glacial drift.

border. Observations of shorelines cut into hillslopes indicate that at its greatest extent, the lake's surface stood at an elevation of 1280 meters (Alden, 1953), meaning that the entire Flathead Valley (average elevation, 945 meters) would have been submerged under more than 350 meters of water. The tremendous extent and numerous episodes of the filling and draining of this lake accounts for the formation of widespread deposits (Alden, 1953).

Such lacustrine deposits are surficially expressed in the valleys of the Stillwater and Whitefish rivers, as well as on the terraces between the Swan Range and Flathead River. They are also common in the area south and west of the Polson moraine, and are present in the moraine itself (Alden, 1953). From the experiences of this study (examination of dozens of roadcuts and fresh excavations), it would appear that subsurface deposits of this nature are equally extensive.

Outwash and ice contact deposits are scattered throughout the area (Konizeski et al., 1968), as evidenced by the numerous excavations made to extract their sands and gravels for construction purposes. Notable examples occur just east of Kalispell, and between Kalispell and Whitefish. Sand dunes are present north of the Bigfork area, and in the vicinity of Pablo in Lake County (Alden, 1953). Large areas of alluvial deposits are found along the watercourses of all the major rivers in the valley.

To summarize, the unconsolidated materials from which the soils in the valley have evolved are predominantly glacial or glacially-related. The processes responsible for these deposits have created a complex landscape of great inherent variability in both a horizontal and vertical plane.

Soils

Following the glacial episodes described above, pedogenic processes began to transform the freshly deposited sediments into soil. The factors that influence the development of an individual soil unit can be described in sentence form as climate, relief, and biological organisms (e.g. vegetation, micro-organisms) acting on a geologic parent material over time (Jenny, 1941). Through these processes unique soils will develop that may be differentiated on the basis of their individual characteristics into separate soil series, whose distribution throughout the landscape may be determined by field investigation and mapping.

The recent publication Soils of Montana (Montagne et al., 1982) includes a small-scale map (1:1,000,000) which shows the general distribution of the soil resources throughout the state. Soil associations at the Great Group level are the mapping units, and six general associations are shown for the soils that encompass the study area:

Cryochrepts-Ustochrepts-Eutroboralfs
Xerochrepts-Xerofluvents-Haplaquolls
Haploxerolls-Xerochrepts-Xeropsamments
Natrixerolls-Argixerolls
Xerochrepts-Xerorthents-Ustochrepts
Haploxerolls-Natrixerolls

Mapping units at this scale are of little practical value for a study of this nature. More detailed, larger-scale mapping of the soil resource has been completed in parts of the study area by the Soil Conservation Service (SCS). The most recent work was completed in 1947, and culminated in the publication of the Soil Survey of the Upper Flathead Valley in 1960 (U.S. Soil Conservation Service, 1960). The geographical extent of this survey was essentially the part of Flathead Valley north of Flathead Lake. Earlier work produced the Soil Survey of the Lower Flathead Area (U.S. Soil Conservation Service, 1934), defined as the Mission, Camas, and Jocko Valleys. This area is presently being mapped for a new soil survey which should be published within the next few years. Much information has already been collected and is available through the Soil Survey party leader in Polson.

In general the soil maps reflect the dominance of glacial activities on the soils of the area. Most soils are described as being formed from glacial materials, or as the result of stream activity reworking glacial deposits. An examination of the descriptions of each of the series shows that the typical profiles of the majority of the soils occupying positions other than the lower slopes of the mountain ranges that border the valley, exhibit stratification within the C horizon, which reflects the mode of deposition of these materials. The sites examined in this study also reflect this dominance of stratification in the lower soil profile. As will be discussed later, such stratification may have a significant effect on the operation of a septic system.

While these surveys provide a valuable data base from which to begin further evaluation of the soil resource, their value is limited in this study. The purpose of these surveys was soil interpretations for agricultural use, and as such they focused on the characteristics of the upper soil profile, whereas this study is primarily interested in subsoil characteristics for purposes of treatment and disposal of septic system effluent.

A supplement to the Upper Flathead survey was published in 1970 which does provides interpretations for these soils for engineering and resource planning applications (U.S. Soil Conservation Service, 1970). The interpretations include soil ratings for septic systems and an estimate of the permeability of each series. Such ratings are useful for larger-scale evaluations of the general suitability of an area for on-site waste disposal. They serve as an excellent first source of information regarding the potential limitations of any given soil for a number of different uses. However, the inherent variability of the study area soils serves to restrict the application of such ratings to those situations requiring less detailed information (U.S. Soil Conservation Service, 1983). Likewise, the permeability values found in this reference are of limited value when site-specific data is required (as when determining the land area needed for a septic system drainfield). This is because they are based on estimates made from laboratory and field determinations of the texture, structure, and density of a representative soil profile, and not from actual on-site measurements of soils from the survey area (Bouma, 1973).

These kinds of estimates can be used to imply general relationships between soil properties and the glacial parent materials from which they have developed. Glacial till soils commonly have textures in the sandy loam to silty clay loam range, and their permeabilities will usually range from moderate to slow, depending on both texture and the degree to which the sediments have been compacted. Soils developed in outwash, ice-contact stratified drift, or eolian sediments are typically coarse-textured, and may possess moderate to very rapid permeabilities. Soils influenced by lacustrine parent materials will be silty and/or clayey, and permeabilities will often range from moderately slow to very slow (Bouma et al., 1972).

Because of the intimate association between the surface geology and local soils, the dominant theme is variability. The soil landscape in many areas is very complex, and the nature of the subsurface soil cannot easily be predicted from an interpretation of the appearance of the surface soil. Soils are spread throughout the landscape in complex patterns, and exhibit considerable variability in both the vertical and horizontal directions. Such variability increases the difficulty in obtaining accurate soil information for use in septic system design. The result may be an inadequately designed soil absorption field, which in turn may contribute to of premature failure of the sewage treatment system.

Ground-water Hydrology

The ultimate destination of most of the effluent treated by soil absorption systems is the ground-water system existing at depth below the drainfield. While septic systems have the potential to contaminate groundwater resources, systems that have been properly sited and operated pose few problems for water quality (U.S. Environmental Protection Agency, 1978). Conversely, ground water can also impact the operation of the septic system drainfield. If the water table rises close to or into the drainfield area, soil absorption of effluent will be slowed, and treatment of the effluent seriously reduced (Bouma et al., 1975). For these reasons it is important to understand the local hydrologic system into which the septic system is placed.

The report by Konizeski et al. (1968) described the principle aquifers of the upper Flathead Valley. They include: Precambrian bedrock aquifers, ranging from 10-140 meters deep, storage capacity mainly from fractures, and generally of small yield; deep (30-120 meters) Pleistocene artesian aquifers composed of unconsolidated sands and gravels, generally high-yielding; and shallow (less than 30 meters) Pleistocene artesian aquifers of minor importance; and Recent age aquifers in flood plain deposits of sand and gravel. The gravel aquifer is high yielding but susceptible to pollution, while the sand aquifer is only slightly permeable.

The study also outlined the properties of three perched Pleistocene aquifers of limited areal extent, separated from the artesian aquifers by relatively impermeable clay, glacial till, or cemented gravel. The dune and lacustrine sand aquifer crops out on terraces, is poorly permeable, and may contain high nitrate levels. The outwash sand and gravel aquifer fills depressions between drumlins northwest of Kalispell, and is high yielding for both domestic and irrigation uses. A glacial drift aquifer is also present but has seen limited exploitation.

Of particular interest are the shallow systems defined as the Pleistocene perched aquifers, and the recent flood-plain aquifers, as they are the most susceptible to contamination from surface sources (e.g. septic systems). While shallow aquifers may be most susceptible to potential pollution from septic systems, deeper aquifers can also experience such contamination, particularly those consisting of highly fractured or channelized bedrock, conditions often found in limestone aquifers. Recent investigation by the local 208 Water Quality Project in the Somers area have indicated that such a problem may exist in the dolomitic limestone aquifer found there (Newman, 1982).

A recent report by Boettcher (1982) describes the geohydrology in the southern part of the study area around Polson. He found production of less than 40 liters/minute from wells and springs developed in Proterozoic rocks. The main water-bearing units are composed of glacial materials ranging in size from boulders to clay, including till and outwash. Well yields are in the 40-4,000 liters/minute range, but are unpredictable due to the variability of the glacial deposits. Alluvial deposits are also good sources, but have experienced little development, as in such areas surface water is plentiful. Water quality from all wells in this area is generally good.

Climate

The climatic regime can play an important role in the proper functioning of on-site waste disposal systems. Soil moisture conditions as influenced by seasonal precipitation and evaporative demand will affect the performance of drainfields. Annual precipitation in the study area ranges from 39.4 cm at Kalispell to 38.3 cm in Polson. Air temperatures influence soil absorption systems primarily in respect to evapotranspiration, as higher rates of evapotranspiration by vegetation growing over septic system drainfields decrease the net hydraulic load imposed on the soil. Potential evapotranspiration estimates range from 56 cm at Kalispell to 61 cm in Polson. Mean annual air temperatures, which approximate the mean annual soil temperature, are found to be 6.1 degrees Celsius (43 degrees Fahrenheit) at Kalispell, and 7.8 degrees (46 degrees Fahrenheit) at Polson (National Oceanic and Atmospheric Administration, 1980).

The next section describes the procedures used to examine soil water movement in the soils and sediments of the study area.

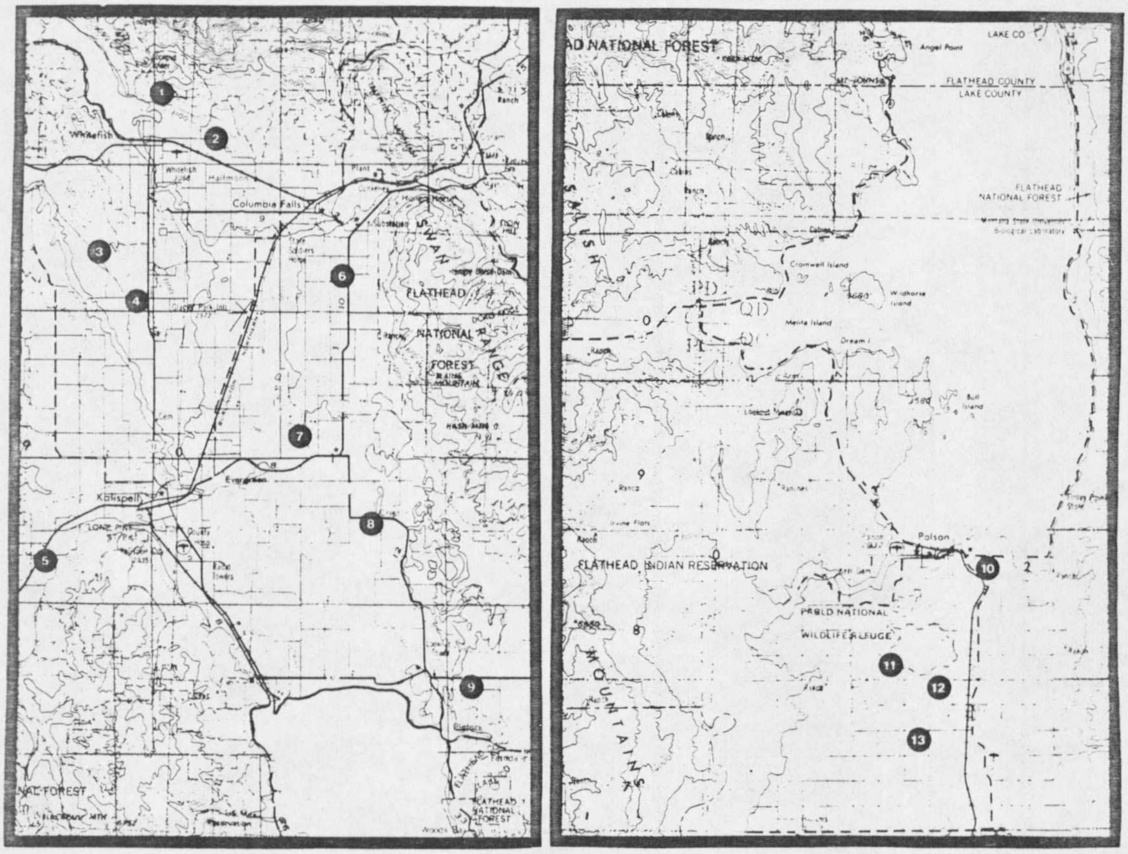
METHODS AND PROCEDURES

Soil Sampling and Analysis

A total of 13 sites spread throughout the Flathead Valley were chosen (Figure 4), based on the recommendations of the Soils Steering Committee of the Flathead River Basin Environmental Impact Study. These sites were selected to represent a wide variety of soil parent materials, reflecting the variability of the glacial deposits found in the area. At each of these sites a backhoe pit was excavated to a depth of two meters or more, and the soil profile described according to standard Soil Conservation Service methods (U.S. Soil Conservation Service, 1983). Each soil horizon was sampled by hand, placed in a plastic bag, labeled, and transported to the Soil Testing Laboratory at Montana State University for further physical and chemical analyses. Each sample was air dried, and the material sieved to remove particles greater than 2 mm in diameter. A complete listing of all the analyses performed on each sample, as well as soil properties calculated from these analyses, is provided in Table 3. Complete field descriptions of the soil profiles and results of the laboratory analyses are provided in Appendices 2 and 3.

Measurement of In Situ Hydraulic Conductivity

At the onset of this research project, it was proposed to use the instantaneous profile method of Sisson et al. (1980) for the



Site Number	Soil Series	Surficial Geology	Cooperator
1	Whitefish	kame terrace	Fritz Royer
2	Whitefish	continental till	Tom Edwards
3	Depew	lacustrine	Norman Wendt
4	Whitefish	continental till	Flathead Co.
5	Prospect	till/lacustrine	Harold Keller
6	Blanchard	outwash	Jerry Weber
7	Flathead	outwash	Darrell Logan
8	Creston	lacustrine	Creston A.E.S.
9	Blanchard	eolian dune	Dick Conley
10	Krause	continental till	Paddy Trusler
11	Quigley	lacustrine	Oliver Dupuis
12	Polson	lacustrine	Ed Unger
13	Gird	outwash	Brent Gregg

Figure 4. Study site locations, soil series, surficial geology, and cooperators (landowners).

Table 3. Physical and chemical parameters analyzed and calculated for all soil samples[1].

ANALYZED

- particle size distribution
- moisture characteristic (0, 0.1, 0.3, and 15 bars)
- bulk density (saran-coated clod method)
- clay mineralogy (for 16 horizons, Klages and Hopper, 1982)
- organic carbon
- total nitrogen
- pH:
  - 1:1 soil/water
  - 1:2 soil/$CaCl_2$
  - saturated paste
- electrical conductance
- soluble and NH_4OAc extractable Ca, Mg, Na
- cation exchange capacity
- bicarbonate

CALCULATED

- available water
- C/N ratio
- sodium adsorption ratio (SAR)
- base saturation
- exchangable sodium percentage (ESP)

1) Except as noted, all analytical procedures were performed according to the methods outlined in "Soil Survey Laboratory Methods and Procedures for Collecting Soil Samples"; Soil Conservation Service, U.S.D.A., Soil Survey Investigations Report #1, 1972.

determination of saturated and unsaturated hydraulic conductivity (K) *in situ*. After considerable effort in attempting this method at three sites, it was found to be unsuitable for the following reasons: the textural stratification of most of the soil profiles (which violates the uniform profile assumption of the method); the difficulty of installing tight-fitting neutron probe access tubes and obtaining reliable neutron probe calibration curves in the many soil profiles with coarse fragments; and the inaccessibility of several sites.

Few alternatives for in situ field K measurements exist (Bouma et al., 1982), and the one identified as most appropriate for the site and soil conditions of the study area was determined to be the "crust test" method developed at the University of Wisconsin (Bouma, 1971). This technique is not limited by the problems encountered with the instantaneous profile method described in the preceeding paragraph. Also contributing to its appeal was its extensive use in a multi-year study in Wisconsin whose goals were similar to those of this study (evaluation of soil hydraulic parameters for on-site sewage treatment systems). A general description of this procedure is presented below. A detailed description can be found in Bouma et al., (1974).

A backhoe is used to expose a soil profile to a depth suitable to allow access to the soil horizons of interest (typically 2 meters in this study). A column of soil (roughly 30 cm in diameter) in the horizon that is to be measured is then isolated from the rest of the soil profile by careful removal of the soil above and to the sides. This leaves an undisturbed pedestal of soil with its base still firmly united with the soil below it (Figure 5). A plastic ring of a diameter slightly less than the carved column is then pushed firmly downward over the soil column, its beveled lower edge scraping away excess soil, providing a tight seal between soil and ring. About two inches of the ring are allowed to project above the soil column surface to serve as an infiltration mechanism . This column is then instrumented with a tensiometer approximately 3 cm below its surface for the measurement of matric potential. Tensiometers were installed by drilling a horizontal hole (using a battery-operated hand drill) slightly larger than the

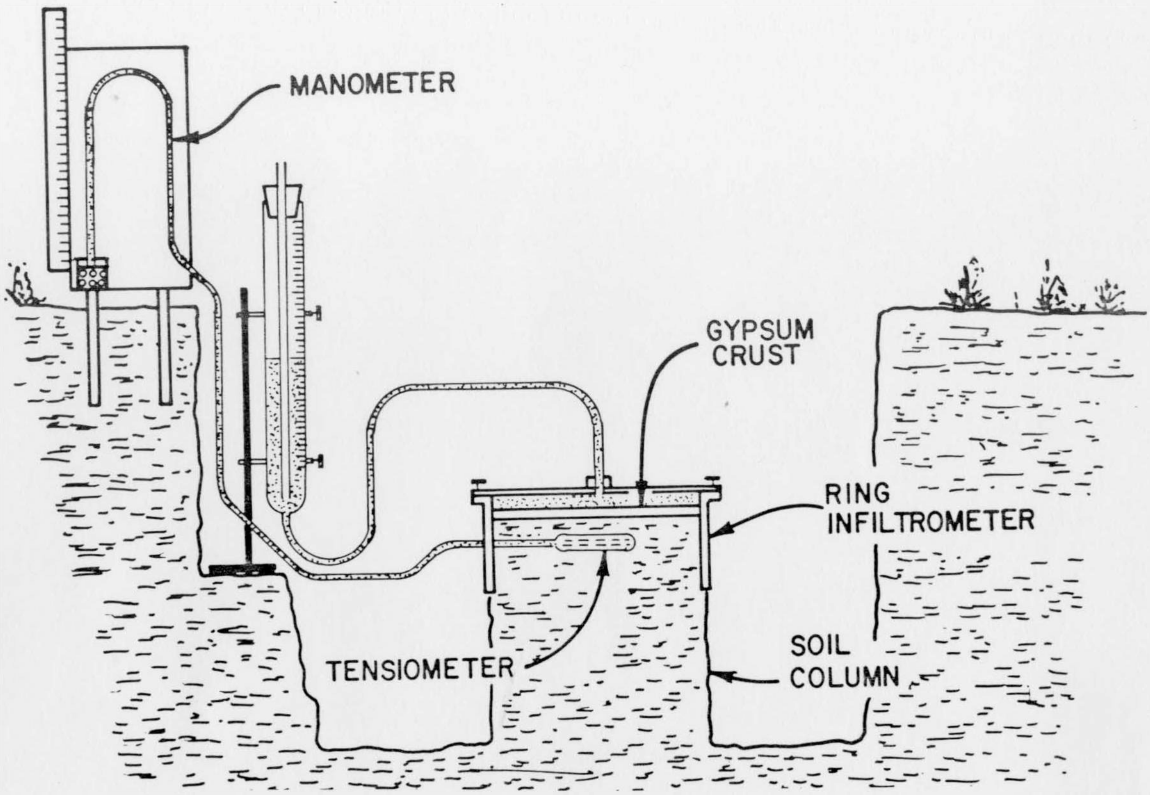


Figure 5. Schematic cross-section of the field set-up for the crust test.

ceramic tip of the tensiometer to the center of the soil column. A second hole slightly smaller than the ceramic tip is then drilled, and the ceramic tip forced into it, insuring good pore continuity between the tensiometer and soil. The column is then wrapped with aluminum foil to prevent evaporation. A schematic representation is presented in Figure 5, and photographs of a carved soil column and an instrumented soil column in Figures 6 and 7.

A mixture of water, silica sand, and gypsum (Hydrocal, a product of the U.S. Gypsum Co. was used) is prepared, poured on top of the soil column, spread out to the edges of the ring, and allowed to harden for about 15-30 minutes. A water solution (0.05M $CaCl_2$) is then ponded on the crust surface, a plexiglass cover used to seal the top of the

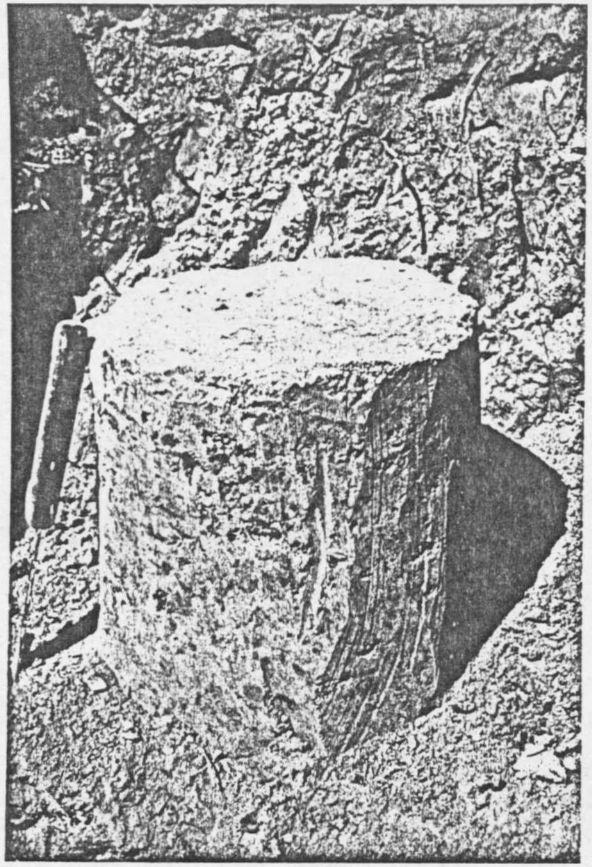


Figure 6. Soil column prepared for the crust test procedure.

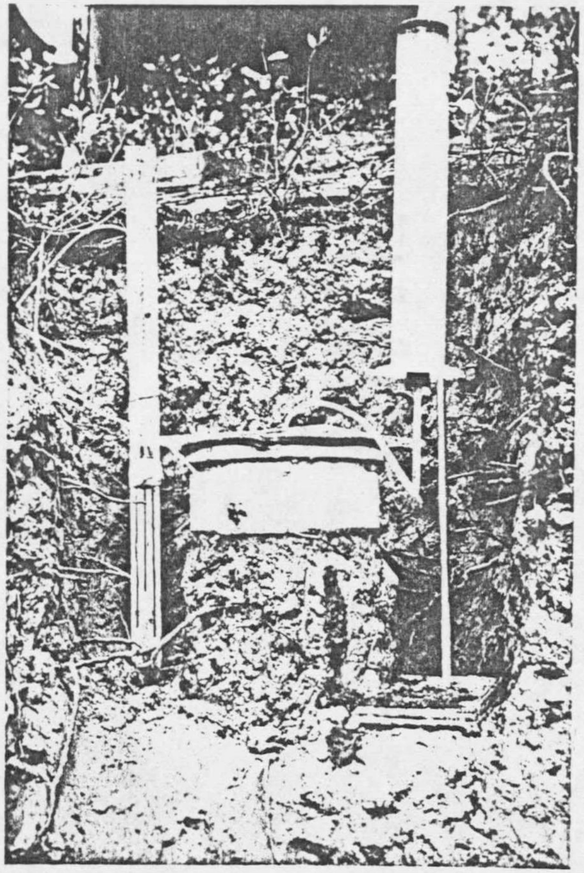


Figure 7. Field set-up of the crust test instrumentation

infiltration ring, and more water introduced until there is no air between the gypsum crust and the cover (air is allowed to escape from the infiltration ring by means of a air-bleeder valve). A supply tube connected on one end to the cover and on the other to a plastic 1000 ml graduated cylinder, modified to serve as a marriot device provides water at a constant head to replace that which infiltrates through the crust (Figure 5).

The integrity of the crust can be checked by lightly pressing down on the plexiglas cover, and then removing the pressure. If leaks are present (which would allow excess flow to the soil column), small air bubbles will be seen rising from the crust, or especially around the edges of the crust. If such bubbles are noticed, the crust must be removed and the soil column allowed to dry.

Because the crust serves as a restrictive barrier to flow, and limits the amount of water reaching the soil below, unsaturated flow occurs within the soil column. The water entering the soil column through the crust results in an increase in soil matric potential, and over a period of time (usually 30 minutes to several hours) the system equilibrates and the matric potential stabilizes. Work by Bouma et al. (1972) demonstrated that at this stage the soil column has a uniform matric potential, and therefore only gravitational potential changes with depth at a unit rate (1 cm/cm,). At this point then the infiltration rate (flux) is equal to hydraulic conductivity as expressed mathematically in the following equations.

For one-dimensional, steady-state, saturated or unsaturated flow, Darcy's law states that:

$$V = K\ (dh/dl) \qquad \textbf{Eq. 1}$$

where V = flux ($cm^3/cm^2/sec$), K = hydraulic conductivity (cm/sec), and dh/dl is the hydraulic gradient (dimensionless). When subcrust matric potential has stabilized, dh/dl = 1, and therefore:

$$V = K \qquad \textbf{Eq. 2}$$

When the tensiometer has stabilized, the infiltration rate is observed.

This rate may be determined by measuring the drop of the water level in the graduated cylinder over a prescribed period of time. Usually 4-8 measurements of fifteen minutes each were taken after equilibrium had been reached, and the average value used to calculate hydraulic conductivity. The calculation involves dividing the average volume (in cm^3) of water which has infiltrated through the gypsum crust in fifteen minutes by the area of the soil column (729.7 cm^2) to provide the hydraulic conductivity for that 15 minute period, for the particular matric potential measured by the tensiometer. This value is then multiplied by 96 (24 hours X 4 — there are four 15 minute periods in an hour) to obtain a hydraulic conductivity in the units of cm/day.

Following the completion of an individual crust test, the gypsum crust is removed, using care not to disrupt the soil column in the process (this topic is dealt with further in the Results and Discussion chapter). In this study, use was made of a battery-operated power drill to perforate the crust in several places, which weakened its integrity and facilitated its removal by subsequent chiseling. Another crust, this time made more porous by increasing the ratio of sand:gypsum, is poured on the soil and the process repeated. In this study, sand:gypsum ratios of 25:75, 50:50, 75:25, and 90:10 were commonly used. Each succeeding crust, being slightly more permeable to water, will allow a greater movement of water through it, and will result in a matric potential slightly closer to saturated conditions in the soil column. Two or three different crusts may be used to obtain K values at various potentials. After coating the soil column with plaster to prevent boundary flow along the edges of the soil column (this step is not needed during preceeding measurements, as under unsaturated conditions such flow will not occur), a final measurement is made with no crust to obtain a value for saturated K.

Each measurement with a particular crust produces a pair of values; a vertical hydraulic conductivity value (y) at a particular matric potential (x). These paired numbers can then be plotted to obtain a curve representing the change in hydraulic conductivity as a function of soil moisture tension in the saturated and near-saturation range.

At each site, one or two soil horizons were chosen for measurement. The horizons were selected on the basis of which were thought to be the most limiting hydraulic horizons, that is, which would likely be the least permeable, based upon on-site observation of soil texture, structure, and bulk density. A single series of determinations was made on each horizon, although at two sites the procedure was replicated to assess the reproducibility of the technique.

Statistical Analysis

Data from these measurements and from the results of the physical and chemical laboratory analyses of each of the soil horizons described at each site, were subjected to a series of statistical evaluations using the Statistical Analyis System (SAS) software package (SAS Institute, 1982). Data were first inspected for normality, and log transformations were performed where necessary. Selected variables were then entered into a setwise multiple regression to obtain the best three-variable regression equation for predicting hydraulic conductivity at 0, 10, 20, and 30 cm of matric tension.

For subsequent multivariate analyses, all variables were standardized to a mean of 0 and a standard deviation of 1 to eliminate bias due to differing measurement scales. Principle component analysis was used to reduce the original number of variables (35) to a smaller set by determining which variables were most responsible for explaining differences among the experimental units. This statistical technique was also used to obtain a graphical expression of the variability contained within profiles as well as among them. Cluster analysis was used on the reduced and standardized variable set to examine the nature of the similarities and differences of the soil horizons, i.e. to statistically group them, and discriminant analysis used to test the significance of the groups.

RESULTS AND DISCUSSION

The hydraulic conductivity (K) of the soil can be influenced by many properties which may in turn affect the operation of a septic system drainfield. During the course of this study many observations were made in the field and laboratory regarding the nature of soil water movement in the soils of the Flathead Valley. This section describes the relationships between soil water movement, drainfield absorption of effluent, and the physical and chemical soil properties evaluated as part of this research.

Clay Mineralogy

Table 4 presents the clay mineralogy data from selected sites and horizons. Samples were selected from those sites having appreciable clay content, and/or from horizons evaluated for hydraulic conductivity. As the procedure used is only semi-quantitative (Klages and Hopper, 1982), values have been rounded to the nearest 10 percent. Illite is the predominant clay mineral in each of the horizons examined (Table 4), with smectite clays present as about 10 percent of total soil clay. While all clays will experience some swelling upon wetting, smectite clays are known to exhibit the greatest change in volume and illitic clays are subject to minor swelling (Hillel, 1980). Severe swelling will result in significant changes in the pore size distribution of a field soil, reducing the proportion of larger pores responsible for much of the water movement that occurs at low moisture tensions. The result is decreased hydraulic conductivity. The results of this table suggest that little swelling should occur in the soils evaluated in this study, and therefore clay mineralogy is not expected to play an important role in the hydraulic properties of the study area soils.

Table 4. Results of clay mineralogy analysis for selected horizons.

	Clay Mineral (percent of clay fraction)						
Site/ Horizon	Smect.	Vermic.	Chlor.	V/C	Illite	Kaolin	Quartz
1, C1	10	*	10	*	70	5	5
3, B2t	10	0	10	0	50	10	10
4, C1	10	0	10	10	50	20	0
5, C1	10	*	10	*	60	20	0
7, B2	10	0	10	0	60	20	0
9, C1	0	0	0	0	90	10	0
9, ##	0	15	5	0	60	20	0
11, C1	10	*	10	*	60	20	0
12, B2t	10	0	10	0	60	20	0

Smect. = Smectite; Vermic. = Vermiculite; Chlor. = Chlorite; V/C = Vermiculite/Chlorite intergrade; Kaolin. = Kaolinite

* = Vermiculite, Chlorite, and V/C intergrade reported as Chlorite

= Clay lamellae

In Situ Hydraulic Conductivity

Results of the hydraulic conductivity tests performed on selected horizons at each site are discussed in the following paragraphs. Field data for each test is presented in Table 5. In obtaining the field hydraulic conductivity data, an attempt was made to conduct the test out to a matric tension of at least 30 cm water, as tensions in this

Table 5. Field data for *in situ* hydraulic conductivity tests.

SITE	HORIZON	MATRIC TENSION (cm)	HYDRAULIC CONDUCTIVITY (cm/day)
1	C1 (top pit)	42	0.8
		8	1.5
		0	72.4
1	C1 (middle pit, left)	42	1.2
		17	4.7
		3	215
		0	340
1	C1 (middle pit, right)	40	0.8
		10	1.4
		4	240
		0	375
1	C1 (bottom pit)	65	0.4
		16	2.3
		0	161
3	C1	26	0.8
		12	2.7
		0	31
4	B2 (1st run)	43	1.3
		27	2.6
		0	105
4	B2 (2nd run)	36	2.4
		11	35
		0	78
4	C1	40	2.5
		23	6.9
		0	24
6	B21	30	23
		12	71
		0	220
6	IIIC3	23	19
		15	40
		0	3200

Table 5 (continued). Field data of hydraulic conductivity tests.

SITE	HORIZON	MATRIC TENSION (cm)	HYDRAULIC CONDUCTIVITY (cm/day)
7	C1ca	63	9
		32	25
		0	80
7	IIC2	25	40
		0	265
9	C1	41	16
		32	50
		0	405
11	A3	49	4.8
		11	19
		0	195
11	B2	38	41
		15	13
		10	24
		0	59
12	B2t	19	0.4
		6	1.0
		0	2.9
13	C1	82	2.0
		60	45
		31	290
		23	360
		0	595

range are typical of those found beneath absorption fields (Bouma et al., 1972). Also, as water flux through the soil column at higher tensions becomes very slow, a much longer period of time is required to reach equilibrium conditions, sometimes a period of days. In order to have enough time to evaluate as many different horizons as possible, the 30 cm matric tension limit was used as a reasonable cutoff point for the test.

At three of the 13 sites, in situ tests were not conducted. The lacustrine deposit at site 8 was similar to those of two other sites where horizons were tested (3 and 5), and therefore was not evaluated. At sites 2 and 10, a combination of high coarse fragment content and a brittle till made it impossible to carve out a soil column on which to conduct the test. This limitation of the crust method is discussed further in a later section.

Lacustrine Sites

At site 5, columns were carved out in each of two horizons containing varves (couplets consisting of clay and silt laminae) with thick (3-5 cm) laminae. Clay layers in the varves served to retard downward water movement, and the required steady-state conditions were never achieved. Instead, the silt layer above the clay became saturated and began to flow out and down the sides of the soil column. Analyses of the silt and clay portions of the varves at site 5 revealed the silt layers to be 87 percent silt, and the clay layers to be 71 percent clay. Any individual clay layer would serve to greatly reduce overall permeability, and a series of them would drastically reduce flow. It was clear from this test that in lacustrine materials of this type, the vertical hydraulic conductivity would be negligible. Flow would occur predominantly in a horizontal direction along the tops of the restrictive clay layers.

While no quantitative conductivity value was obtained, the qualitative nature of flow in such soils was clearly demonstrated. Review of the literature yielded saturated hydraulic conductivity values in the range of 10^{-3} cm/day for varved materials (Ali et al., 1980; Wu et al., 1978; Warzyn Engineering, Madison, Wis., personal communication). This would be a value for combined vertical and horizontal flow, with the horizontal component dominating. It should be noted that the K values obtained from other gypsum crust test measurements represent vertical conductivity estimates only.

Crust test results were obtained for three other horizons derived from lacustrine parent materials. Site 3 was strongly varved, yet the hydraulic conductivity values (Figure 8) are much higher than expected for such a layered and clayey (68 percent) soil. This can be explained by the strongly expressed soil structure at that site which provided many larger interpedal pores. Hydraulic conductivity in the near-saturated range would be quite rapid through such large pores. Also present were continuous vertical cracks extending to a depth of at least two meters. These cracks were coated heavily with clay cutans, reflecting the preferential flow of water through those larger pores under saturated and near-saturated conditions. Cracking of this nature is most commonly observed in soils with smectite clays and with an elevated exchangeable sodium percentage (ESP) or sodium absorption ratio (SAR). The smectite clay fraction of this site was approximately

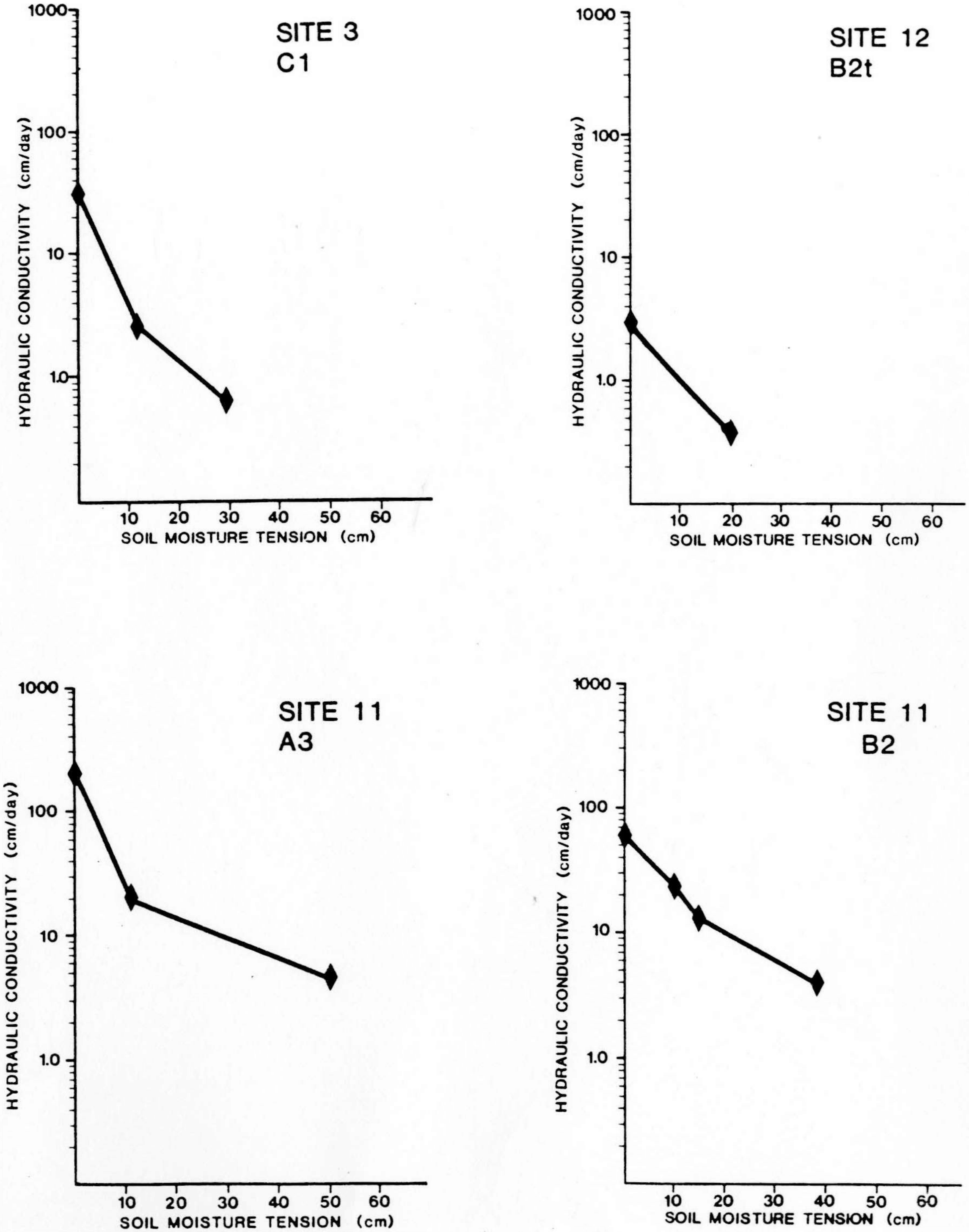


Figure 8. Hydraulic conductivity curves for soil horizons formed in lacustrine materials.

10 percent (Table 4), and ESP and SAR values were below 1.5. However, columnar structure was observed in the upper horizons, perhaps a relict indicating higher sodium contents in the geologic past, which have been subsequently leached from the profile.

Strongly expressed structure of this nature provides many larger interpedal pores that will conduct substantial volumes of water at the low matric tensions developed during the crust test. Smectite clays represent only a small fraction of the clay in this horizon (Table 4). However, in a high clay content soil of this kind, even limited inter-particle swelling of illitic clays might be expected to close the interpedal pores. The soil column used for this test was wetted for a period of nearly 36 hours, and wetted to saturation for just under six hours. This length of time may have been insufficient to cause appreciable swelling of the soil. However, when exposed to prolonged wetting conditions like those imposed by a septic system drainfield, there is an increased likelihood that considerable swelling could occur, enough to decrease the hydraulic conductivity to values considerably less than obtained in this field test.

Site 11 is a lacustrine soil, but lacks interbedded silts and clays. It is dominantly silty (all horizons contain more than 75 percent silt). The lack of varves is probably the result of deposition in a somewhat higher energy environment. Its inherited geologic structure is laminated silt layers, some with higher clay content (15-24 percent), but not as much as observed in the other lacustrine sites and not expressed as well-defined varves. The saturated and unsaturated K values of the two horizons tested are relatively high

(Figure 8). This can be explained by the silty textures and the absence of high clay content laminae (i.e. no varves), and the geologic (rather than pedogenic) structure inherent in these horizons, that of thinly bedded, highly fractured silt laminae. Such fractures provide many relatively large, connected pores which will conduct much water in the near saturated range.

Site 12, less than a mile from site 11, is a sodic-lacustrine soil, with a very high clay content (48-60 percent) in the B2t, C1ca, and C2 horizons. Illite again is the dominant clay mineral (Table 4). Columnar structure was observed in the B2t, and poorly expressed varves are evident in the C3 and C4 horizons. Columnar structure is often noted in soils with high sodium content (U.S. Soil Conservation Service, 1983), and the poor expression of varves could have been caused by sodium-influenced swelling (the subsoil ESP = 10-11, SAR = 12-15) and subsequent disruption/mixing of the varved layers. The low hydraulic conductivity values obtained for the B2t horizon (Figure 8) are probably due to the high clay content and tight structure (bordering on massive). In such systems, no larger interpedal pores are present, and all water movement must occur in the finer pores, the result being low permeability.

Glacial Till Sites

Only one of the three glacial till sites (site 4) was tested because of the difficulties encountered in trying to carve out a coherent soil column in brittle horizons containing numerous coarse fragments at sites 2 and 10. Two consecutive tests were performed on a column in the B2 horizon at site 4 to serve as a check on the reproducibility of the gypsum crust method. After completion of one entire series of tests, the apparatus was left in place for a period of 10 days. A series of gypsum crust tests was then repeated on this same soil column. The results of the duplicate tests were in good agreement as seen in Figure 9. While the shapes of the two K-curves differ slightly, there is little difference in the K values obtained for specific matric tensions (less than one-half order of magnitude).

Results from the C1 horizon were very close to those of the B2 horizon at higher tensions (Figure 9). The higher saturated K value of the upper horizon is probably due to the presence of large (1 mm range) pores observed in that column. These pores were formed from old root channels (this was a forested site, and such pores are common in forest soils), and would strongly contribute to flow during saturated

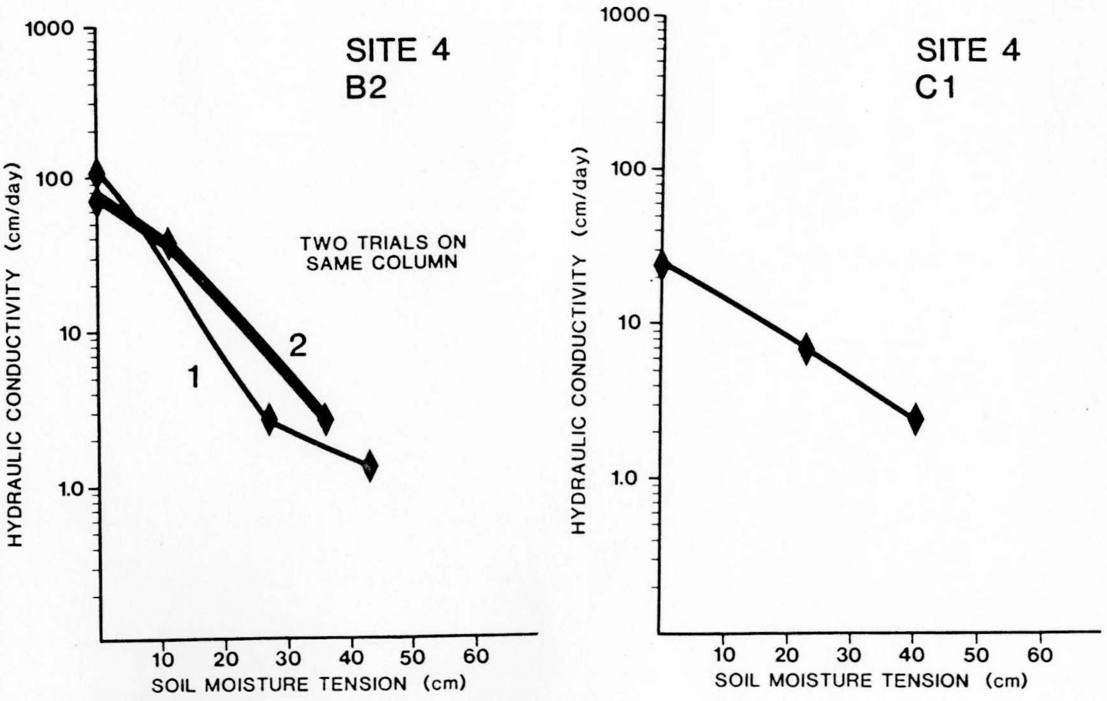


Figure 9. Hydraulic conductivity curves for soil horizons formed in glacial till at site 4.

and near-saturated conditions. Large pores were not observed in the C1 horizon column, which may account for the smaller saturated K values determined for this horizon. Textural properties of the two horizons were similar.

Coarse-Textured Sites (fluvial and aeolian)

As might be expected, the coarse-textured sites (1, 6, 7, 9, 13) exhibited the greatest hydraulic conductivities, and the largest drops in conductivity with increased matric tension. For example, the IIIC3 horizon at site 6, composed of coarse sands (86 percent coarse and medium sands) had a saturated conductivity in excess of 3000 cm/day, yet at a relatively low tension of 15 cm, unsaturated K had decreased two orders of magnitude to 40 cm/day (Figure 10). Such a coarse, sandy soil can be expected to have a high percentage of large pores that would conduct much water at saturation. Pores of this size will contribute little to water movement at higher soil tensions (Bouma et al., 1972), as reflected in the K-curve for this horizon (Figure 10). It should be noted that for this horizon, the saturated K value may lack the accuracy of other values in this study. The combination of very rapid flow through the sandy soil and the limited water reservoir capacity (1000 ml) of the field apparatus only allowed evaluation of saturated flow for periods of less than 10 minutes.

The hydraulic conductivity curve of the B21 horizon in the same profile (Site 6) displayed much less sensitivity to increasing moisture tension (Figure 10). While this is also a sandy horizon (83 percent versus 94 percent for the IIIC3), it has a much more even distribution of sand sizes (Table 37, Appendix 3). This would allow for more dense

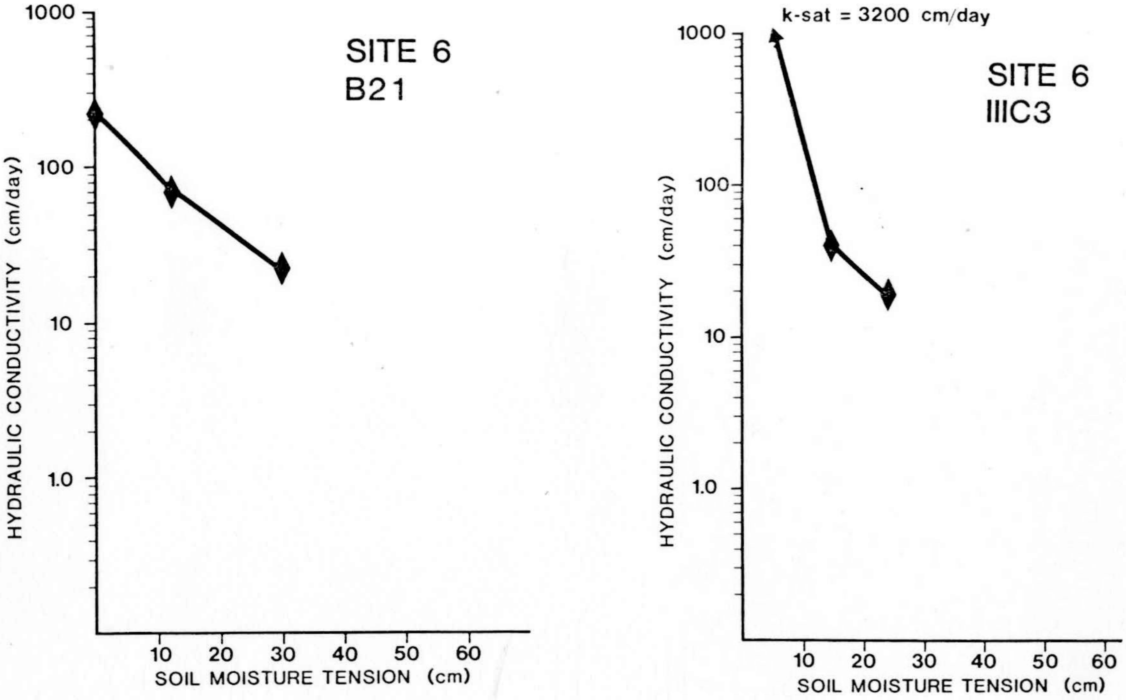


Figure 10. Hydraulic conductivity curves for soil horizons formed in sandy outwash at site 6.

packing of sand particles, both reducing overall porosity, and resulting in smaller pore sizes (Fetter, 1980). It also would explain the much lower saturated hydraulic conductivity of this sandy horizon compared to the IIIC3 (220 versus 3200 cm/day).

The C1 horizon at site 13 is interesting because it too had a high saturated K, yet maintained it over a rather wide range of potentials before dramatically decreasing (Figure 11). This can be explained by the rather unique particle size distribution of this soil (Figure 12), which shows that 80 percent of the soil grains have diameters in the relatively narrow range of 0.03-0.10 mm (coarse silts-very fine sands). Combined with a lack of pedological structure, this results in a rather uniform pore size distribution, allowing most soil pores to remain full until a critical matric tension is reached (in this soil, apparently in

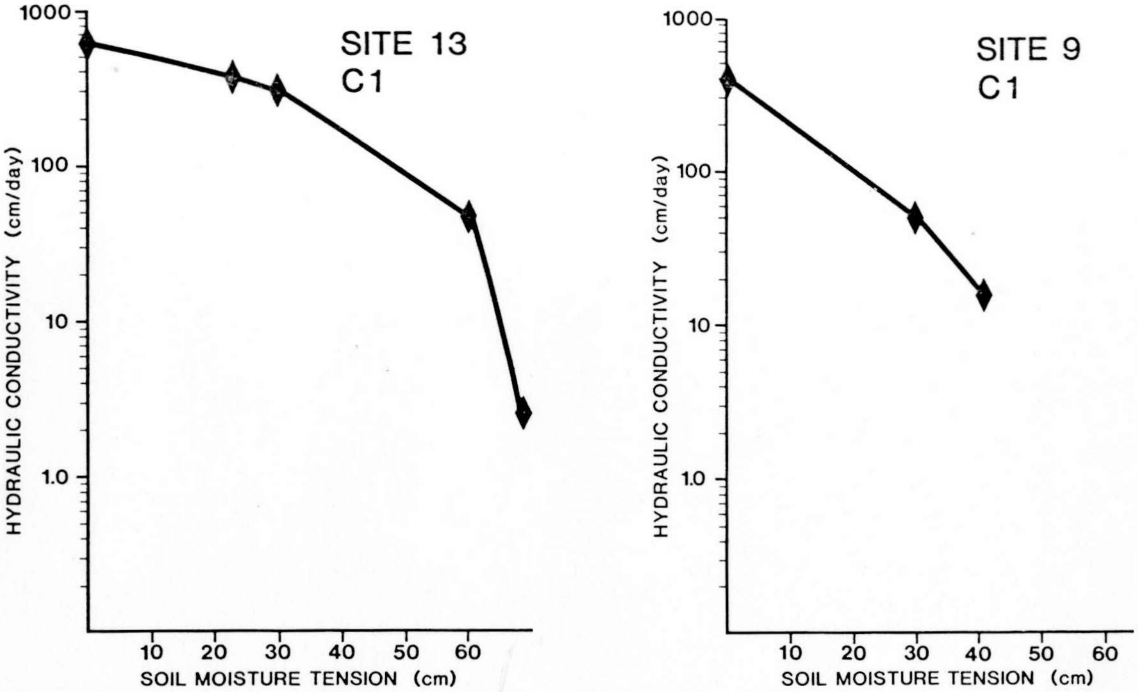


Figure 11. Hydraulic conductivity curves for soils formed from sandy materials at sites 13 and 9.

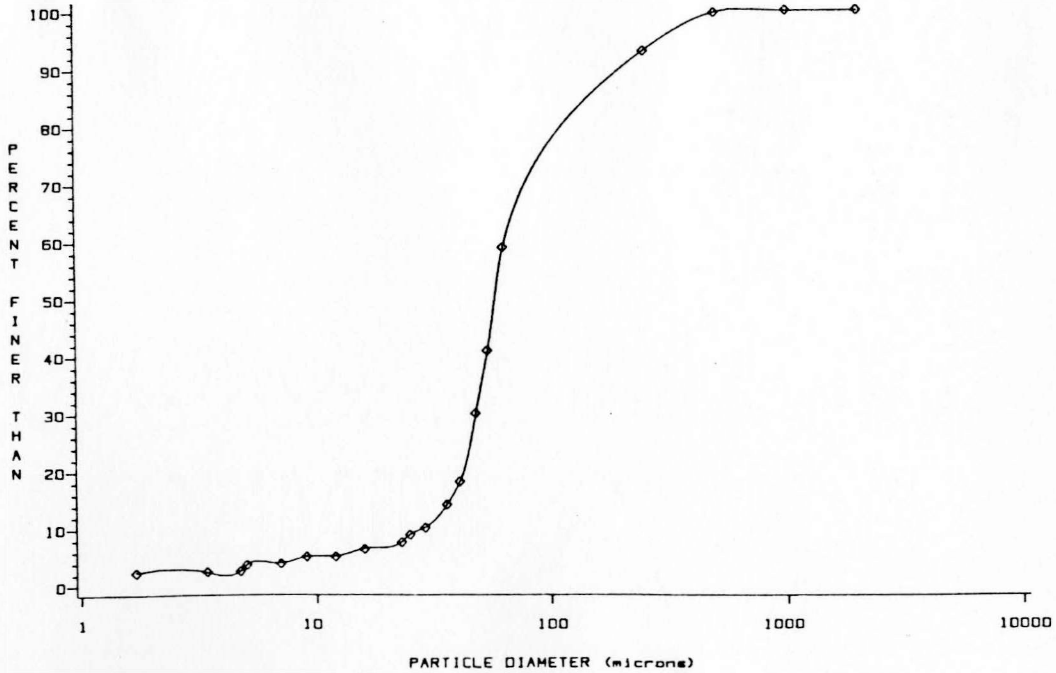


Figure 12. Particle size distribution curve for the C1 horizon, at site 13.

the range of 30-50 cm). At that time, most larger pores will empty over a narrow range of further tension increases, leaving a small percentage of the total pore volume (the small pores) to conduct water, resulting in low values of unsaturated K.

Site 9 was a soil developed in sand dunes. Its average sand content was 90 percent, primarily medium and fine sands (36 and 34 percent, respectively). Thin (1-3 cm) horizontal bands of clay-enriched zones (lamellae) were present at intervals of approximately 15-25 cm throughout the profile. These bands contained an average of 10 percent clay versus 0-2 percent clay for the matrix soil. Apparently this was not enough of a clay increase to significantly influence pore size distribution or water movement in the C1 horizon. The hydraulic conductivity curve of this horizon (Figure 11) is similar to that of the sandy B21 horizon at site 6 (Figure 10).

Particle size distribution curves for the C1ca and C2 horizons of site 7 showed that in both horizons, coarse silts and very fine sands are dominant (over 65 percent of soil matrix). Pedogenic structure was not evident in either horizon. The C2 horizon is somewhat coarser-textured (Table 38, Appendix 3), and this is reflected in its higher saturated permeability (Figure 13).

The landscape at site 1 offered an opportunity to examine the differences in soil characteristics and hydraulic conductivity over a relatively short distance in soils developed from ice-contact stratified drift. The original soil pit was at midslope. In the second summer of field work, two additional pits were opened, one 60 meters upslope, and the other 180 meters downslope. Profiles of the three

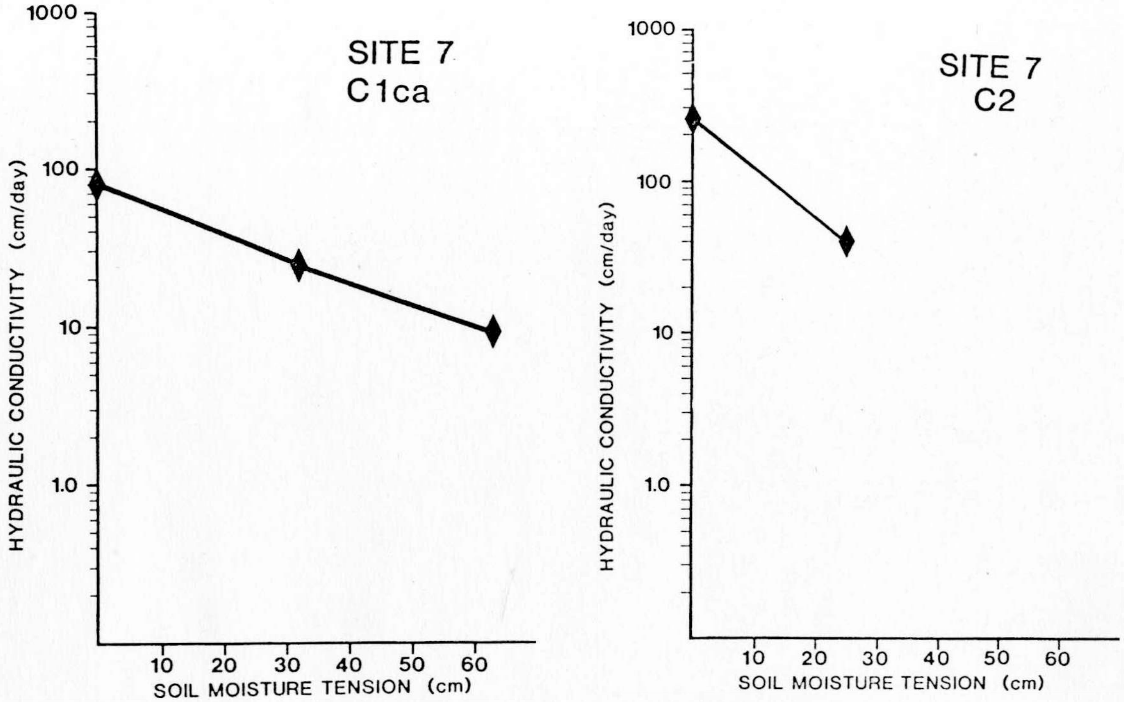


Figure 13. Hydraulic conductivity curves for horizons at site 7.

pits expressed the variability typically present in ice-contact glacial deposits of this nature. The upper pit subsoil was dominated by soil particles in the fine sand/coarse silt range (50 percent) with weakly expressed bedding and 25 percent coarse fragments. The original middle pit profile was less uniform, with generally coarser textures, high (25-50 percent) coarse fragment content, and clearly expressed stratification. At the bottom of the slope the subsoil profile was stratified into an upper horizon of medium sands with a few (less than 10 percent) small coarse fragments, and a lower, coarser horizon with 20-30 percent coarse fragments.

Crust tests were performed on one horizon from each soil pit. Each horizon tested contained at least 25 percent coarse fragments. At the middle pit, two columns in the C11 horizon were carved out to again evaluate the reproducibility of the gypsum crust technique. Results were similar to the coarser textured horizons evaluated at other sites, with K values rapidly dropping after initial high saturation values. The conductivity values (Figure 14) of the two columns in the middle pit displayed relatively good agreement, again supporting the repeatability of this method. Shapes of the K-curves were similar, and similar K values were obtained at most matric tensions evaluated.

Both horizons were sandy loams soils, and had a high percentage (greater than 50 percent) of fine gravel. The rapid decrease in hydraulic conductivity for both horizons is probably related to the presence of a number of very large pores, the result of the high coarse fragment content. Again these large pores allow rapid water movement under saturated conditions, but contribute little to hydraulic conductivity as matric tension increases. This same pattern is seen in the horizons from the other two pits (Figure 14), and again apparently reflects the role that coarse fragments play in providing macropores in coarser-textured horizons.

One further observation at this site deserves mention. The soils here have developed in deposits of ice-contact stratified drift, an inherently variable glacial deposit. Because of this variability, subsurface water movement may be complicated, as demonstrated by the presence of a small ephemeral stream at this site. As this stream travels downslope, it disappears suddenly, resurfacing a few hundred feet further down the slope. This unusual phenomenom can be explained by noting that the soil over which the stream flows is fine-textured

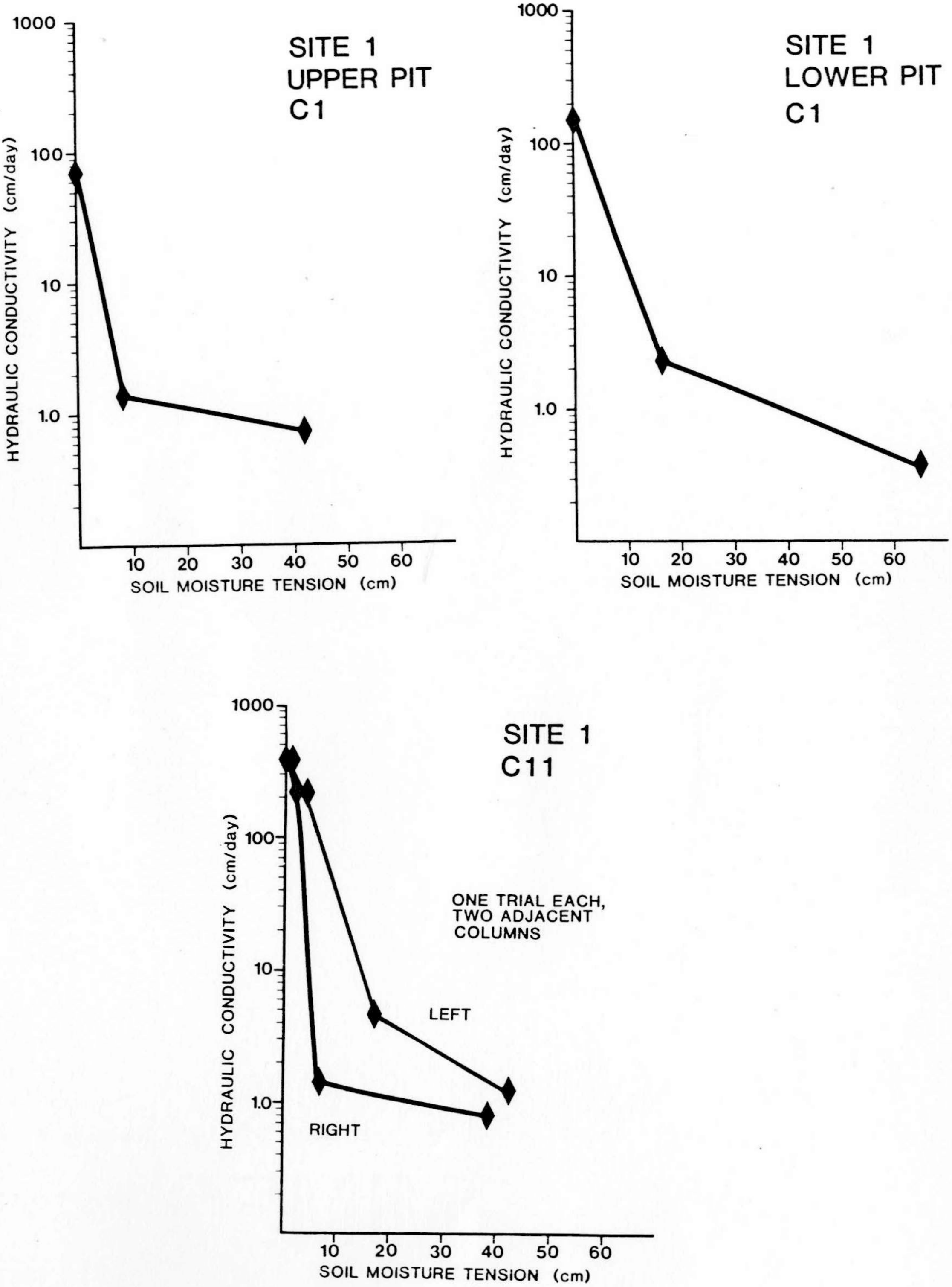


Figure 14. Hydraulic conductivity curves for soil horizons formed in ice-contact stratified drift deposits at site 1.

(predominantly silty), while where it disappears the soil becomes very sandy. Here the soil is permeable enough to absorb all the streamflow. It percolates downward through the soil until it reaches a layer of reduced permeability, and then flows laterally until it again intersects the surface slope and reappears. This natural example demonstrates the potential complexity of subsurface flow in this area.

Variable deposits of this nature cover much of the lower slopes of the Whitefish Range where this site was located. The complexity of the soils in this area would indicate that detailed on-site investigations be conducted to adequately characterize the soil potentials and limitations for septic systems.

Discussion of the Results of the Hydraulic Conductivity Measurements

The field work completed in this study has established a data base for estimates of the saturated and unsaturated hydraulic conductivity of a number of soil horizons in the Flathead Valley. In addition, a number of general observations have been made regarding relationships of soil properties to soil permeability. Interpretation of these values requires that two questions be asked. What do these values explain about the nature of soil water movement in the Flathead Valley? What implications exist for septic system operation in this area?

Hydraulic Conductivity

In answering such questions, it is first important to gain some perspective on the inherent variability of soil hydraulic conductivity. Many researchers have addressed this topic, concluding that this is one of the most variable of all soil properties. High coefficients of variation are common even when many repeated <u>in situ</u> measurements are taken from the same soil horizon (Nielsen et al., 1973; Gumaa, 1978). Given such inherent variability in this soil property, it is possible, perhaps even probable, that the actual hydraulic conductivity of other horizons similar to the ones tested may vary by more than an order of magnitude from the single determinations of hydraulic conductivity obtained in this research. By themselves then, the hydraulic conductivity curves obtained from this field study should be accepted as first approximations, recognizing the desirability for confirmation through further research.

However, some general, yet powerful conclusions can be drawn from this work regarding the nature of soil water movement in the Flathead Valley. If the results of the <u>in situ</u> hydraulic conductivity tests are grouped according to depositional process/soil texture, it is evident that there is some consistency in the results obtained for all the horizons within a group. Glacial till (Figure 15) and ice-contact deposits (Figure 15) display the greatest within-group uniformity, although this is somewhat biased as in each case, all of the observations came from either a single profile (till), or from several profiles in close proximity (ice-contact).

The fluvial/aeolian group (Figure 16) shows somewhat greater variability, representative of both the variety of sites evaluated, but more importantly, of the differences in the particle size characteristics among these sandy horizons. Some are composed primarily of coarse sands, and others, fine or very fine sands. The influence of sand size on saturated hydraulic conductivity was well-defined in a study by

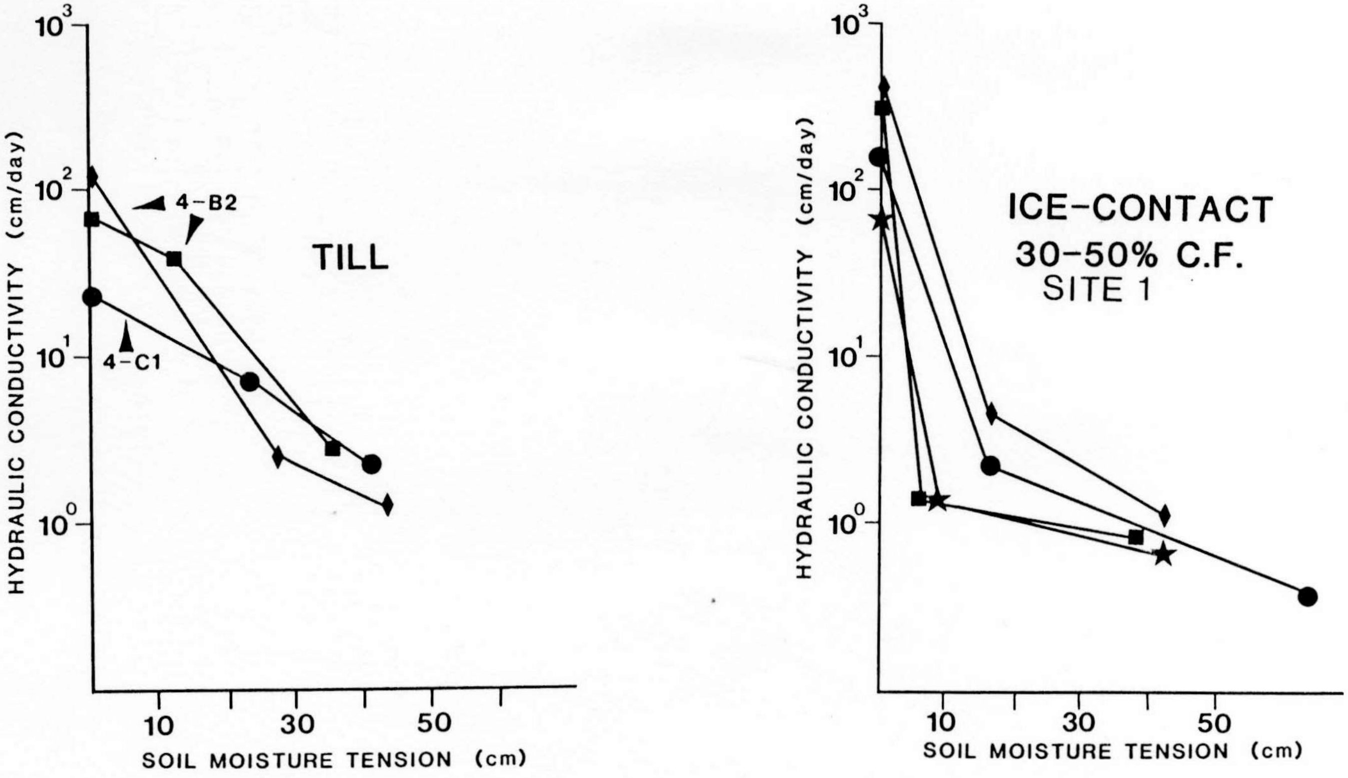


Figure 15. Hydraulic conductivity curves for soil horizons developed from glacial till and ice-contact stratified drift. (Refer to Figure 15 for key to ice-contact K-curves).

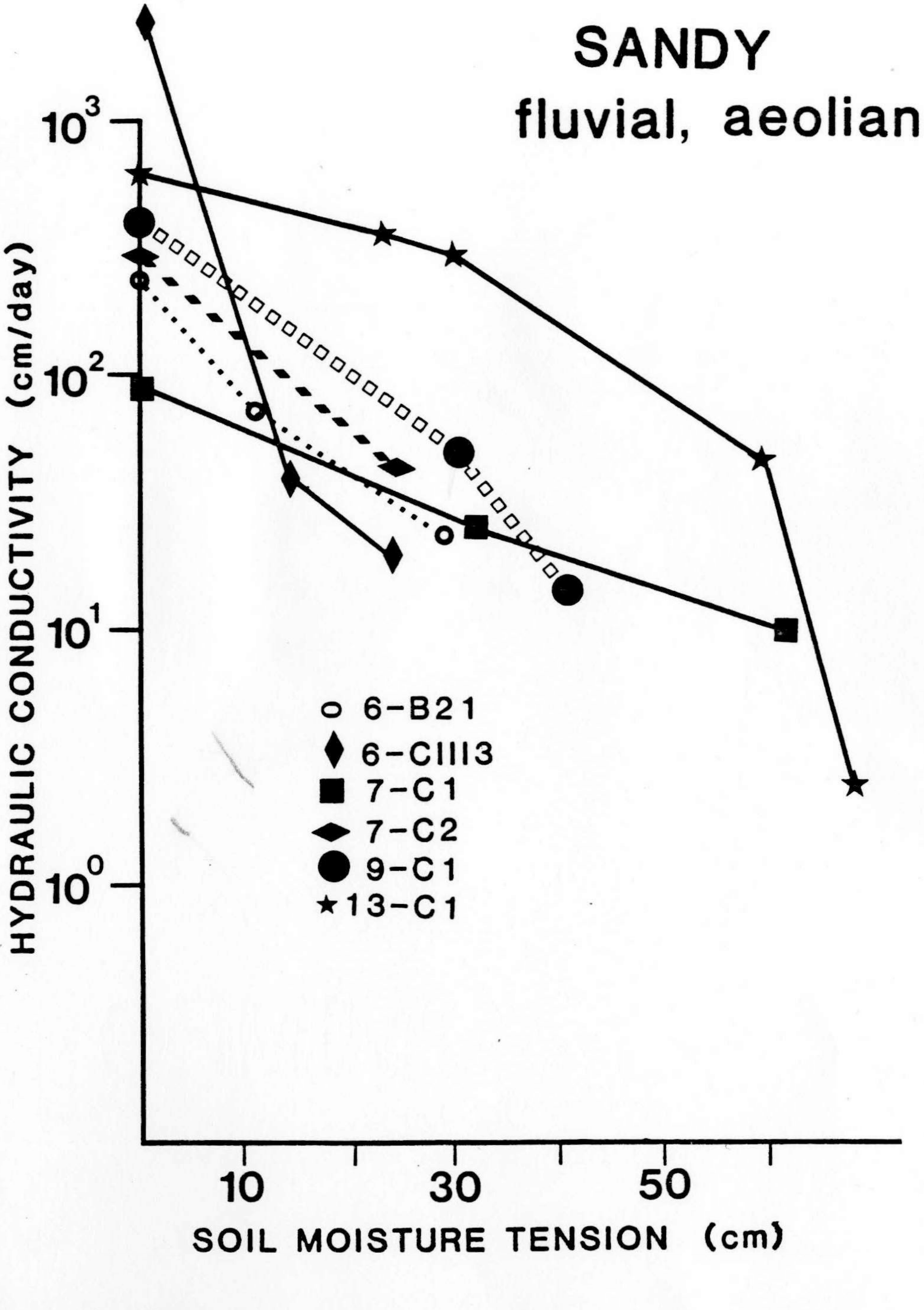


Figure 16. Hydraulic conductivity curves for soil horizons developed in sandy materials.

Masch and Denny (1966). They noted that saturated hydraulic conductivity in sands could be predicted on the basis of the average particle size standard deviation. For samples with identical standard deviations, increasing particle size results in increasing K (Masch and Denny, 1966). For samples with identical particle size, K decreases as standard deviation increases. These observations reflect the basic differences in the kinds of pore size distributions produced by varying particle size and diameter. When a variety of particle sizes are present (high standard deviation), smaller particles fill the voids between the larger ones, decreasing average pore size and total porosity. When such small particles are absent, large pores are plentiful, and K is high.

Direct comparison of the saturated K values obtained in this study with the work of Masch and Denny (1966) is difficult, as that study used samples composed only of sand, and was conducted in the laboratory. Table 6 compares saturated K values predicted from the method of Masch and Denny (1966) with observed field values from this study for the four horizons tested that contained more than 75 percent sand and less than 5 percent coarse fragments. Relatively good agreement is found between observed and predicted values of 3 of the horizons, the predicted value varying by less than 31 percent of the observed value. The worst comparison is for the IIIC3 horizon at site 6. As discussed earlier, rapid saturated hydraulic conductivity for this horizon limited the confidence placed on its measurement, which may explain the poor agreement between observed and predicted values.

Table 6. Observed *in situ* saturated hydraulic conductivity compared to values predicted by the method of Masch and Denny (1966).

SITE	HORIZON	HYDRAULIC CONDUCTIVITY (cm/day) OBSERVED	CALCULATED	PERCENT DIFFERENCE
6	B21	220	245	11
6	IIIC3	1650	3200	94
9	C1	405	531	31
13	C1	595	450	24

The variability of hydraulic conductivity values within the lacustrine group (Figure 17) was explained in a preceeding section as the result of some horizons having either: 1) silty texture; 2) strong structure and relatively large interpedal pores (with or without well-defined varves); or 3) varves with near-massive structure.

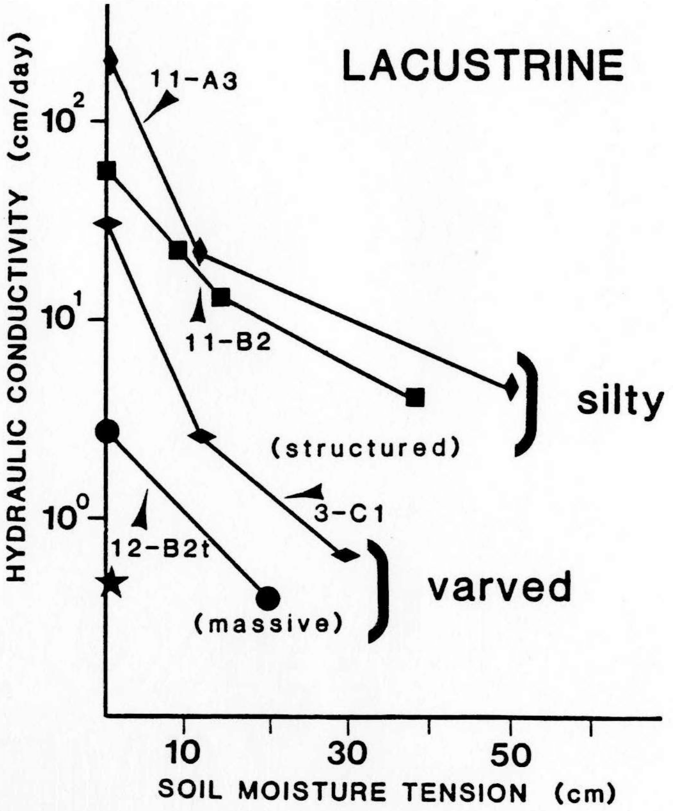


Figure 17. Hydraulic conductivity curves for soil horizons formed in lacustrine deposits. (Star symbol on vertical axis represents estimate for K at site 5).

If the hydraulic conductivity curves of all non-lacustrine horizons are superimposed as in Figure 18, the general grouping becomes more apparent. The sandy sites have the highest conductivities over the spectrum of moisture tensions, with ice-contact horizons having high saturated K values that drop off rapidly with increasing tension, and glacial till horizons showing lower saturated permeabilities but a more gradual decrease as matric tension increases.

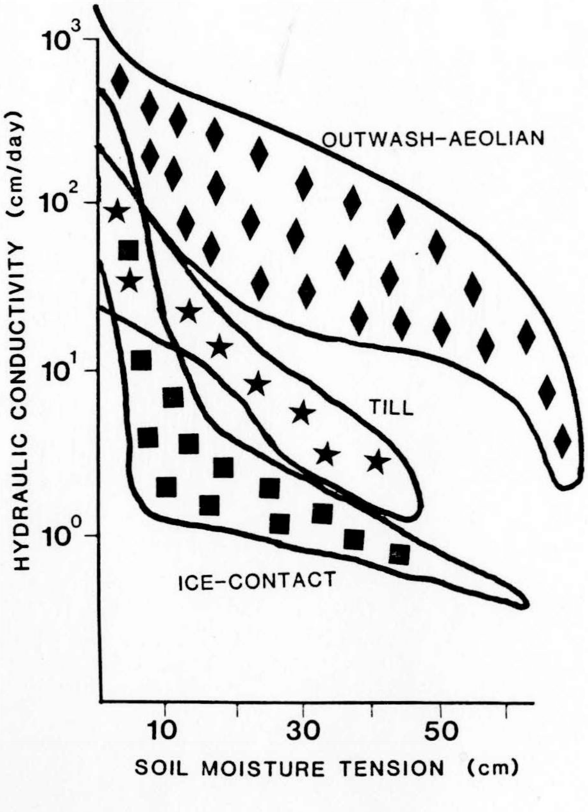


Figure 18. General grouping of hydraulic conductivity values for horizons formed in outwash-aeolian, glacial till, or ice-contact deposits.

Stratification

One of the more important findings of this research was the documentation of widespread textural stratification in the top two meters of many of the surficial deposits/soil profiles throughout much of the study area. This stratification may be expressed as varved lacustrine deposits, or as an intermingling of till, glacio-fluvial, or lacustrine deposits. Since by definition these types of deposits should express stratification, to a geologist this should not seem surprising. However, from the perspective of a soil scientist concerned with the movement of water through the soil, the presence of two, three, or even four different horizons with contrasting texture and abrupt horizon boundaries, all within the surface two meters (or less) of the soil profile, suggests that stratification is a dominant property of such soils, especially as it influences soil hydraulic conductivity. Such stratification was documented in most of the soils evaluated formally in this study, and also observed in many of the roadcuts and soil pits examined during the course of this research.

Soils at five sites (3, 5, 8, 11, and 12) have formed from lacustrine sediments, and with the exception of site 11, contain alternating layers of high silt and high clay content. Sites with fluvial deposits (1, 6, and 7) have interbedded sands and gravels, or sands and silts. The three glacial till sites (2, 4, and 10) exhibit textural stratification in their lower horizons. The soil at site 9 developed in relatively uniform windblown sands, yet contains repeated horizontal bands of increased clay content (clay lamellae) throughout its profile. The intriguing formation of these bands is discussed by

Torrent et al. (1980). Of the 13 sites, only site number 13 lacked noticeable stratification.

The source of such ubiquitous textural stratification is the variety of depositional sedimentary environments resulting from the complex nature of glacial and proglacial activities during the Pleistocene Epoch. Perhaps it is most commonly expressed as lacustrine deposits (both with and without varves). Such deposits are widespread due to the areal enormity of glacial Lake Missoula, and other, more localized glacial lakes during the Pleistocene. Such deposits may be found virtually anywhere in the area, from the floodplains of the Whitefish River (site 3, elevation = 917 m), to the heights of the Polson Moraine (site 10, elevation = 950 m). They may dominate an entire profile (as they do at site 3), or be found sandwiched between an overlying ablation till and buried outwash (site 5).

Co-dominating with lacustrine deposits are proglacial fluvial deposits, and other deposits reworked by river action during the last 10,000 years. This is a reflection of the three separate lobes of ice that alternately and collectively entered into and retreated from the valley, and the presence of several major rivers in the upper valley. Glacial tills also exhibit stratification, with looser, more permeable ablation tills perched atop compacted basal tills. The complex nature of these depositional (and erosional) forces results in a soil landscape of considerable variability, both vertically within a profile, and horizontally across the landscape. Several times during this study soil pits were observed with radical profile textural changes from one end of the pit to another, a distance of less than 2 meters. Figure 19 contains photographs of typical examples of stratification in the soils of the study area.

The textural stratification present in the soils of the study area may exercise a strong influence on vertical water movement, depending on the abruptness and degree of the textural change, and the thickness of the varying layers. Hillel (1982), demonstrates that it is the hydraulic <u>resistance</u> (R_s) of the various soil layers (rather than the hydraulic <u>conductivity</u>), that controls the overall vertical K. R_s is defined as the quotient of the length (L) or thickness of the soil layer divided by the hydraulic conductivity of the layer ($R_s = L/K$).

Total flux (V) per unit area through a layered profile can be caluculated using the following equation:

$$V = \Delta H/(R_{s1} + R_{s2} \cdot \cdot \cdot R_{si}) \qquad \textbf{Eq. 3}$$

where ΔH is the total hydraulic head drop across the entire profile, and R_{si} is the hydraulic resistance for i^{th} soil layer. Thick horizons with low hydraulic conductivities will provide large values of summed R_s, as will profiles with many layers of varying K (such as in varved systems), and result in low total fluxes through the profile.

<u>Stratification and Septic Systems</u>

Textural variability in both the horizontal and vertical plane has several important implications for the operation of septic systems. The potential for lateral discontinuity of soil deposits requires on-site soil profile investigations at most proposed drainfield locations. Extrapolation of profile information from adjacent sites may often be insufficient, and may result in unsatisfactory drainfield design.

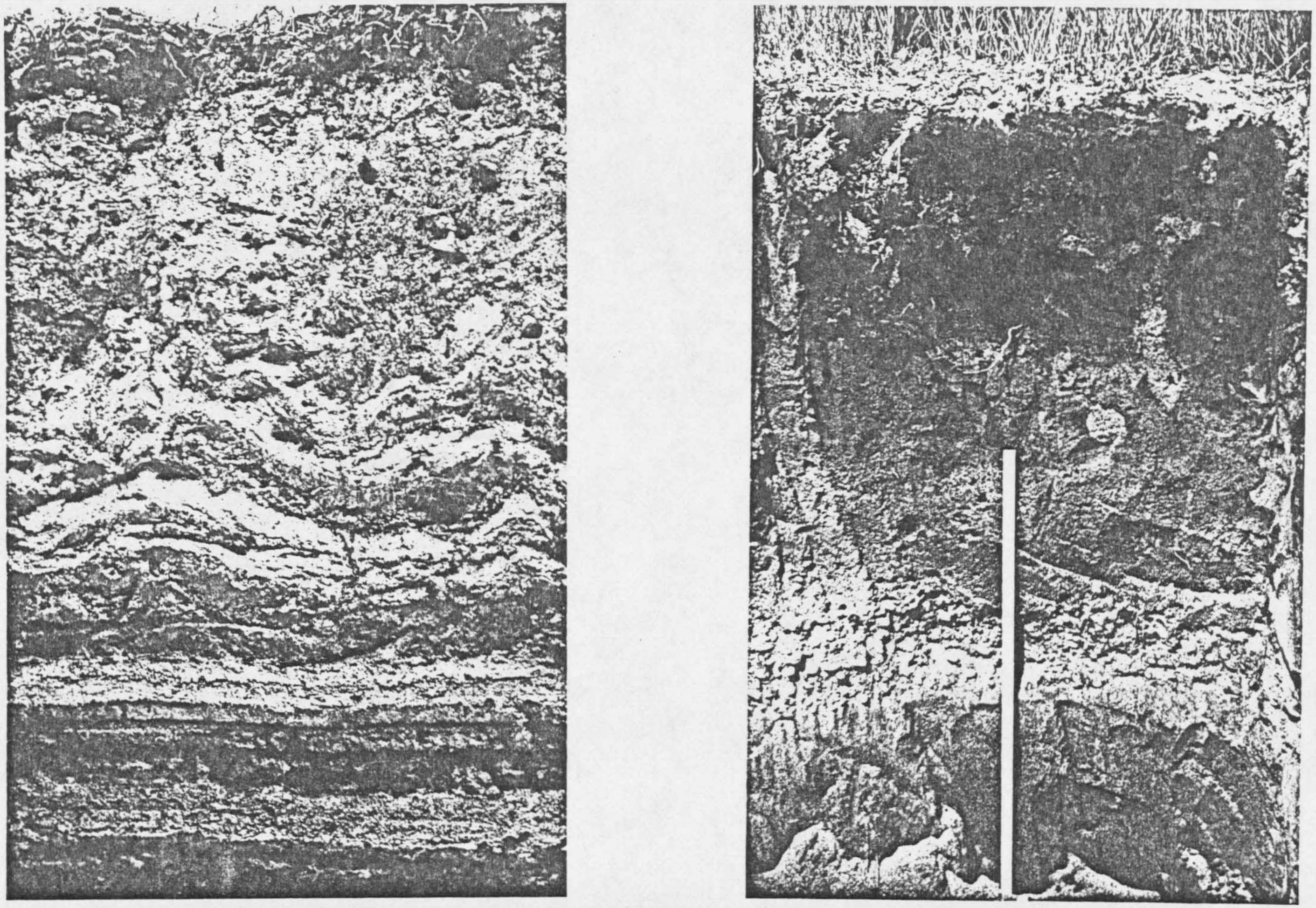


Figure 19. Photographs of stratified soil profiles in the study area. A till-varved deposit is present on the left, and an outwash deposit on the right.

Stratification may also complicate the percolation test procedure. While in general the perc test is not recommended as a method for determining site suitability or drainfield size because of its inherent variability, it is recognized that in fact the perc test is commonly used in this manner. In stratified profiles containing horizons of both high and low permeability, significant lateral flow into the more permeable horizon may result in perc rates that are not representative of vertical flow. This was noted in a study by Lewis (1975), who conducted perc tests on many soils in Nebraska, and found that stratified profiles exhibited the greatest variability in perc rates. He attributed this to differential horizontal flow into soil layers of highly different permeablity.

Figure 20 shows the effects that stratification may have on the perc test, as well as the proper way to conduct the test in stratified soils. During measurement of the percolation rate, the water level in the hole should be maintained within the soil layer of interest (the least permeable layer). Should the water level rise above the less permeable soil layer, faster (unrepresentative) perc rates will be obtained. As a result, the effluent loading rates used to design the drainfield will be too high. Drainfields designed from these rates will probably be smaller than needed to handle the daily flow of effluent, and may fail prematurely.

This discussion demonstrates that in stratified soils, considerable care needs to be exercised in performing the perc test and in interpreting the results. Usually the hole should only be dug as deep as the proposed level of the bottom of the drainfield trench.

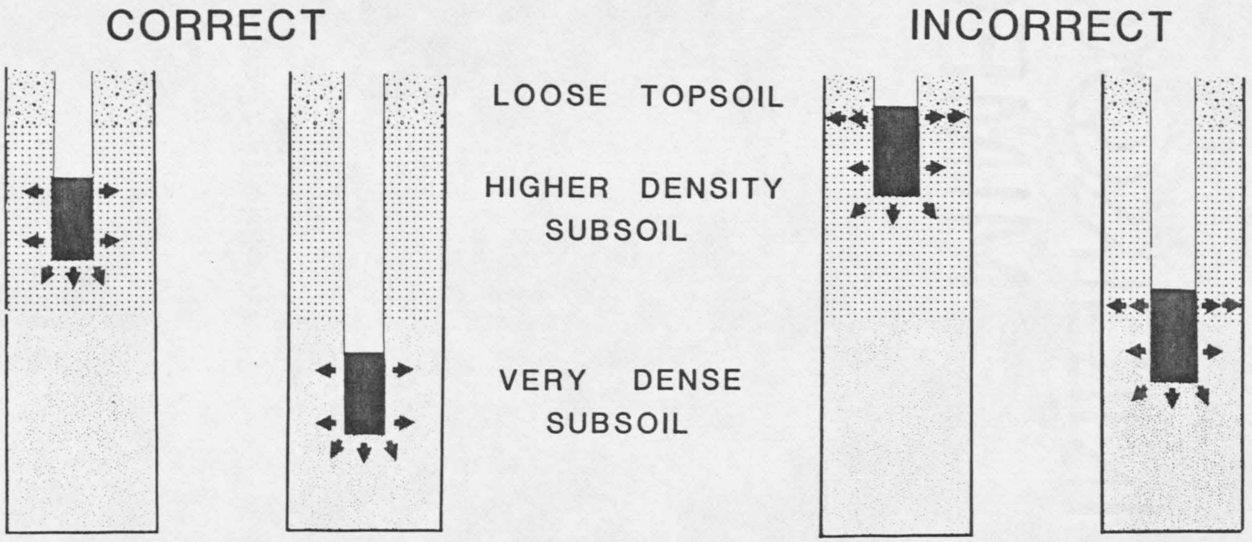


Figure 20. Hypothetical example of the influence of stratified subsoil conditions on the performance of the percolation test.

However, if examination of the soil profile reveals a low permeability layer within 1.5-2 meters of the soil surface, an attempt should be made to test that layer, and those results used for final engineering design of the drainfield.

Stratification may also play a role in the long-term performance of the septic system drainfield because of its influence on vertical hydraulic conductivity. Should a horizon of lower permeability exist at depth below the trench bottom (0.6-2 meters, for example), the potential exists for a perched water table to develop, especially during wet seasons (e.g. the spring). As the distance between the water table and drainfield trench decreases, there will be reduced flow of effluent from the drainfield trenches due to a reduction in the hydraulic gradient (Janni et al., 1980). This study found that the amount of flow reduction will be greatest in sandy soils and least in clayey soils, a function of the difference in pore size distribution between the two textures.

In this regard it should also be noted that septic systems themselves may be responsible for increases in the height of the water table. Finnemore and Hantzsche (1983) examined the potential of ground-water mounding beneath septic systems over projected lifespans (10-20 years) and concluded that this was most likely to be a problem only in systems disposing of volumes of wastewater much greater than that generated by a typical single-family household. Such larger systems are becoming increasingly popular (American Society of Agricultural Engineers, 1982), requiring the careful consideration of such ground-water mounding on system performance.

Biomat development at the bottom of the drainfield trench may also be affected by such processes, contributing to premature failure of the system. The biomat is a dynamic entity tending towards equilibrium. At equilibrium, it is simultaneously being built up by anaerobic bacteria inside the trench, and being oxidized (destroyed) at an equivalent rate by aerobic bacteria in the unsaturated soil just below the trench. If stratification causes perched water tables and/or generally wetter soil profiles from increased water retention (Miller, 1969), it is likely that diffusion of oxygen to the soil beneath the drainfield trench will be inhibited (oxygen diffusion through water is 10,000 times slower than through air). This may cause a decrease in the biomat destruction process, allowing the mat to thicken. The hydraulic resistance of the biomat is largely determined by its thickness (Bouma et al., 1972). The net result will be increased ponding of effluent in the trench, and, if biomat development is severe enough, sufficient clogging of soil porosity to cause system failure.

The above discussion suggests that the presence of stratified soils requires that management decisions regarding the use of these soils for septic systems be based on a thorough knowledge of the site characteristics, and the implication of these characteristics on soil water movement. To maximize the potential for successful operation of a septic system, a higher level of expertise is required than is typically applied to the process of septic system siting, design, and installation. Sanitarians, septic system designers, and system installers need to be made aware of the implications of this soil variability for on-site treatment systems.

Critique of the Gypsum Crust Method

There are few methods available for obtaining both saturated and unsaturated hydraulic conductivity measurements from soils *in situ*. The three most widely used are the instantaneous profile (with a number of variations, it is by far the most popular), air-permeameter, and gypsum crust methods (Bouma et al., 1982). As discussed in the Methods and Procedures section, the instantaneous profile method was not suitable for this particular application. The gypsum crust method rarely has been used outside of Wisconsin, where it was developed. Likewise, the air permeameter method has found only limited application. Like the other methods, the crust test has its limitations. The comments below are the result of many hours of field use of this method on a wide variety of soils, and are intended as supplementary information on the technique which is not available in the literature.

The foremost problem to be overcome with the crust test method is maintaining the structural integrity of the isolated soil column. There are two major disruptive periods: during the initial carving of the column, and during subsequent removal of the hardened gypsum crusts after a particular test has been completed. Carving out the soil column without creating structural cracks is primarily a function of soil texture, consistence, moisture content, coarse fragment content, and expertise of the carver. Loose, sandy soils and friable, silty soils are easy to work with, and a coherent column can be carved in less than thirty minutes, while the process might take several hours with a tight, clayey soil. Limited amounts (5-50 percent) of small coarse fragments (less than 4-6 mm) do not preclude use of the method, but do complicate the carving process.

Clayey soils, soils with high coarse fragment content, and brittle, fine-textured soils pose significant challenges to successful isolation of a soil column. Up to six hours per column were spent during this study in unsuccessful attempts at isolating a single column in brittle glacial tills. At some sites, wetting the soil prior to the carving process was helpful, but at others, columns could not be isolated. As the desired column diameter was approached, removal of soil resulted in major disruption of part of the column, either by cracking or loss of excess soil material.

The second disruptive process involves removal of the gypsum crust at the conclusion of an individual measurement. Removal of gypsum crusts occurs 2-3 times for each column, and must be performed with great care to maintain column integrity. These crusts are very sturdy, and adhere solidly to both the infiltration ring and the soil column surface. The only satisfactory method for removing them is by breaking them apart using a hammer and fine chisel point. The initial pieces require considerable force to break up and remove. This process was greatly facilitated by the use of a battery-operated hand drill which was used to drill holes in the crust, weakening its cohesiveness. Once the first few pieces have been dislodged, the rest of the crust is easily removed. The hammering necessary during this procedure can disrupt the column, either by creating structural cracks in fine-textured soils, or causing total collapse of the column in loose, sandy soils. More than once during the course of this study this did occur, necessitating abandonment of the column and repetition of the entire experimental process.

After developing a sufficient level of expertise (at the expense of making many mistakes), a column can be isolated and instrumented within one or two hours. Usually a horizon can be evaluated within about 36 hours, and several horizons can be instrumented and monitored simultaneously. This is desirable, especially in research where the objective (unlike this study) is to characterize the hydraulic conductivity of a single soil series.

Once the instrumentation is in place, continuous monitoring until the completion of the experiment is the most effective means of data acquisition. This results in little sleep for the observer, as the apparatus needs to be checked every hour or two. Somnambulism is a desired trait for researchers interested in using this method.

If care is exercised during the critical steps, the method appears to provide satisfactory results. The concept of making direct measurements (as opposed to indirect measurements with the instantaneous profile method) of hydraulic conductivity on an undisturbed field soil is very attractive, and provides great confidence in the accuracy of the results. Given the inherent variability of soil hydraulic conductivity, the method is limited in that it makes a measurement of a small volume of soil that may or may not be representative of the surrounding soil. This is a limitation of all such techniques that can only be overcome by experimental replication.

Multivariate Statistical Analysis

An underlying goal of this study was to employ multivariate statistical techniques for development of regression equations relating soil hydraulic conductivity to other soil properties. Other multivariate methods such as principle component analysis, cluster analysis, and discriminant analysis have been widely used as classification tools in the earth sciences, but have only rarely been used to analyze and classify data from soil profiles. The intent was to develop an expertise in these techniques, and evaluate their utility in distinguishing the similarities and differences among the many soil horizons evaluated in this study. A key to the abbreviations used for variables throughout this discussion, as well as for those variables that required log transformations, is contained in Table 7.

Multiple Regression on Hydraulic Conductivity

The results of the setwise multiple regression of selected soil physical characteristics on log-transformed hydraulic conductivity values at 0, 10, 20, and 30 cm of matric tension were used to select the variables inserted in a standard direct multiple regression. The best three-variable model was selected in order to decrease the risk of overfitting the model (because of the small number of cases evaluated, 13), and because the four-variable models generally contributed little additional correlation.

The major statistics from the multiple regression analyses are found in Table 8. Adjusted R^2 is used as suggested by Tobachnick and Fidell (1983) because of the potential for inflated R^2 when the number of

Table 7. Key to the variable abbreviations used in the statistical analysis.

AVAILH2O	plant available water
BULKDENS	dry bulk density
DRYCONS	dry consistence
EC	electrical conductance
EFFERVES	effervescence
EXTRACA	extractable calcium
FIELDPH	field pH
FINESAND	fine sand content
H2OSAT	saturation percentage
LOGBAR15	log, 15 bar moisture characteristic
LOGCEC	log, cation exchange capacity
LOGCLAY	log, percent clay
LOGESP	log, exchangeable sodium percentage
LOGFRAG	log, coarse fragments
LOGHCO3	log, bicarbonate
LOGORGC	log, organic carbon
LOGSAR	log, sodium adsorption ratio
LOGSAT0	log, saturated hydraulic conductivity
LOGSAT10	log, hydraulic conductivity at 10 cm tension
LOGSAT20	log, hydraulic conductivity at 20 cm tension
LOGSAT30	log, hydraulic conductivity at 30 cm tension
LOGSOLCA	log, soluble calcium
LOGSOLMG	log, soluble magnesium
LOGSOLNA	log, soluble sodium
LOGTOTLN	log, total nitrogen
LOGXTRMG	log, extractable magnesium
LOGXTRNA	log, extractable sodium
MEDSAND	medium sand content
MOISTCON	moist consistence
PHPASTE	pH, saturated paste
PH1_1	pH, 1:1 soil:water
PH1_2	pH, 1:2 soil:calcium chloride
PLASTCON	wet consistence, plasticity
SAND	percent sand
SILT	percent silt
STICKCON	wet consistence, stickiness
STRGRADE	structure, grade
STRKIND	structure, kind
STRSIZE	structure, size
TENTHBAR	0.1 bar moisture characteristic
THIRDBAR	0.3 bar moisture characteristic
VCORSAND	coarse sand content
VFINSAND	very fine sand content

Table 8. Multiple regression equations for hydraulic conductivity, selected by highest adjusted R^2 for any group of three variables. (LSAT0, LSAT10, etc. = log K at 0 cm matric tension, 10 cm, etc.)

$$\mathrm{LSAT0} = 3.59 - 1.43(\mathrm{LOGCLAY}) - 0.04(\mathrm{FINESAND}) + 0.02(\mathrm{MEDSAND})$$

$R^2 = 0.81$
ADJUSTED $R^2 = 0.75$
$F = 12.78^{**}$

Variable	sr^2
LOGCLAY	0.45
FINESAND	0.10
MEDSAND	0.04

$$\mathrm{LSAT10} = 2.80 - 2.62(\mathrm{LOGCLAY}) + 0.11(\mathrm{TENTHBAR}) - 1.67(\mathrm{LOGAVAIL})$$

$R^2 = 0.72$
ADJUSTED $R^2 = 0.63$
$F = 7.83^{**}$

Variable	sr^2
LOGCLAY	0.46
TENTHBAR	0.19
LOGAVAIL	0.09

$$\mathrm{LSAT20} = 1.99 - 2.06(\mathrm{LOGCLAY}) + 0.02(\mathrm{VFINSAND}) + 0.05(\mathrm{THIRDBAR})$$

$R^2 = 0.68$
ADJUSTED $R^2 = 0.57$
$F = 6.40^{*}$

Variable	sr^2
LOGCLAY	0.23
VFINSAND	0.13
THIRDBAR	0.08

$$\mathrm{LSAT30} = 1.68 - 1.95(\mathrm{LOGCLAY}) + 0.02(\mathrm{VFINSAND}) + 0.04(\mathrm{THIRDBAR})$$

$R^2 = 0.68$
ADJUSTED $R^2 = 0.58$
$F = 6.50^{*}$

Variable	sr^2
LOGCLAY	0.20
VFINSAND	0.14
THIRDBAR	0.07

** Significant at the 0.01 level
* Significant at the 0.05 level

cases is small. In each case the log-transformed clay content contributes the most towards the overall multiple correlation, as shown by the squared semi-partial correlations (sr^2), with either various sand fractions or moisture characteristic values accounting for the rest of the correlation. The correlation is best for prediction of saturated hydraulic conductivity (adjusted $R^2 = 0.75$).

The correlations obtained from these regressions are reasonably high as well as statistically significant (Table 8). However, plots of predicted versus actual values for hydraulic conductivity in Figures 21-24 reveal that the confidence limits are about plus or minus one order of magnitude. The practical applications of these regression equations are limited both by these wide confidence limits and by the spatial variability of soil hydraulic conductivity, a property not evaluated in this study. Such limitations notwithstanding, the K values and these equations may provide a useful first approximation of soil hydraulic conductivity in some Flathead Valley soils. Further research is needed to more completely characterize this important soil property in the study area.

Principle Components, Cluster, and Discriminant Analysis

Principle component analysis was used to facilitate interpretation of subsequent statistical analyses by identifying a subset of variables which could be used that would still enable maximum separation of the experimental units (soil horizons). It also can provide a plot of the data (individual soil horizons) as defined by the major principle components. Principle components are first extracted from the data set. The first principle component represents a linear combination of

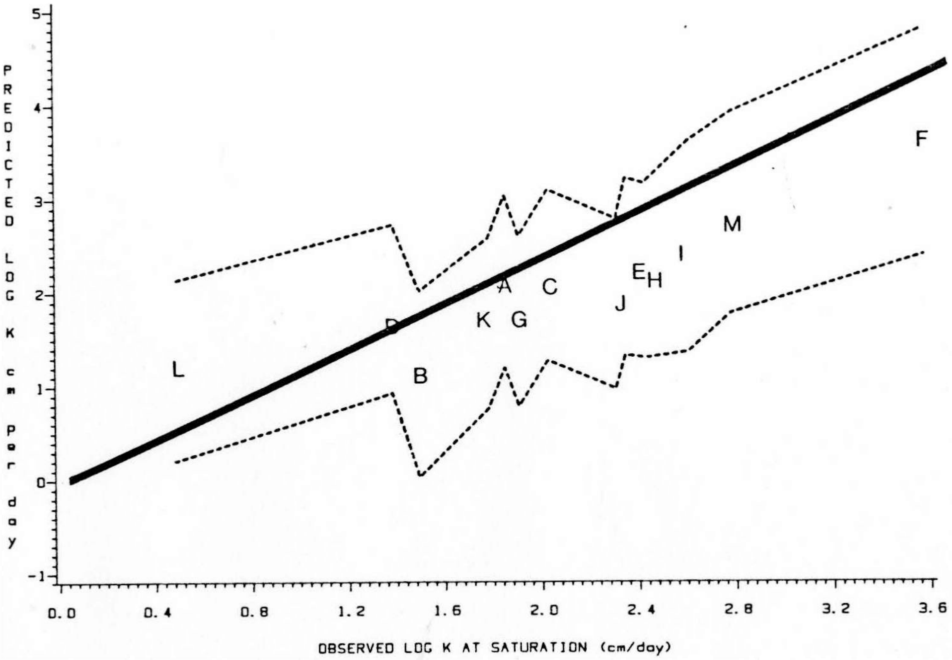


Figure 21. Predicted versus observed log hydraulic conductivity at saturation, with 95% confidence interval, and perfect fit line. (Key to letters may be found in Table 9).

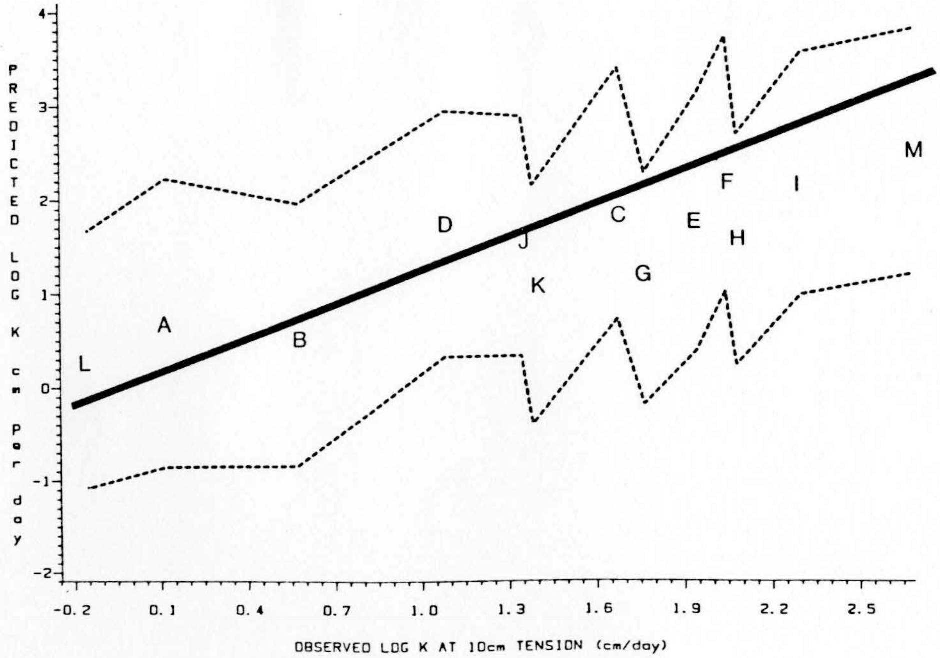


Figure 22. Predicted versus observed log hydraulic conductivity at 10 cm matric tension, with 95% confidence interval, and perfect fit line. (Key to letters may be found in Table 9).

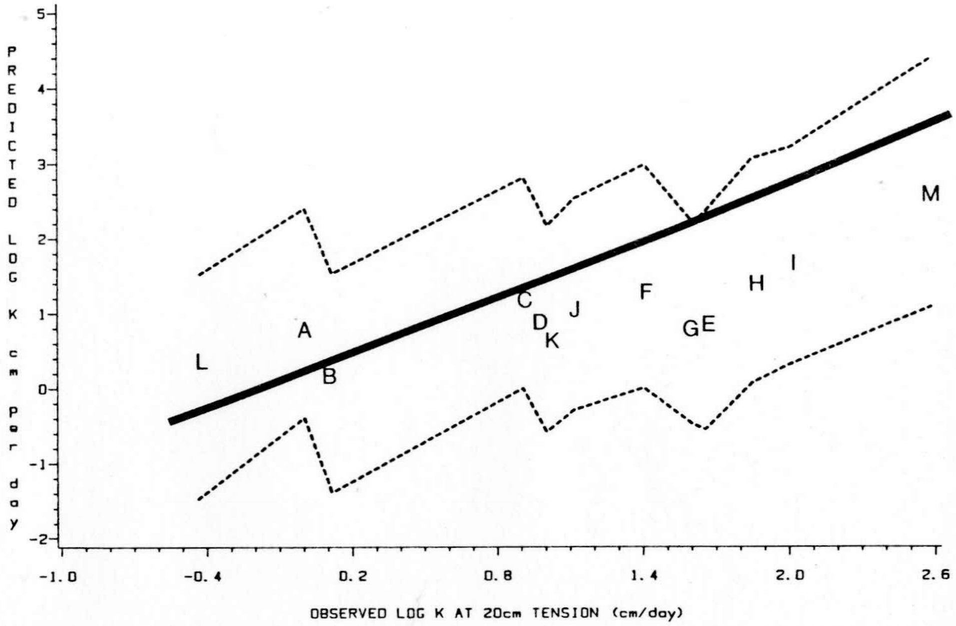


Figure 23. Predicted versus observed log hydraulic conductivity at 20 cm matric tension, with 95% confidence interval, and perfect fit line. (Key to letters may be found in Table 9).

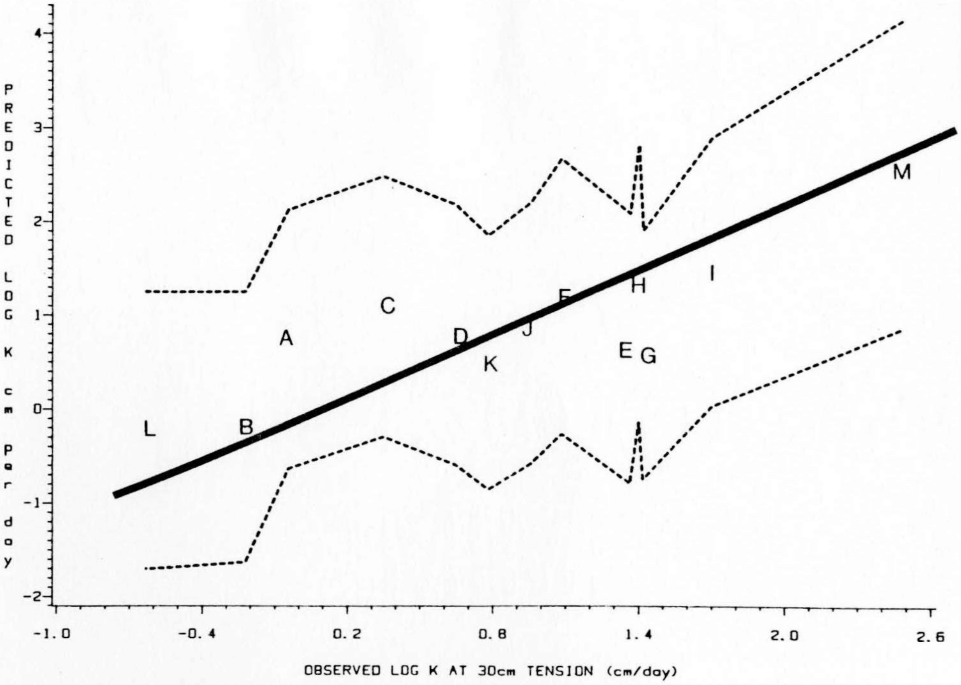


Figure 24. Predicted versus observed log hydraulic conductivity at 30 cm matric tension, with 95% confidence interval, and perfect fit line. (Key to letters may be found in Table 9).

Table 9. Key to the letters used as plotting symbols in Figures 21-24.

PLOTTING SYMBOL	SITE	HORIZON
A	1	C11
B	3	C1
C	4	B2t
D	4	C1
E	6	B21
F	6	IIIC3
G	7	C1ca
H	7	C2
I	9	C1
J	10	A3
K	11	B22
L	12	B2t
M	13	C1

variables that maximally separates the cases (soil horizons) by maximizing the variance of their component scores. The second principle component is generated based on the variability remaining in the data set after the variance associated with the first principle component is removed. It extracts maximum variability uncorrelated with the first component. Subsequent principle components will account for successively less variance. Each principle component can be used to calculate a single score for each horizon, which can then be plotted, using each principle component as an axis on a graph. The result is a grouping of cases based on their scores from the number of principle components in an n-dimensional space (n representing the number of principle components). This plotting process can be simplified to two dimensions if the first two principle components account for a suitable proportion of the variance in the data set.

In this data set, a total of 10 separate principle components or factors (representing linear composites of the original variables) were extracted (Table 10). The first two principle components cumulatively represent 55 percent (37 and 18 percent, respectively) of the variance contained in the original variables. This is considered good for soil data sets (Norris, 1971), and means that a two-dimensional plot of horizons by their scores on the first two principle components will provide a good visual representation of their distribution in an n-dimensional space (i.e. if all principle component scores were calculated and graphed in n-dimensions, one dimension for each component). Subsequently extracted principle components (i.e. 3-10, Table 10) account for much less variance, with a maximum of 8 percent for the third principle component. Thus they will only slightly influence the position of any point plotted from the first two factors.

Table 10. Variance accounted for by extracted principle components.

PRINCIPLE COMPONENT	------VARIANCE------ PROPORTION	CUMULATIVE
1	0.370	0.370
2	0.181	0.551
3	0.085	0.636
4	0.064	0.699
5	0.048	0.748
6	0.039	0.787
7	0.034	0.821
8	0.025	0.846
9	0.022	0.868
10	0.019	0.887

The values listed in Table 11 are loadings of the original variables on each of the two principle components used to plot Figures 25-29. (Table 7 provides a key for the variable abbreviations used in the statistical analyses). A cutoff for significant loading values of

Table 11. Factor loadings for variables from principle components analysis[1]. (See Table 7 for key to abbreviations)

VARIABLE	PRINCIPLE COMPONENT ONE	TWO
*THIRDBAR	0.92	0[2]
TENTHBAR	0.87	0
*SAND	0.87	0
*LOGCLAY	0.85	0
*LOGBAR15	0.84	0
*DRYCONS	0.83	0
PLASTCON	0.80	0
MOISTCON	0.78	0
ZEROBAR	0.78	0
STICKCON	0.75	0
*AVAILH2O	0.74	0
LOGXTRMG	0.73	0
LOGCEC	0.67	0.58
STRGRADE	0.62	0
*LOGORGC	0.60	0.62
STRSIZE	0.58	0
*STRKIND	0.56	0
SILT	0.52	0
LOGSOLMG	0.52	0
*PHPASTE	0	0.82
*LOGSAR	0	0.79
LOGSOLNA	0.49	0.72
*EFFERVES	0	0.63
BULKDENS	0	0.55
LOGXTRNA	0.50	0.54
EXTRCA	0.46	0.50
LOGTOTLN	0	0.70

[1] Variables wet chroma, dry chroma, wet value, dry value, coarse fragments, log ESP, log HCO_3, and electrical conductance did not load significantly on either factor.

[2] Values lower than 0.45 are replaced by 0.

VARIABLES PREFIXED BY AN ASTERISK (*) WERE SELECTED FOR USE IN CLUSTER AND CANONICAL DISCRIMINANT ANALYSIS

0.45 is used as suggested by Tobachick and Fidell (1983), and values below that are replaced by zeros. The table shows that Principle Component One is heavily loaded by soil physical characteristics (moisture characteristics, particle size, etc.), and Principle Component Two by what can be considered soil chemical characteristics (soluble cations, organic carbon, CEC, etc.). Thus in Figures 25-29, changes in plotted positions along the horizontal axis reflect changes in soil physical properties, and changes in vertical position represent differences in chemical properties.

Following the method of Norris (1971), each of the horizons was plotted by its values on the first two principle components (i.e. as each principle component is a linear composite of many variables, for each of the two principle components, a single score for a horizon based on its values for each of the variables can be calculated, and the scores plotted). Figure 25 is such a plot, with each plotted point represented by the number of the site from which the horizon came. To aid in the interpretation of this figure, it has been separated into four separate graphs, Figures 26-28. In each of these figures the horizons from the same profile are joined by lines in sequence from upper horizons to lower horizons (upper horizons at bottom of graph).

Figure 26 represents the far left side of the original figure. Horizons from sites 1 (A), 6 (F), 9(I), and 13 (M) are found in this region, all of which are sandy horizons. The variability of these sites can be compared by examining the nature of the linkage between the horizons within a profile. Site 9 was an Entisol formed in sand dunes showing very little change in any soil property with depth, and

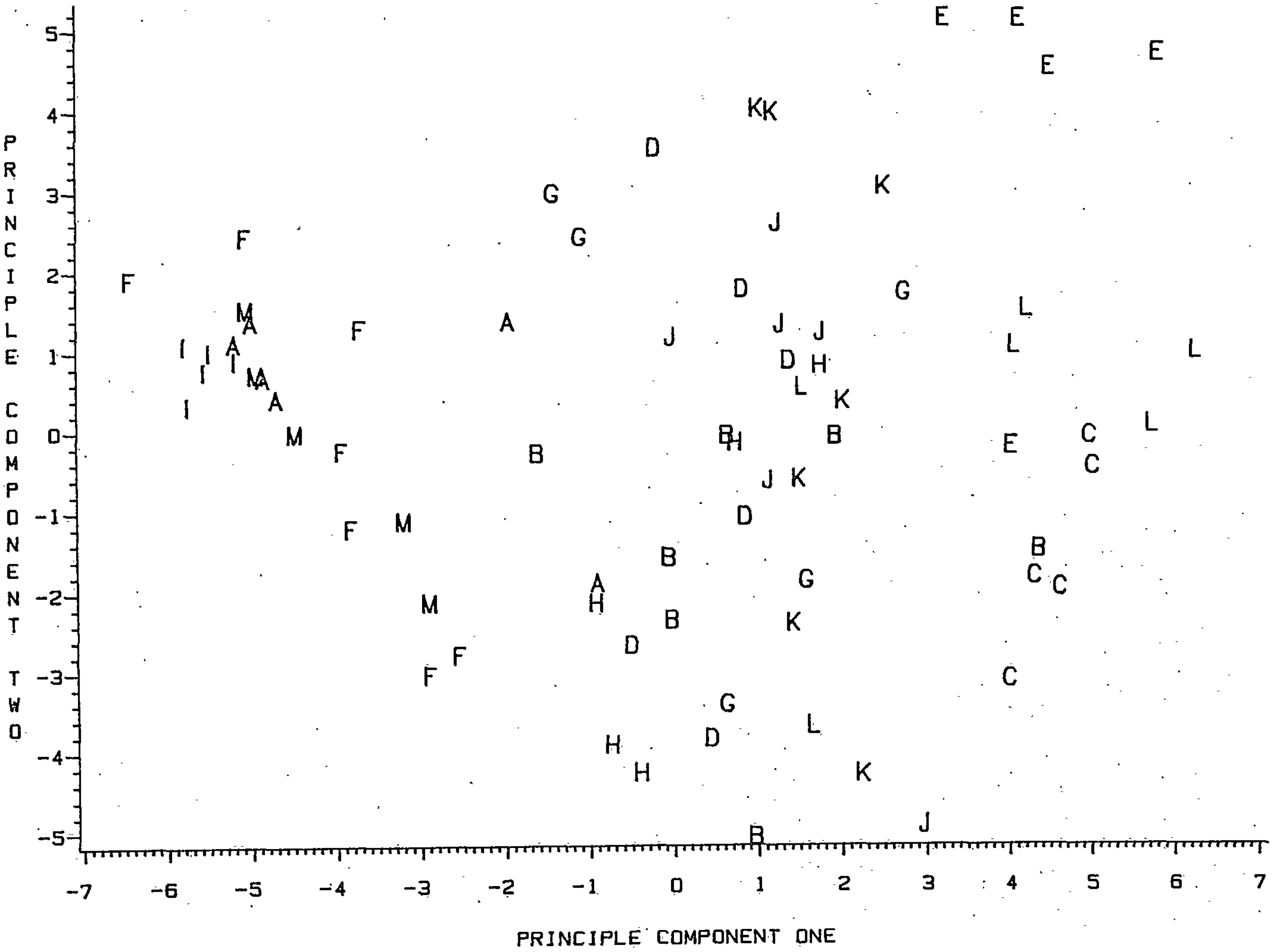


Figure 25. Plot of all scores on Principle Components One and Two for all sites. (Letters A through M = sites 1 through 13)

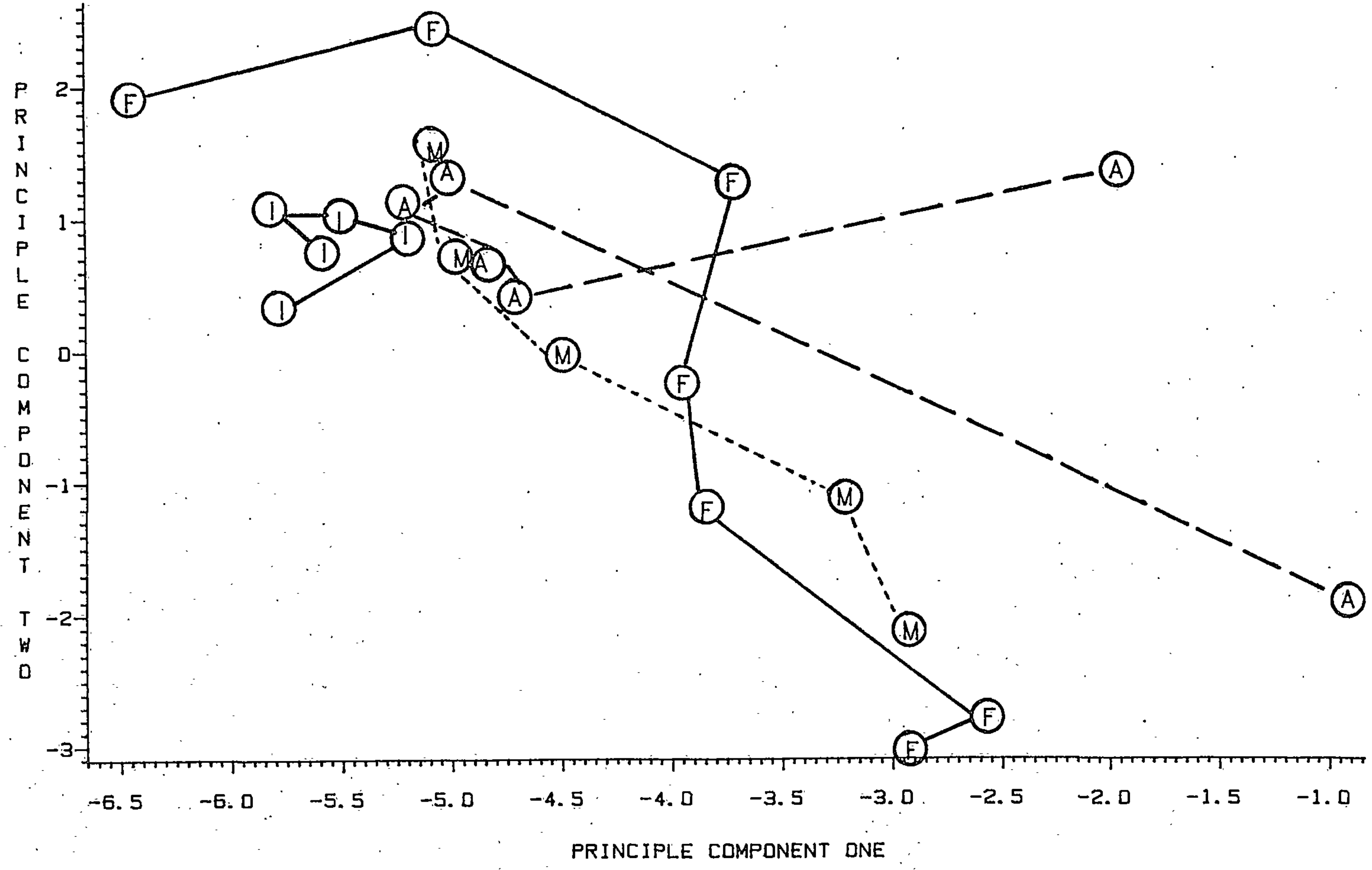


Figure 26. Plot of scores on Principle Components One and Two for sites 1, 6, 9, 13 (A, F, I, M).

as a result all five horizons are closely grouped. Sites 6 and 13 are sandy Mollisols formed in outwash that exhibit regular changes with depth for CEC and pH, and also exhibit variation in texture with depth. The more irregular nature of the textural changes at site 6 are reflected in the somewhat more irregular nature of its linked horizons. Site 1 shows the greatest variability in the figure, especially in its uppermost and lowest horizons. It is a coarse-textured Alfisol with a volcanic ash-influenced surface horizon over ice-contact stratified drift subsoils. The bottom horizon, IVC4, is much finer-textured than those above it, and also has a considerably higher pH and ESP.

Figure 27 represents the right-hand side of Figure 25. Sites 3 (C), 5 (E), and 12 (L) plotted here are clayey lacustrine soils. The close grouping of the horizons from site 3 shows that the profile is relatively uniform. Site 5 displays more variability, primarily due to a surface horizon of coarser texture and lower sodicity. Variability throughout the profile is evident in site 12. A large increase in clay content accompanied by high CEC separates the middle horizons from the suface and lower horizons.

The profiles in Figures 28 and 29 were those plotted in the central portion of Figure 25. Figure 28 examines sites 2 (B), 4 (D), and 10 (J), all with soils developed from glacial till. Profiles from sites 7 (G), 8 (H), and 11 (K) are shown in Figure 29. These are soils formed in silty lacustrine materials. Variability is seen to be greatest in site 2 (B in Figure 28), as evidenced by its criss-crossing linkage pattern. Site 7 (G in Figure 29) also exhibits considerable variability from its upper to lower horizons.

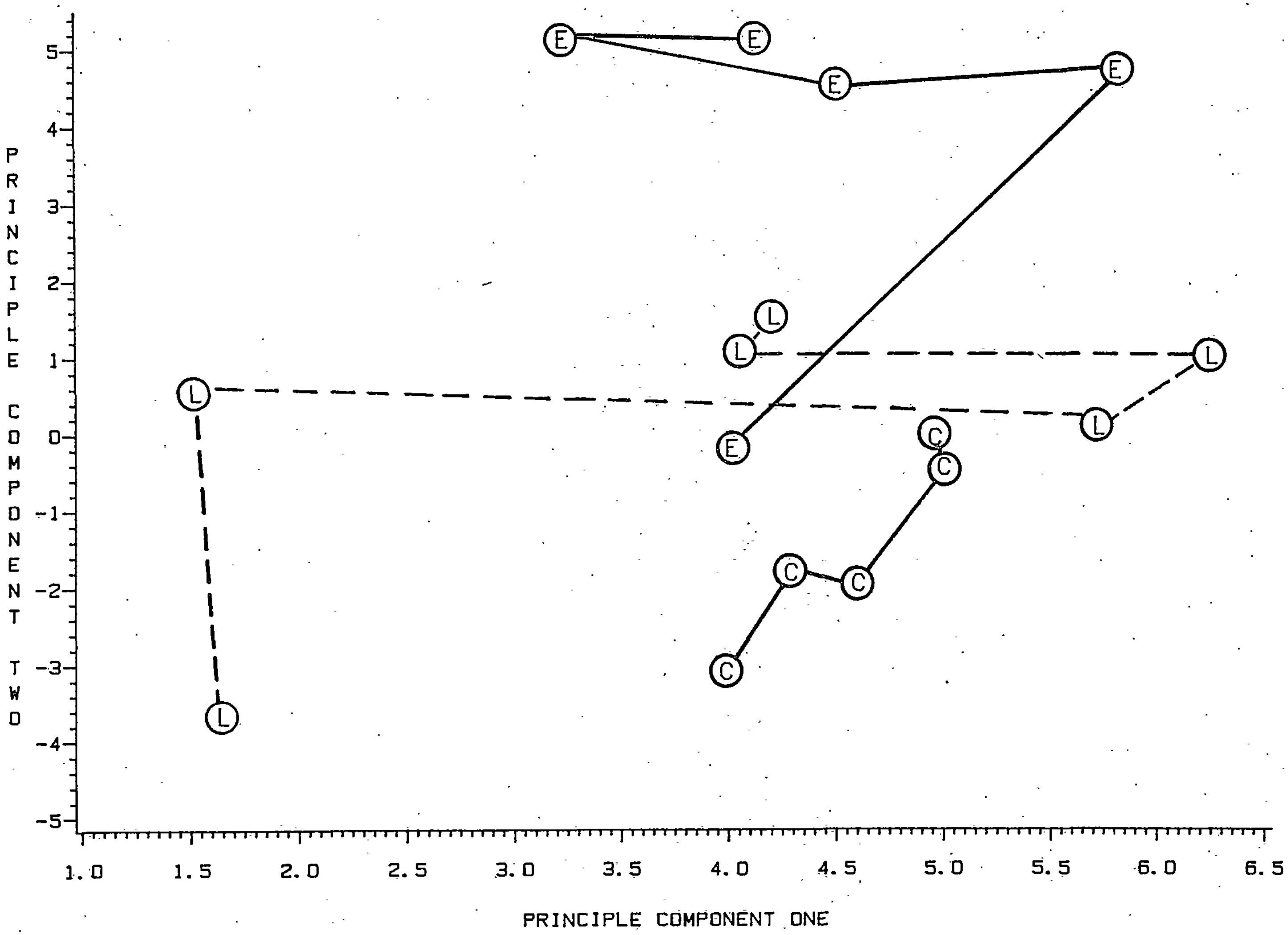


Figure 27. Plot of scores on Principle Components One and Two for sites 3, 5, 12 (C, E, L).

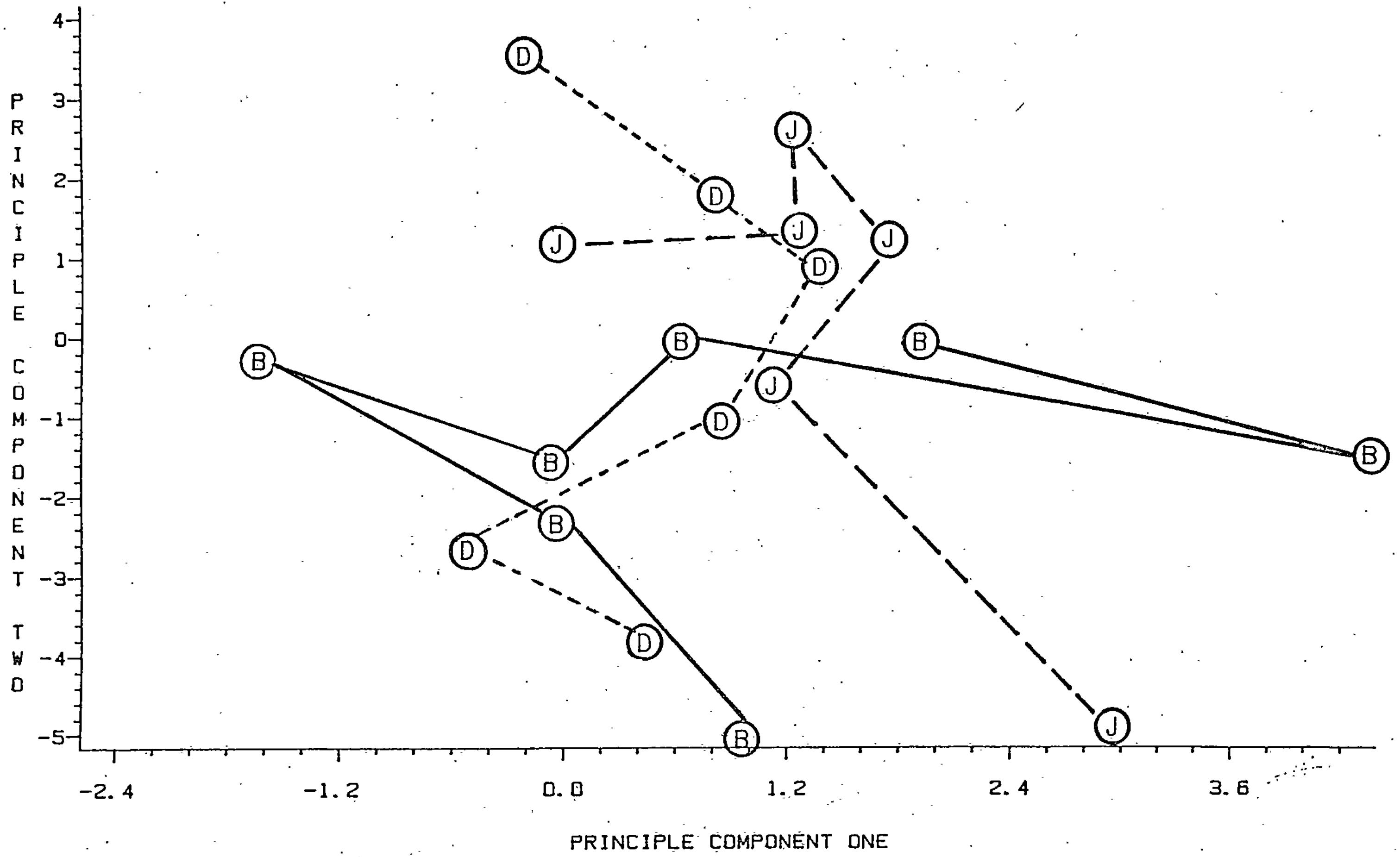


Figure 28. Plot of scores on Principle Components One and Two for sites 2, 4, 10 (B, D, J).

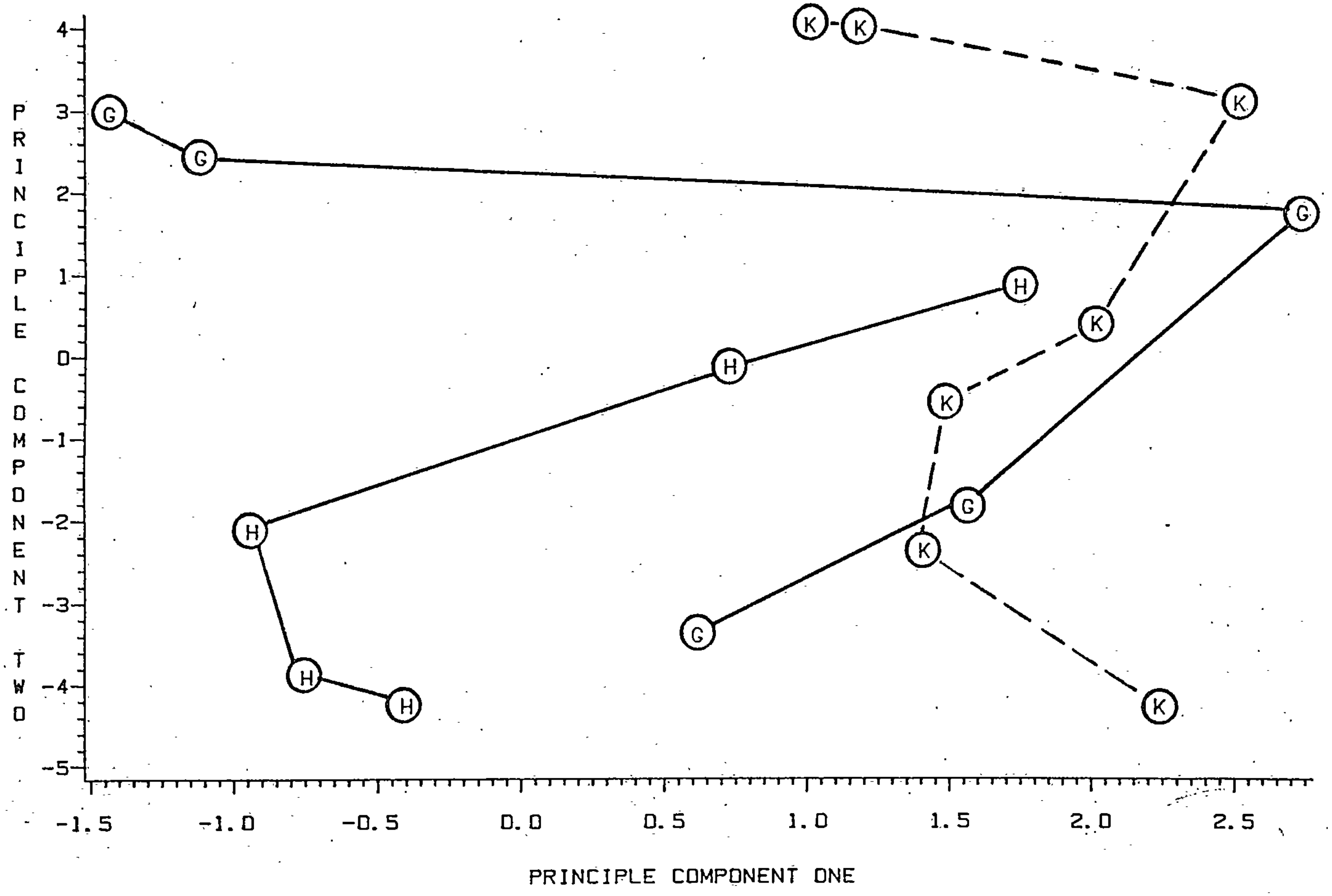


Figure 29. Plot of scores on Principle Components One and Two for sites 7, 8, 11 (G, H, K).

In the study by Norris (1971), plots of the principle component scores of horizons were successfully used to compare the groupings of soils based on field versus laboratory data. The linkage plots obtained were much more regular than those of this study. The irregularity of the linkage plots for individual profiles or groups of profiles is used in this discussion as a means for graphically expressing the complex stratification that was so commonly manifested in the soils examined in the study area. As such it may be a useful tool for comparing relative variability between soils from widespread geographic locations, as well as from within a single location.

From the list of 28 significant variables shown in Table 11, a reduced set of eleven variables (those with asterisks in Table 11) was chosen for use in cluster and canonical discriminant analysis. Cluster analysis was used as another technique to compare each soil horizon with all others, and to find groupings of similar horizons. As there are no techniques available which enable a determination of a significant number of clusters (Green, 1978), inspection of the data led to a decision to break the 76 horizons into 5 clusters, each consisting of horizons which were statistically more similar to other horizons within that same group than to horizons of other groups. The five clusters (or groups) of horizons are listed in Table 12, and the tree diagram from which they were selected is shown in Figure 30. The tree diagram reveals that the population of horizons are most strongly separated into two groups, Class A consisting of groups 1 and 2, and Class B with groups 3, 4, and 5. Class B is split into B1 (group 3) and B2 (groups 4 and 5). The next division breaks out groups 1 and 2

Table 12. Groups broken out by cluster analysis (site, horizon).

CLASS A: COARSE-TEXTURED HORIZONS

GROUP 1

SITE 1, C11
1, C12
1, IIC2
1, IIIC3
6, IIC2
6, IIIC3
9, C1
9, C2
9, C3
9, C4
9, C5
13, C2
13, C3

GROUP 2

SITE 1, IIIC4
2, C1
2, C12
2, C2
4, IIC3
6, Ap
6, A3
6, B21
6, B22
6, C1
7, C2
7, C3
13, Ap
13, B2
13, C1

##

CLASS B: FINE-TEXTURED HORIZONS

GROUP 3

SITE 1, B2ir
2, A1
2, B2t
3, Ap
4, A1
4, A2
7, A3
8, A1
8, A12
8, B2
10, Ap
11, Ap
11, A3

GROUP 4

SITE 2, IIIC4
4, C1
4, C2
5, C1
5, C2
7, C1ca
10, C1
11, C1ca
11, IIC2
11, IIIC3

GROUP 5

SITE 2, IIC3
3, B21t
3, B22t
3, C1
3, C3
4, B2t
5, Ap
5, B2t
5, B3t
5, IIC2
8, C1ca
8, C2
10, B21
10, B22
10, B3
11, B21
11, B22
12, B2t
12, C1ca
12, C3
12, C4

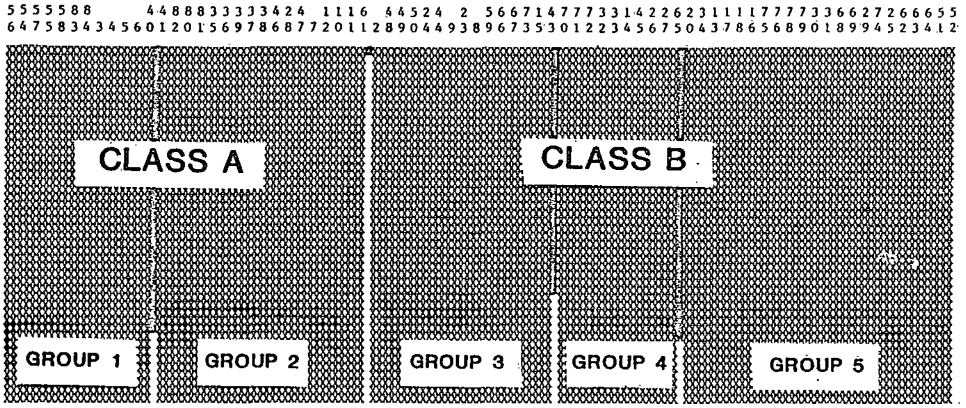


Figure 30. Tree diagram graphic from cluster analysis showing how groups listed in Table 12 were separated.

of Class A, and the last groups to be distinguished are 4 and 5. These two groups are only marginally distinct.

It is interesting to examine the nature of the groups which were separated (Table 12). Classes A and B can generally be defined as coarse-textured and fine-textured soils, respectively. The coarse-textured horizons within Class A are broken into two groups. Those in group 1 are all C horizons, and have sand contents in excess of 50 percent. Group 2 contains a mixture of coarse-textured A, B, and C horizons. Class B separates rather neatly into 3 groups. Group 3 is almost all A horizons, Group 4 is all C horizons, and Group 5 contains both B and C horizons.

These groupings were then used in a canonical discriminant analysis to obtain a two-dimensional graphic representation of the distribution of the horizons, and to determine if the five clusters were significantly different from one another. The statistic for evaluating the significance of the four discriminant functions used to separate the five groups of horizons is Wilk's Lambda. The F-value for Wilk's Lambda was 15.06, significant at the 0.01 level, indicating that these five groups can be distinguished on the basis of linear composites of the 11 predictor variables used in each of the discriminant functions.

A two-dimensional plot of the horizons as separated by the discriminant functions is provided in Figure 31. It is evident that groups 1 and 2 (the coarse-textured horizons) are well separated from each other and from the remaining three groups. Group 3 (fine-textured A horizons) is well separated from groups 4 and 5, which are more poorly distinguished, reflecting the fact that they were the last two groups broken out by the cluster analysis, and also that the many C horizons of Group 5 have similarities with the C horizons of Group 4.

Of interest in this figure is that one horizon (the circled number in group 3) placed in group 4 (fine C horizons) by cluster analysis has been plotted with the horizons of group 3 (fine A horizons). This horizon is a IIIC4 horizon with high organic carbon (3.2 percent). It is from a profile formed in glacial till, and apparently represents an old marsh or bog deposit buried by the till. Its high carbon content statistically distinguishes it as an A rather than a C horizon.

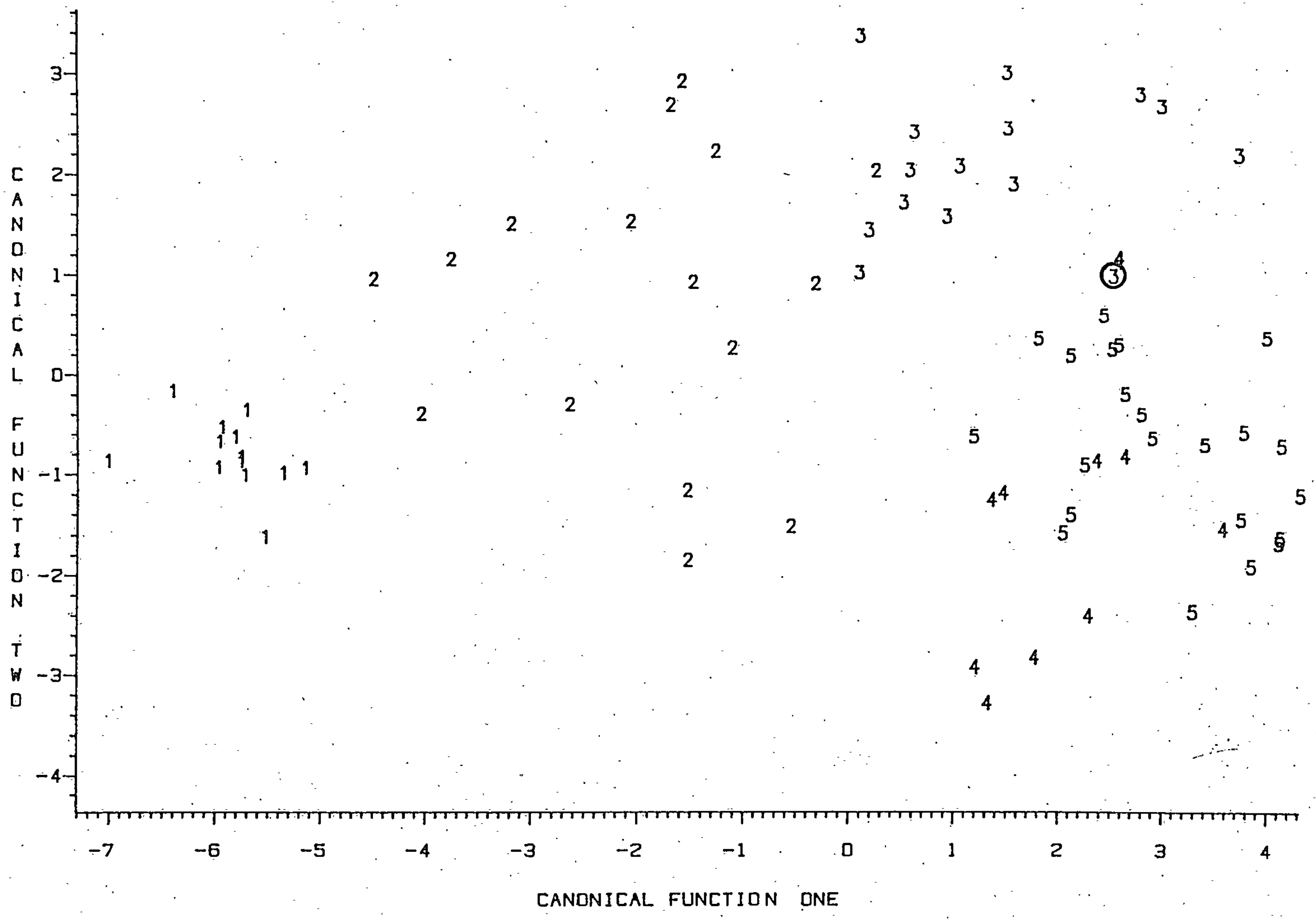


Figure 31. Plot of scores on canonical functions one and two for discriminant analysis based on cluster groups 1-5.

SUMMARY

Complex glacial and proglacial depositional environments in the Flathead Valley have resulted in a soil landscape with great inherent variability of soil physical properties in both a vertical and horizontal plane. While soils formed from similar parent materials generally exhibit similar hydraulic characteristics in the near-saturated range, substantial variability within such groups is not uncommon, especially in lacustrine soils. This variability demands that site suitability for septic systems should be determined by on-site soil profile descriptions. Recognition of this variability and its implications for soil water movement is important for proper design of septic systems.

Further, the utility of multivariate statistical methods for revealing the underlying structure of soil horizon data, and for graphically expressing the variability both among horizons from a single profile and between profiles has been demonstrated. Such methods would appear to be a useful tool for those scientists faced with the complex task of interpreting the results of many physical and chemical analyses from large numbers of soil profiles.

ESTIMATING GROUND-WATER QUALITY IMPACTS FROM ON-SITE SEWAGE TREATMENT SYSTEMS

INTRODUCTION

The primary objective of on-site wastewater treatment systems is to provide acceptable treatment and disposal of domestic wastewater with minimal impact upon the quality of local water resources. The properties of the soil resource play a vital role in determining what these potential impacts may be, but it is important to also consider the properties of the ground-water system, which serves as the ultimate medium of disposal for the treated effluent, and its relation to local surface water bodies (streams and lakes). It is the integrated properties of these three components (soils, ground water, and surface water) which determine the potential of the natural system to assimilate man-made wastes while minimizing threats to public health and environmental quality. There are two principle issues of concern: the ability of the soil to accept and treat septic tank effluent; and the impact of the treated effluent upon the local surface and ground-water resources.

Historically, the determination of site suitability for septic systems has been a site specific process, with emphasis on the evaluation of soil properties for acceptance and treatment of the effluent produced from an <u>individual</u> septic system (Anderson et al., 1977). Little consideration has been given to the possible impacts on water quality from a single system or many systems. This in spite of the fact that a major problem of ground-water contamination from septic systems was documented in the late 1950's (Woodward et al., 1961), and many more have come to light in recent years (Fabryka, 1978). A recent study (Pye et al., 1983) stated that septic systems are both the most frequently reported source of ground-water contamination in the United States, and the single largest source (by volume) of wastewater discharged to ground water.

Such contamination is a serious problem, as it may take years or even decades before an aquifer can rid itself of pollutants. This is because ground-water movement is often very slow, with velocities of less than 0.40 km/year (Freeze and Cherry, 1979). Contaminated ground water often may travel several kilometers, and past many wells before it is discharged to a surface source. Also contributing to the slow restoration of ground-water quality is that often a reservoir of the contaminant may have built up in the soils above the aquifer. This pool of contaminants may continue to leach to the water table for many years after cessation of current polluting activities (Katz et al., 1980).

In the opinion of the author, even with recent increased concern for threats to the ground-water resource, it appears that in general, little distinction has been made between the isolated impact of individual septic systems, and the cumulative, long-term impact of hundreds or thousands of systems upon local or regional ground-water quality. Perhaps this is because ground-water pollution from septic systems may develop in an insidious manner, as illustrated in the following hypothetical example.

In a newly developed subdivision, the first 10, 100, or possibly even 1000 septic systems in an area may not create any apparent degradation in water quality, as the ground-water system may have sufficient dilution capacity to mitigate the impact of the added nitrate loading. If another 1000 systems are added, some contamination may become noticeable, but still remain within acceptable limits. However, the addition of another 1000 septic systems might overload the system, exceeding its capacity to adequately dilute the incoming nitrates, resulting in an intolerable level of pollution. This scenario further demonstrates that the contribution of any one septic system is relatively innocuous, yet their cumulative impact may be substantial. This aspect of on-site sewage treatment needs to be addressed during the site evaluation process in order to effectively manage and protect the quality of the ground-water resource.

The traditional goal of the site evaluation process has been an estimate of an acceptable hydraulic loading rate of effluent (i.e. the volume of effluent that can be absorbed by a unit area of soil) to the drainfield trenches (Anderson et al., 1977). Early research with septic systems was directed towards prevention of hydraulic failures, where effluent backs up in the trench and breaks through to the ground surface, creating an obvious health hazard (McCaughey and Krone, 1967). In the early 1970's, the emphasis shifted to insuring adequate treatment of the effluent as it passed through the soil, i.e., prevention of treatment failures (U.S. Environmental Protection Agency, 1978).

Past experiences with septic system-nitrate contamination of ground-water (Fabryka, 1978), and recent studies documenting the conservative nature of nitrate movement through soil (Willman et al., 1981; Brown et al., 1984), suggest that nitrate pollution of ground water is perhaps the greatest environmental threat from septic systems. Yet thorough review of the literature concerning septic systems and ground-water contamination suggests that evaluation of the local hydrogeology in terms of the potential impact of nitrate contamination of ground water is a concept that has not been integrated into the site evaluation process.

To reduce the potential of future problems from nitrate contamination of ground-water resources, it is proposed here that it is important for a rough estimate to be made of an acceptable "loading rate" of nitrates to an aquifer. This level of nitrate loading, if not exceeded, will prevent ground-water nitrate concentrations from reaching unacceptable levels.

For more effective management of future issues concerning on-site wastewater treatment, there is a need for an examination of the impacts of septic systems on ground-water quality. It is the intent of the following discussion to:

1) outline the environmental and public health issues associated with on-site sewage treatment systems;

2) describe the fate of the nitrogen produced and its potential for significantly degrading water quality;

3) examine, through the use of a model, the possible impacts of nitrate loading from septic systems, and the factors influencing such impacts;

4) propose additions to criteria used in the site evaluation process.

There have been reports of several cases of septic system pollution of ground water in Montana (Spratt, 1980; Subdivision Bureau, Montana Dept. of Health and Environmental Sciences, 1977; Montana Dept. of Health and Environmental Sciences, 1978b). Many states have initiated substantial programs to deal with such problems and prevent new ones from developing. This is not the case in Montana, and in essence, there has been a decrease in state efforts to review and regulate the public health and environmental impacts of septic systems. Appendix 1 contains an assessment of the current trends in the growth of on-site sewage treatment systems in Montana, an evaluation of recent regulatory efforts, and suggestions for improving state management of septic systems.

LITERATURE REVIEW

Pollution Hazards Associated with Septic Systems

Domestic wastewaters contain many substances which may adversely impact water quality, most notably nitrogen (N), phosporous (P), bacteria, and viruses (U.S. Environmental Protection Agency, 1978). Recently additional concern has been expressed about toxic trace organic compounds commonly found in household cleaning products and cosmetics, or used to clean septic tanks (DeWalle et al., 1982).

Soil treatment of the common wastewater contaminants has been discussed thoroughly in several publications (Tyler et al., 1977; U.S. Environmental Protection Agency, 1978; Bauman and Schafer, 1983), and will not be considered in detail here. The main processes influencing soil treatment of wastewaters are filtration, adsorption and chemical precipitation. Filtration removes bacteria and larger viruses, while smaller bacteria and viruses are adsorbed onto soil particles and rapidly die (Green and Cliver, 1974). Phosphorous (in the form of orthophosphates), is either precipitated in reactions with calcium, aluminum, and iron , or may be adsorbed to oxides of these elements (Sawhney, 1977). Research has demonstrated that for all but very-coarse textured soils, sufficient treatment (i.e. removal of all micro-organisms and P) of wastewater occurs during travel through three feet of unsaturated soil (Bouma et al., 1972; Tyler et al., 1977).

Soil texture and moisture conditions play the dominant roles in determining the efficacy of soil treatment of septic tank effluent. Generally speaking, superior treatment is provided by finer-textured soils. Their lower hydraulic conductivities result in increased residence times for the wastewater in the soil, their smaller pores provide more effective filtration of micro-organisms, and their greater surface area provides increased cation exchange and adsorption capacity (Bouma, 1975). However, even most coarse-textured soils will provide suitable treatment of pathogenic organisms and phosphorus, provided unsaturated conditions prevail.

While examples of ground-water contamination from enteric micro-organisms (McGinnis and DeWalle, 1982; Hagedorn et al., 1981) and phosphorous (Dudley and Stevenson, 1973; Ellis and Childs, 1973) have been documented, they are generally limited to situations of shallow, fractured bedrock, or coarse-textured soils with shallow water tables. With proper regulation (i.e. proper siting of the drainfield), it is possible to almost completely protect against the occurence of contamination from these pollutants. The site constraints which may allow such pollution are easily recognized, and precautions employed to alleviate the threat to ground-water quality (e.g. Brandes, 1977).

Only recently recognized, perhaps a more serious threat to ground-water supplies comes from organic chemicals. These contaminants that may find their way into septic systems are coming under increasing scrutiny, as they may be health-threatening at even very dilute concentrations. DeWalle et al. (1982) found numerous volatile organic compounds in a large septic tank serving many homes, and concluded that there would be little removal of such chemicals in the tank, nor would they be adsorbed or degraded in the soil. A chemical sometimes used as a degreasing agent when septic tanks are commercially cleaned (1,1,1, trichloroethane), was found to be responsible for contamination and closure of a public water supply well in New Jersey (Pye et al., 1983). While the threat of serious contamination from such chemicals is evident, it is also clear that proper regulatory actions and increased public awareness can eliminate this threat by preventing the disposal or use of these powerful contaminants in septic systems.

The fate of wastewater nitrogen in soils has been widely studied (Preul and Schroepfer, 1968; Lance, 1972; Walker et al., 1973; Lance et al., 1976; Sikora and Corey, 1976). Briefly, nitrogen (N) in septic tank effluent is in the form of ammonium (NH_4^+). As it passes into the soil from the drainfield trench it encounters oxidizing conditions, is rapidly converted by microbes to nitrate (NO_3^-), and as an anion will move freely with the percolating effluent to the water table. As a result, usually there is little if any removal of nitrogen from effluent during soil treatment (Sikora and Corey, 1976; Stewart, 1979; Brown et al., 1984).

Compared to the relatively few instances of aquifer contamination by micro-organisms, phosphorus, or organic chemicals, there have been many reported instances of nitrate-contaminated ground water due to septic systems over a wide variety of environmental conditions (Fabryka, 1978). Of further concern, at present there are no technically sound or economically feasible methods that have been proven effective in preventing such nitrates from contaminating groundwater. In essence, virtually every operating septic system represents a point-source of nitrate contamination to the ground water. The following paragrphs will discuss the implications of this form of pollution from on-site sewage treatment systems.

Public Health, Water Quality, and Nitrate Contamination

Accepting the fact that septic systems contribute nitrates to the groundwater, it is necessary to ask what are the implications of such contamination. Nitrate itself has a relatively low toxicity to mammals, but can be transformed to the much more toxic nitrite in the gastrointestinal tract. For this reason, the U.S. Public Health Service recommends a drinking water standard of 10 ppm NO_3^--N, based on studies that showed concentrations of NO_3^--N above that level to be associated with infant methemoglobinemia, or blue-baby disease (Aldrich, 1980). Susceptibility to this disease is almost exclusively limited to fetuses and infants less than three months old.

There has been much recent debate about the 10 mg/L standard. An excellent review is presented by Aldrich (1980). Briefly summarized, Aldrich notes that in the studies (from the 1940's and 1950's) used to establish the standard, only 2 percent of the cases of methemoglobinemia (and no deaths) occurred at nitrate nitrogen levels of 10-20 mg/L. Several studies have investigated populations whose drinking water exceed the standard by 2-10 times, yet exhibit no special health problems. Further, the State of California has a standard of 20 mg/L nitrate nitrogen, and has had no cases of methemoglobinemia that could be attributed to high nitrate water.

Of greater concern in recent years are findings that nitrate converted to nitrite (as may occur in the human stomach) may combine with amines to form N-nitroso compounds, which have been shown to be carcinogenic at high doses in animal tests (National Academy of Sciences, 1981). Effects of low levels on humans are unknown. This same study noted that the average nitrate concentration in drinking water in the U.S was less than 1 ppm, and would only contribute about 2.6 percent of dietary nitrate intake. However, daily use of drinking water with high nitrates could substantially increase total nitrate consumption, and the report recommended reducing dietary intake of nitrates wherever feasible. This is of special concern in areas with septic systems, because usually drinking water is obtained from shallow individual household wells, which commonly draw water from the same aquifer which receives the treated septic tank effluent, and elevated nitrate levels in such wells are not uncommon.

It would appear that the human health hazards associated with higher levels of nitrate in drinking water are not well-defined, and there is considerable room for discussion concerning the defensibility of the 10 mg/L NO_3^--N as a protective standard. However, in the interest of public safety, health officials would prefer to err on the safe side. Accordingly, as there is little known about the consequences of low-level, long-term exposure to nitrates, it is likely that the standard will be maintained for some time.

In terms of environmental water quality, nitrate contamination of shallow ground water may result in increased nitrate loading of local surface waters, as the two systems are often interconnected. This may result in overenrichment of the surface waters, and is of concern in those areas where nitrogen may be the limiting nutrient. It is interesting to note that (unlike most of the rest of the U.S.) the productivity in many/most lakes and streams in Montana (with the exception of northwest Montana) are nitrogen-limited (Wright, 1980). Increased productivity may be beneficial for some waters, but may be detrimental for others, depending on current nutrient levels and trophic status. The effects of long-term nitrate enrichment are difficult to assess. Generally, lakes are more susceptible to overenrichment than are streams and rivers, a result of the greater opportunity for within-system recycling of nutrients.

This brief discussion has raised the prospect of several potential undesirable consequences associated with nitrate contamination of ground water. What is unclear is the level of contamination which results in unacceptable health and environmental risks. When such levels have not been quantified, a strong argument can be made that it is best to use conservative standards. This is particularly true in this case. Society is increasingly turning to the ground-water resource to satisfy its increasing demands for water. Shallow ground water is an especially attractive source, as it is easily accessed, and often has rapid recharge. With such a potentially useful resource, it would seem prudent to protect it from significant degradation, which might prevent its highest beneficial use (i.e. public water supply).

In a rational approach to protection of shallow ground-water quality, it is helpful to evaluate the actual contribution of septic systems to ground-water degradation. This involves determining the quantity of nitrates produced by septic systems, and examining the factors influencing the ultimate amount of nitrate reaching the water table.

The Fate of Septic System Nitrogen

Numerous studies have analyzed the quality of septic tank effluent (the liquid leaving the septic tank). Using this information, a nitrogen loading rate for septic systems can be generated. Many papers have cited Walker et al. (1973) when stating that effluent nitrogen is commonly in the range of 40-80 mg/L. To confirm this value (as the Walker et al. study only involved four septic systems), available literature was reviewed, and data from from 20 studies reporting over 500 separate effluent analyses are summarized in Table 13.

The range of values of total nitrogen in septic tank effluent is 31-116 mg/L (Table 13). The average nitrogen concentration is 62.7 mg/L total nitrogen, with a standard deviation of 22 mg/L, which compares very favorably with the Walker et al. estimate. This may be a conservative estimate, as a number of studies listed in Table 13 only analyzed the ammonia-N in the effluent, as opposed to total-N (which would include other nitrogen sources, e.g. organic N). For these studies, the ammonia-N value was also used as total-N. A weighted mean was also calculated for those studies reporting the number of separate samples of effluent analyzed, and found to be 65.5 mg/L, ±15 mg/L.

Typically 70-90 percent of this N is in the form of ammonium (NH_4^+), and the rest organic-N, which is mineralized to NH_4^+ in the

Table 13. Summary of literature values of the nitrogen content in septic tank effluent.

Source	NH_3-N (mg/L)	Total-N (mg/L)	Number of Samples
Andreoli et al. (1980)	41	61	115
Ronayne et al. (1982)	41	57	54
Bouma et al. (1975)	42	58	11
	34	50	13
	33	40	10
	36	49	5
Brown et al. (1984)	25	32	
Magdoff et al. (1974)	34	43	
Cogger & Carlile (1984)	38	47	5
	39	43	5
	40	41	9
	35	44	9
Kristiansen (1981)	68	85	
Viraraghavan (1975)	97	97*	
Dearth (1978)	39	55	53
Harkin et al. (1979)	54	81	215
Karikari et al. (1975)		73	8
Otis et al. (1975)	34	50	13
	42	58	11
	46	76	8
	33	40	10
	20	31	11
	38	57	11
Machmeier & Mattson (1978)		110	
Siegrist (1978)	54	79	22
Cole and Sharp (1982)		76	
		90	
		61	
		100	
		45	
		65	
		59	
		70	
		62	
		116	
Uebler (1984)	58	58*	12
Walker et al. (1973)	60	60*	
	70	70*	
	75	75*	
	60	60*	
Stewart et al. (1979)		44	12

MEAN = 62.7, STD. DEV. = 22.0

* = Total N value used is actually NH_3-N value, no total-N reported

anaerobic conditions which prevail in the drainfield trench (U.S. Environmental Protection Agency, 1978). A paper by Sikora and Corey (1976) states that immobilization of nitrogen in the soil absorption field will be minimal (1-3 percent). Thus it is reasonable to assume an average concentration of about 60 mg/L NH_4^+-N in the effluent leaving the drainfield trenches.

A properly sited septic system will have at least a one meter separation between the trench bottom and the water table. Under these conditions, redox potentials are high enough that the ammonium will be rapidly oxidized to nitrate, usually within 30-60 cm of travel (Walker et al., 1973). Assuming no loss of N, this results in effluent with 60 mg/L NO_3^--N moving freely to the water table. While this is the most common scenario for nitrogen movement below a drainfield, there are other possibilities. Should the water table rise close to or above the drainfield trench, oxidation of ammonium will not occur, rather the NH_4^+ ion will be adsorbed on cation exchange sites. This can also occur during times of the year when the soil profile is very wet, as oxygen diffusion below the trench is limited, and during colder periods, when the microbial activity needed for nitrification is depressed. However, in most situations it is inevitable that warmer, drier, conditions will return, and the adsorbed ammonium will be quickly nitrified. This may cause a "slug" of higher-than-normal nitrate-laden effluent to pass to the water table (Starr and Sawhney, 1980).

The most desirable fate for the nitrogen leaving the drainfield is for it to be converted to N_2 by denitrification and escape to the atmosphere. This would require that the effluent first travel through an oxidizing environment, resulting in the conversion of ammonia to nitrate. If the nitrate is then exposed to reducing conditions, it will be converted to nitrite, and ultimately gaseous nitrogen, which may escape to the atmosphere. At first it may appear that this process would be a common situation below drainfields, as the ammonium is rapidly nitrified, and the nitrate will encounter reducing conditions when it reaches the water table. However, a prerequisite for denitrification is a carbon energy source for the microbes responsible for the process. While Meeks et al. (1970) showed that almost complete denitrification can occur at and near the water table when a sufficient carbon source is available, Lance (1972), noted that the denitrification process requires a minimum carbon:nitrogen ratio of about 1.3:1. He also noted that secondary effluent typically has about a 1:1 C:N ratio, but that most of the carbon would be utilized by heterotrophic bacteria as the effluent traveled through the aerated zone, which would further decrease the potential for later denitrification in the reducing zone at the water table.

There is support in the literature that certain soil conditions or properties may promote denitrification. Lund et al. (1974), and Devitt et al. (1976) examined soil cores removed from profiles subject to high levels of nitrate leaching. They found lower nitrate levels in cores below clay layers, or below textural discontinuities in general. They reasoned that such textural changes create local zones of saturation, resulting in lower redox potentials, and increasing opportunities for denitrification. Schmidt (1972) attributed differences in groundwater nitrate in a large area with many septic systems to occasional lenses of clay or hardpan materials which would similarly provide opportunities for denitrification. Reneau (1977) described septic systems above shallow water tables with high soluble carbon concentrations where it appeared that denitrification had occurred.

Several attempts have been made to design septic systems that will promote denitrification (Andreoli et al., 1979; Laak, 1981; Sikora and Keeney, 1976). While such designs have been shown to be effective in nitrogen removal, they have not been demonstrated to be practical, as they require a higher level of maintenance, and are considerably more costly than conventional septic systems. An increasingly popular alternative septic system, the elevated sand mound, also has the potential to promote denitrification when used over finer-textured soils. The effluent is nitrified as it passes through the sandy fill material, and reducing conditions are created at the base of the mound as effluent travel is slowed due to lower hydraulic conductivity of the finer-textured natural soil. Average nitrogen removal of 44 percent was found by Harkin et al. (1979). Conventional and alternative septic system designs incorporating periodic dosing of the effluent to the absorption area also stimulate denitrification (Lance et al., 1976).

While clearly there are cases where significant denitrification of percolating septic tank effluent may occur, they are probably the exception rather than the rule for the majority of septic systems. Much development occurs on well-drained, coarse-textured soils because of their favorable building characteristics. Denitrification is unlikely in such soils. Thus, under these conditions it is probable that almost all the nitrogen exiting the septic tank will eventually reach the water table. Several laboratory and field studies support this conservative behavior of septic system nitrogen (Stewart et al., 1979; Willman et al., 1981; Brown et al., 1984).

Nitrate Contamination of Ground Water

Before addressing the influence of man's activities on ground-water quality, it should be pointed out that it is possible for nitrate contamination to result from natural sources, as has been noted by several investigations (Kreitler and Jones, 1975; Custer, 1976); Hendry, 1984). These studies noted that natural nitrates may occur in the geologic materials making up an aquifer, or may be leached from overlying soils where organic nitrogen is being mineralized to nitrate. When there is doubt as to the source of nitrates, stable-isotope analysis of ratios of $^{15}N/^{14}N$ can be used to differentiate among natural, fertilizer, and animal waste nitrate (Kreitler and Jones, 1975).

While natural nitrate contamination is possible, septic system nitrates have also been proven as serious ground-water pollutants (Woodward et al., 1961). In attempting to illustrate the potential for ground-water contamination by septic systems, it is helpful to first examine a number of examples from the literature of nitrate pollution of ground water in order to establish a cause/effect relationship between nitrogen loading rates to an aquifer, and the resultant concentration of ground-water nitrate. Unfortunately published studies of septic system nitrate contamination do not quantify housing density, and so it is not possible to estimate of loading rate of nitrogen to the water table. The four examples presented in Table 14 involve leaching of nitrogen fertilizer from agricultural lands, and are informative because they do contain measurements or estimates of the amount of nitrogen leached to the ground water per hectare of land.

Table 14. Summary of nitrogen loading rate (amount leached from rooting zone, ground-water depth, and resultant ground-water nitrogen concentration) from several published studies.

Reference	Estimated NO_3^--N Loading Rate	Depth to Ground Water	NO_3^--N in Ground Water
Baier & Rykbost (1976)	50-100 kg/ha	6m (approx.)	8-23 mg/L
Saffigna & Keeney (1977)	>120 "	5m "	>15 "
Spalding et al. (1978)	90-110 "	3m "	15-45 "
Hill (1982)	60-100 "	3-6m "	11-51 "
" "	" "	>6m "	0.2-5 "

From the data presented in this table it would appear that nitrogen loading rates on irrigated, well-drained agricultural soils, in the neighborhood of 50-100 kg/ha can lead to concentrations of 10-30 mg/L NO_3^--N in the ground water, when the water table is within 10 m of the land surface.

It is possible to calculate a reasonable loading rate of NO_3^--N from septic systems. Average per capita effluent generation has been well-established at 150-190 liters per day (40-50 gallons per day), and for calculations here an average of 170 liters (45 gallons) per day will be used. Using the 60 mg/L NO_3^--N concentration for effluent leaving the drainfield trench (as determined earlier), these two values can be used to estimate a net nitrogen loading for a family of four:

$$60\ \text{mg/L}\ NO_3\text{-N} \times 170\ \text{L/person/day} \times 4\ \text{persons} \times 1\ \text{kg}/10^6\ \text{mg} =$$

$$\begin{aligned} & 0.041\ \text{kg}\ NO_3^-\text{-N per day} \\ = & 0.286\ \text{kg}\ NO_3^-\text{-N per week} \\ = & 14.8\ \ \text{kg}\ NO_3^-\text{-N per year} \end{aligned}$$

The 14.8 kg/year value is less than one-half the 33 kg/yr/family of four nitrogen loading rate calculated by Walker et al. (1973), yet more than twice the 7 kg/yr/household determined by Starr and Sawhney (1980). Both studies utilized data from field observations. Winneberger (1982) calculated a value of 11 kg/yr/family of four, based on per capita nitrogen production of 11 g/day (U.S. Environmental Protection Agency, 1978), and 30 percent loss of nitrogen in the septic tank and drainfield. The estimate of 14.8 kg/yr from this analysis would appear to be as valid as these estimates, as it is based on the average effluent characteristics of over 20 studies (Table 13).

Assuming an average lot size of 0.4 ha (one acre), and no significant loss of nitrogen from the effluent during its travel to the water table, a loading rate to the ground-water system of 37.0 kg NO_3^--N/ha/year is determined. While this value is slightly below the range of 50-100 kg/ha from the fertilizer-N studies outlined above, it still implies that there is potential for elevation of ground-water nitrate concentrations from rural subdivisions with housing densities of about 1 unit/ha or more. This becomes more clear when the nature of the nitrate loading is examined.

The loading from the septic system is a daily, point-source event over a small area, far different than the diffuse nature of agricultural fertilization (e.g. 14.8 kg N applied to 0.05 ha, versus 75 kg N leached from 1.0 ha). This will result in important differences in the distribution of the nitrate within the ground-water system. Given the limited mixing that will occur within an aquifer, it would be expected that relatively higher concentration, elongated plumes of nitrate would result from the input of septic system effluent, while fertilizer-nitrate pollution would exhibit a much more uniform distribution within the aquifer. Such plumes mean that detection of high-nitrate ground water is difficult, especially as one moves farther away from the point source. Childs et al. (1974), and Rea and Upchurch (1980) showed that complex patterns of migrating nitrate plumes complicate monitoring of contamination from septic systems. NO_3^--N concentrations of 54, 74, and 30 mg/L (Scalf et al., 1977, Walker et al., 1973, Peavy and Groves, 1977) have been reported in ground-water samples around septic sytems, with concentrations decreasing with distance from the source.

This analysis provides estimates of potential N-loading to and contamination of the water table, but in order for a prediction to be made of possible nitrate concentrations of the ground water, it is necessary to know more about the hydrologic system. Important parameters to be considered include: depth to the water table, hydraulic gradient of the water table, hydraulic conductivity of the aquifer, and background nitrate levels of the ground water.

Deeper water tables result in both longer flow paths to the saturated zone, and increased residence times of the effluent within the vadose (unsaturated) zone. This enhances the potential for lateral migration of the effluent in the unsaturated zone due to the hydraulic gradient present at the edge of the effluent plume. The result is a more diffuse distribution of the nitrate when it reaches the water table, as well as an increased potential for more storage of NO_3^--N within the vadose zone. Walker et al. (1973) found nitrate-N concentrations of 43-110 mg/L in extracts from unsaturated soils below several drainfields. Stewart et al. (1967) found stored NO_3^--N of 569 kg/ha in the 6.5 meters of soil below irrigated cropland. Also, if any chemical or biochemical nitrogen transformations (e.g. denitrification) are occurring, the increased residence time and storage means that there is a longer opportunity for such changes to occur. Perhaps reflecting these processes, Hill (1982) noted that deeper water tables (more than 6 m below the ground surface) had less than half the nitrate concentration of shallower systems.

Probably the most important properties of an aquifer influencing the ultimate concentration of a pollutant are the hydraulic conductivity and gradient. They determine the net volume of water available for dilution of the incoming stream of contaminants. Further, the lower the initial contaminant level of the ground water, the lower will be the resultant contaminant concentration after the effluent mixes with the ground water. That those ground-water systems with larger hydraulic conductivities, steeper gradients, and higher levels of recharge from precipitation can provide maximum dilution potential of pollutants will be demonstrated in the following model.

METHODS

There are a number of complex numerical models which have been developed to predict pollutant flow within and impact upon aquifers (Perkins, 1984), but in general they demand a high level of mathematical competence, computer access, and often require a more detailed knowledge of aquifer characteristics than is available (e.g. values for coefficient of storage, dispersivity). Given the complexity and diversity of the major components that influence such models (e.g. soils, geology, climate), it would seem unlikely that detailed models developed in a single area can be applied successfully to other areas. Further, local governing bodies, public health officials, sanitarians, planners, (the people who must make the decisions), typically do not have the resources that would allow them to use such models. They could benefit from a simplified model that would both illustrate the mechanics of the natural system of interest, and help them estimate the potential impacts of septic systems on ground-water quality.

With these considerations, the model presented here makes it possible to: 1) obtain a first approximation of the potential impacts of septic system nitrates on ground-water quality; 2) evaluate which physical properties most greatly influence the capacity of an aquifer to adequately dilute septic system nitrates; 3) gain useful information for comparing the relative susceptiblity of various aquifers to nitrate contamination from septic systems. The goal of this model is not to accurately predict ground-water nitrate levels. Rather, through use of the model, local regulatory personnel can develop a better understanding of the physical and chemical processes that determine the ground-water quality impacts of suburban and rural use of septic systems.

Model Development

This model employs both the approach of Mercado (1976), whose analysis of ground-water pollution in Israel reduced a geographically broad and complex system into a single cell, and Fried et al. (1976) who applied the concepts of mass balance and steady state to a California study examining the influence of the agricultural nitrogen budget on ground-water quality. Other simplifying assumptions are used to facilitate development of a model that can be utilized in the decision-making process. The initial step is to define a geographical area or unit of interest, i.e. determine the boundaries of the unit system. Then two mass balance equations must be developed, one for the water budget of this system, and one for the nitrogen budget. By determining the amount of nitrate entering the system (all nitrogen inputs are assumed to be in the form of nitrates), and the volume of water that is discharged at the system boundary, an estimate can be made of the average nitrate concentration of the ground water as it leaves the system. Application of the model is restricted to isotropic and homogeneous water table aquifers composed of unconsolidated sediments.

Water and Nitrogen Budgets

The model considers three main sources of water and nitrate to a ground-water system (Figure 32) which has reached a steady state condition with regards to these inputs (Fried et al., 1976). At the upgradient boundary, ground water (W_g) enters the system containing some level of nitrate-nitrogen (N_g). Both natural precipitation (hereafter referred to as natural recharge, W_r), and septic system effluent (W_e) percolate through the soil to the ground-water system, each contributing some nitrogen to the aquifer (N_r and N_e respectively). Complete mixing within a prescribed depth increment of the aquifer is assumed. No other inputs of water or nitrogen are considered. Impacts of such potential additional inputs from agricultural fertilizer, feedlots, etc. are not considered, as a large subdivision setting is assumed, and an intent of the analysis is to examine the ground-water pollution potential from septic systems alone. It is further assumed that the only output from the system is through the downgradient boundary (i.e. there is no consumptive use of the water removed by domestic wells penetrating the aquifer--it is all returned via septic systems, and there are no other wells or surface vegetation removing water from the system). With these preconditions, and evaluating the system over a time period of one year, values needed for mass balance considerations are simply calculated.

The ground-water volume entering the system at its upgradient boundary can be calculated using Darcy's law:

$$Q/t = W_g = Kb(dh/dl)w \qquad \text{Eq. 4}$$

where Q/t = volume of flow (m^3/yr), K = hydraulic conductivity of the

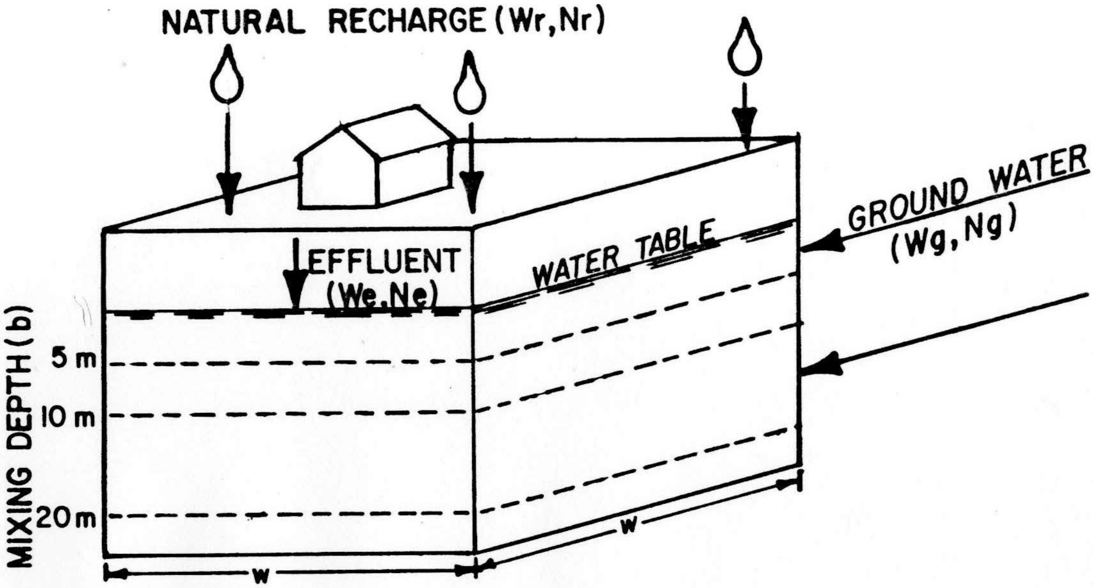


Figure 32. Schematic representation of model inputs.

aquifer (m/yr), b = aquifer thickness (m), dh/dl = the hydraulic gradient (slope of the water table), and w = aquifer width (m). In areas where data on the local hydrogeology is lacking, K can be estimated through knowledge of the particle size distribution of the geologic material comprising the aquifer or through field measurement techniques (Freeze and Cherry, 1978). Likewise, the hydraulic gradient can be established by field measurement of the piezometric surface at several locations, or can be estimated. The width (w) of the aquifer is defined by the areal extent of the system of interest (Figure 32).

Aquifer thickness can be set without knowledge of the actual depth of the aquifer using the rationale that limited mixing of influent nitrates occurs within the aquifer. This tendency for influent nitrate to remain stratified in the upper portions of the aquifers has been noted by both Hill (1982), and Spruill (1983). With this assumption, the depth of such mixing can be estimated to obtain a value for b, now defined as depth of mixing. If the actual aquifer thickness were used, greater dilution of nitrate would erroneously be calculated, as much of the aquifer may remain relatively isolated from the influent nitrate. For this model, b will take on the values 5, 10 and 20 m to evaluate the impact of different degrees of mixing. Complete mixing will be assumed within this prescribed thickness. Nitrate-N concentrations for ground water entering the system can be obtained from existing data, or estimated. Precipitation contributing to recharge of the water table can be estimated using the method of Dunne and Leopold (1978, p. 253). Several values are used in this analysis (Table 15) representing typical values for differing climates, arid to humid.

Nitrate-N concentration of this recharge water must be estimated (this model assumes 3 mg/L). The volume of effluent passing to the water table can be calculated by assuming a water use of 170 L/day/capita, and 3 people per family (from 1980 U.S. Bureau of Census figures for occupancy of rural housing units) for an average yearly water use of 186,510 L per family (186 m^3). The nitrate-N content of this effluent is taken as 62 ± 21 mg/L, as determined earlier in this study. It is assumed that there are no losses of nitrogen after it leaves the septic tank, and that upon exiting the drainfield trench all nitrogen is converted to nitrate-N.

Sensitivity Analysis

Sensitivity analysis can be used to examine the relative importance of the variables in the model. It is performed by selecting a parameter and varying its input value while keeping others constant.

Parameters that produce large changes in the results can be considered sensitive, and are of greater interest than those of low sensitivity. Estimates of hydraulic conductivity and hydraulic gradient (Table 15) represent a range of values commonly encountered in aquifers serving as sources of domestic water supply. Values for other variables are also found in Table 15, followed by an example of how the data used to generate the graphs found in Figures 33-37 were calculated.

Table 15. Parameters and values used in the sensitivity analysis.

W_g: Ground water entering upgradient boundary
  Hydraulic conductivity (K) — 0.01 & 0.001 cm/sec (3154 & 315.4 m/yr)
  Hydraulic gradient (dh/dl) — 0.01 & 0.001
  Aquifer mixing thickness (b) — 5, 10, and 20 m
  Aquifer width (w) — 402 m (one side of a square 16 ha (40 acre) parcel)
N_g: Background nitrate-N in ground water — 1, 3, 5, 7 mg/L
W_r: Natural recharge — 0, 10, 20, 30, 40 cm/yr
N_r: nitrate-N in recharge — 3 mg/L
W_e: Septic system effluent — 186,510 L/family/year
N_e: nitrate-N in effluent — 60, 50, 40, 30 mg/L
Housing density — lot sizes of 5, 4, 3, 2, 1, 0.5 acre

Sample Calculation

(for a 40 acre development, 402 m X 402 m)

Water Budget

1) Ground water entering upgradient boundary (W_g):

K=3154 m/yr; dh/dl=0.01; w=402 m; b=10 m;

$$(3154 \text{ m/yr})(0.01)(402 \text{ m})(10 \text{ m})(1000 \text{ L/m}^3) = 126 \times 10^3 \text{ m}^3$$

2) Natural recharge (W_r): assume 0.10 m/yr (3.9 inches)

$$(402 \text{ m})(402 \text{ m})(0.10 \text{ m})(1000 \text{ L/m}^3) = 16.2 \times 10^3 \text{ m}^3$$

3) Septic system effluent recharge (W_e): (assume one family per acre):

$$40 \text{ acres } (186{,}510 \text{ L/acre}) = 7.46 \times 10^3 \text{ m}^3$$

<u>TOTAL WATER INPUT</u> (W_t): $W_g + W_r + W_e$

$= (126 \text{ X } 10^3 \text{ L}) + (16.2 \text{ X } 10^3 \text{ m}^3) + (7.46 \text{ X } 10^3 \text{ m}^3)$

$= \underline{149.7 \text{ X } 10^3 \text{ m}^3/\text{year}}$

<u>Nitrogen Budget</u>

1) Ground water (N_g): (background concentraton of 1 mg/L nitrate-N):

$$(126 \text{ X } 10^6 \text{ L}) \text{ X } (1 \text{ mg/L}) = 126 \text{ X } 10^3 \text{ g}$$

2) Natural recharge (N_r): (assume 3 mg/L nitrate-N in recharge water):

$$(16.2 \text{ X } 10^6 \text{ L}) \text{ X } (3 \text{ mg/L}) = 48.6 \text{ X } 10^3 \text{ g}$$

3) Septic system effluent (N_e): (one family/acre, 40 acres, 60 mg/L nitrate-N):

$$(7.46 \text{ X } 10^6 \text{ L}) \text{ X } (60 \text{ mg/L}) = 447.6 \text{ X } 10^3 \text{ g}$$

<u>TOTAL NITROGEN INPUT</u> (N_t): $N_g + N_r + N_e$

$= (126 \text{ X } 10^3 \text{ g}) + (48.6 \text{ X } 10^3 \text{ g}) + (447.6 \text{ X } 10^3 \text{ g})$

$= \underline{622.2 \text{ g nitrate-N}}$

<u>NITRATE-N IN GROUND WATER EXITING SYSTEM:</u>

$$\frac{N_t}{W_t} = \frac{622.2 \text{ X } 10^3 \text{ g}}{149.7 \text{ X } 10^3 \text{ m}^3}$$

$$= \underline{4.15 \text{ g/m}^3 \text{ (4.15 mg/L) nitrate-N}}$$

It is important to emphasize that the methodology proposed represents a gross simplification of the complicated hydrogeologic processes involved in aquifer contamination. Such oversimplification can be justified given the intent of the model — to help local regulators lacking hydrologic expertise obtain a better comprehension of the complex processes that determine the ultimate level of contamination that may arise from the use of on-site waste treatment systems.

RESULTS AND DISCUSSION

Sensitivity Analysis

Figures 33-37 illustrate the relationship between predicted ground-water nitrate-N and housing density for various combinations of the above factors. Unless otherwise noted, the mixing thickness used is 10 m, recharge is 5 cm/yr, K = 0.01 cm/sec (3154 m/yr), and dh/dl = 0.01). The nitrate-N concentration of concern is 10 mg/L, the maximum allowable for drinking water (National Academy of Sciences, 1978). In each of these figures the model predicts that at higher housing density (approaching 1 and 2 acres/lot) this standard is likely to be exceeded.

Figure 33 examines the influence of different levels of hydraulic conductivity and gradient on resultant ground-water nitrate-N concentration. Higher conductivities and gradients generally result in higher ground-water velocities, providing a greater diluting capacity (lower nitrate-N concentation) for the system. This effect has been noted in a field study by Pitt et al. (1975) where septic system densities of up to 0.25 acres/lot caused no significant elevation of ground-water nitrates. Lower gradient and conductivity ground-water systems have a lesser capacity for dilution, and may be considered more susceptible to appreciable contamination.

Figure 34 shows the influence of mixing depth on dilution of effluent nitrates for systems with high and low ground-water

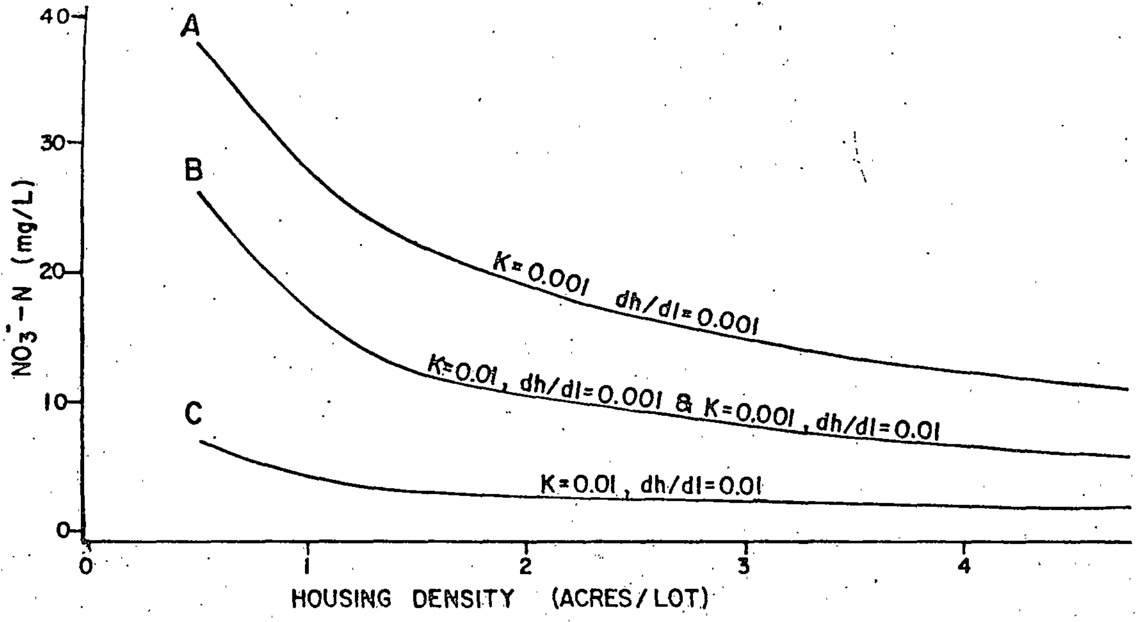


Figure 33. Influence of hydraulic conductivity and gradient on groundwater nitrate-nitrogen. (K units are cm/sec)

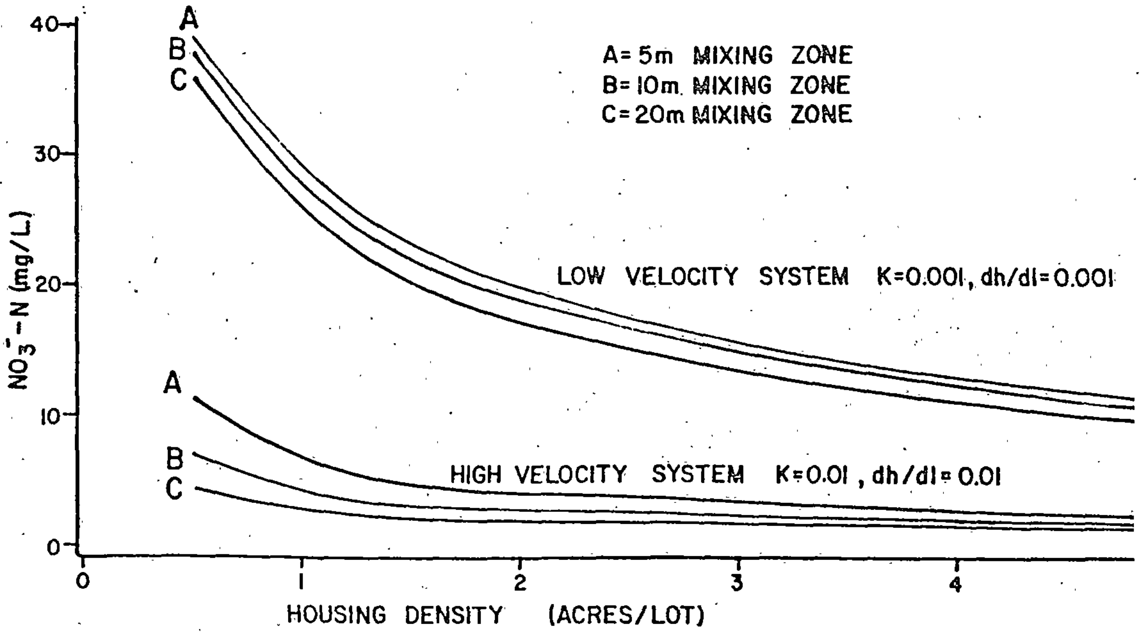


Figure 34. Influence of mixing depth on nitrate-nitrogen in groundwater for a high and low velocity system.

velocities. In the low velocity system, mixing depth has little impact on nitrate-N concentration. A more pronounced dilution effect is seen for the high velocity system at higher housing densities, but even with small lot sizes (0.5 acre), increasing mixing depth from 5 to 20 m only decreases nitrate-N from 11 to 4 mg/L. Another parameter that has little impact in this analysis is the background nitrate-N concentration of incoming ground water (Figure 35). The upper curves representing a low velocity system are so close together they appear as one, indicating that the contribution of nitrogen from incoming ground water plays a relatively minor role in the nitrate loading of the system. The effect is more pronounced for the higher velocity system, however, most values still remain below the 10 mg/L standard. Geographical areas with higher precipitation and infiltration will be better able to dilute septic system nitrogen (Figure 36). In this model, this effect is especially noticeable when natural recharge is less than 20 cm/yr. Thus arid and semi-arid parts of the country may be at greater risk from such contamination.

The effect of lower effluent-N concentrations and/or denitrification are shown in Figure 37. The previous examples have all assumed that 60 mg/L total nitrogen is exiting the drainfield, is all converted to nitrate, all passes to the water table, and out the boundary of the system. If 50 percent denitrification of the nitrate contributed by the effluent is assumed (equivalent to a decrease in effluent nitrate-N to 30 mg/L), it is seen that for the low velocity system, at a density of 1 acre/lot, ground-water nitrate-N decreases from 28 mg/L to 15 mg/L. The high velocity system shows little impact from such a

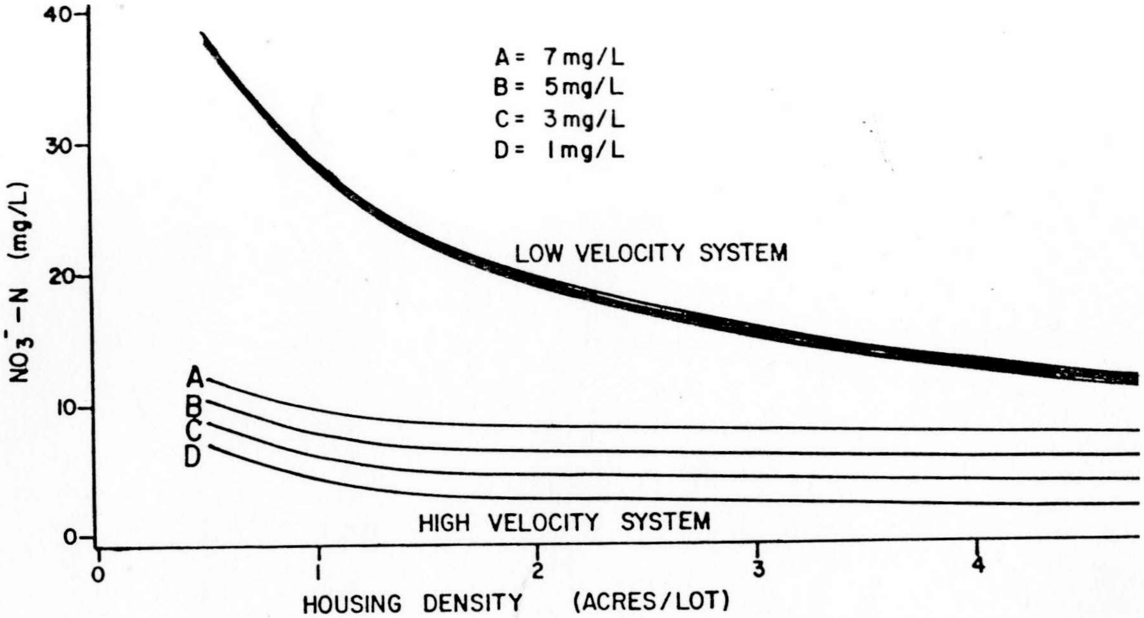


Figure 35. Influence of nitrate-N concentration of incoming ground water on resultant ground-water nitrate-N.

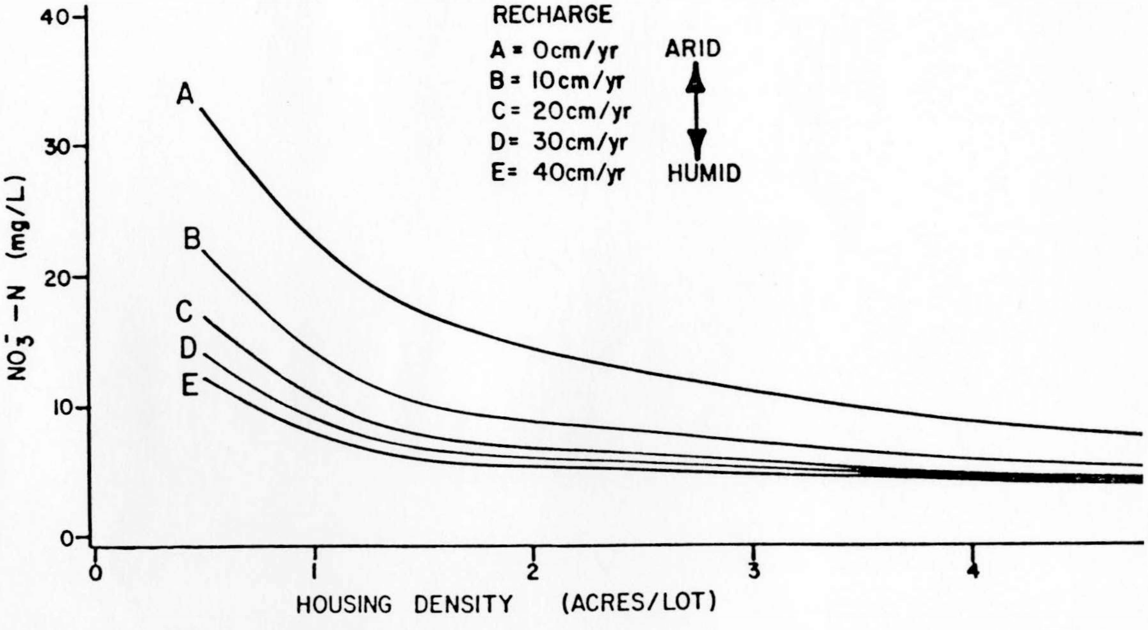


Figure 36. Influence of natural recharge on ground-water nitrate-nitrogen.

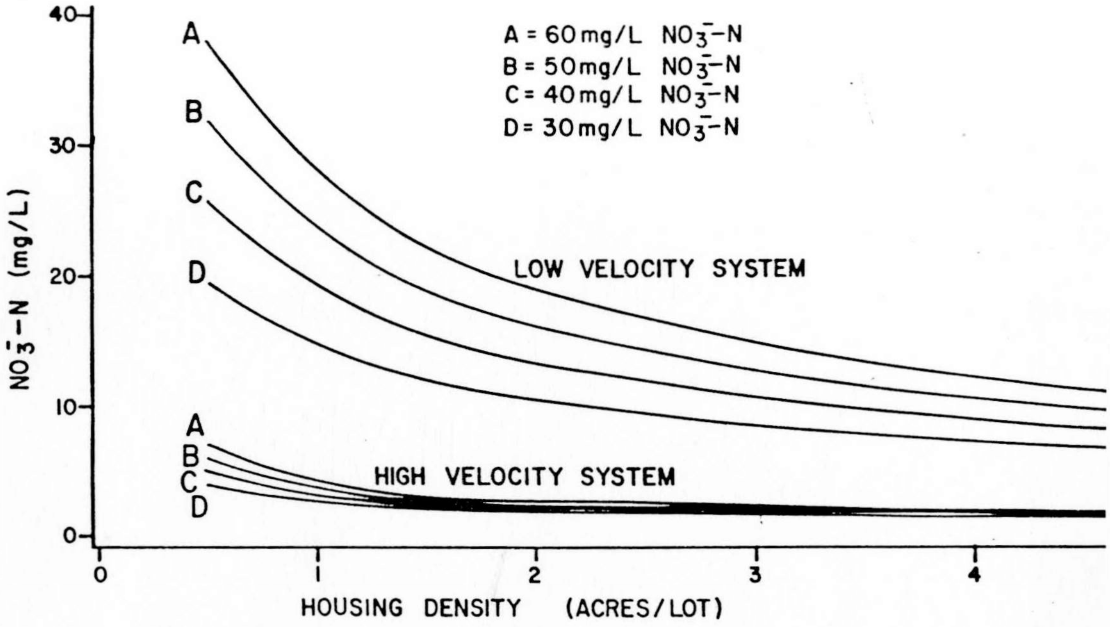


Figure 37. Influence of effluent nitrate-N concentration on ground-water nitrate-nitrogen.

reduction in effluent nitrogen, the result of its high dilution capacity. As shown in Figure 35, if the amount of septic system nitrogen reaching the water table is reduced (for example by denitrification in the unsaturated zone), nitrate-N content of ground water will decrease, especially in low velocity systems. Denitrification can also occur after effluent N reaches the water table (Reneau, 1977).

Factors influencing the potential for denitrification in the system described in the model are summarized below.

1) Presence of restrictive layers between the water table and septic system. Such layers will provide local zones of saturation where anaerobic conditions may develop, promoting denitrification.

2) Temperature. Higher temperatures mean increased metabolic activity for bacteria, increasing the rate of denitrification.

3) Residence time of effluent as it travels to the water table, and then as it travels to the system boundary. Longer residence times provide a greater opportunity (i.e. more time) for denitrification processes to occur. While Figure 33 suggests systems with low groundwater velocities have higher nitrate concentrations, longer residence times will also be longer, increasing the time during which denitrification may occur.

4) Dissolved organic carbon (DOC) content of ground water. Higher concentrations stimulate bacterial activity, increasing the potential for both anaerobic conditions and denitrification. In most aquifers, DOC can be considered the limiting factor for denitrification, as approximately 1.3 g of carbon are required to convert 1 g of nitrate-nitrogen to nitrogen gas (Lance, 1972). While effluent contains a 1:1 C:N ratio, most of the carbon is utilized by heterotrophic bacteria under aerobic conditions, leaving insufficient carbon for denitrification when the effluent reaches an aerobic environment. Champ et al. (1979) reported a median DOC content of 0.7 mg/L in a survey of American ground waters. This value would suggest denitrification potential is limited in most aquifers. However, it would seem that shallow aquifers should have higher DOC levels, as organic carbon is leached from organic matter in surface soils. Also, because of the short travel time to the water table, perhaps less of the DOC in effluent is removed. Further, at least during part of the year, water temperature will be higher. This suggests that placing septic systems

in areas with shallow water tables may be desirable, if suitable protection from contamination by pathogenic micro-organisms is insured. These factors could contribute to considerable denitrification, as found by Reneau (1977).

This sensitivity analysis suggests that the following variables are most responsible for large changes in predicted ground-water nitrate-nitrogen: hydraulic conductivity and gradient, natural recharge, housing unit density, and concentration of effluent nitrate-nitrogen reaching the water table. The first three parameters determine the recharge characteristics of the aquifer, and the second two influence the nitrogen budget (loading rate) of a given system. The hydraulic conductivity of geologic materials can range from 10^2 to 10^{-7} cm/sec, and hydraulic gradient from 10^{-1} to 10^{-4}. Such order of magnitude changes imply that different ground-water systems may vary greatly in their ability to dilute incoming pollutants. Ground-water systems with high conductivities and gradients (high velocities) can tolerate larger loading rates of nitrogen, i.e. will have a greater diluting capacity. Density of septic systems, amount of natural recharge, and amount of effluent-N reaching the water table can be important parameters, especially in systems with low velocities.

A model similar to the one evaluated here was applied to a field study in Illinois (Wehrmann, 1983) and provided reasonably close estimates of observed ground-water nitrate values. However, given the simplifying assumptions of this model, and its lack of testing, care should be exercised in its application. Rather than serving as a predictor of ground-water nitrate concentrations, it might be used as an informative tool for evaluating the relative contribution of various inputs to a "real world" system, and to compare the relative potential for contamination of different sites. Regulatory personnel (e.g. county sanitarians) could gather the local hydrologic data necessary for application of the model. Results might characterize local regions having low, medium, and high predicted nitrogen values that could be interpreted as having low-to high susceptibility for significant ground-water pollution. Such information might indentify those aquifers more sensitive to nitrate contamination from on-site sewage systems, and deserving of more careful study should housing developments be proposed in that area.

Additional Considerations for Aquifer Evaluation

Present assessment of the ground-water system during the site evaluation process is generally limited to determining depth to the water table. The information presented in the preceeding discussion suggests that if protection of ground-water quality is to be genuinely addressed, it is important to consider the aquifer characteristics discussed in the model. Other variables, whose quantification is difficult, and that were not evaluated in the model, may also play important roles in the net impact of septic system effluent on ground-water quality. These variables are included in Table 16. Internal factors define the ability of the ground-water system to dilute the incoming contaminants to acceptable levels. External factors determine the relative significance of the resultant level of contamination to both public health and environmental quality.

Table 16. Factors to consider when evaluating the impact of septic systems on ground-water quality.

INTERNAL FACTORS

- Depth to the water table
- Hydraulic conductivity of the aquifer
- Ground-water gradient and direction of flow
- Aquifer thickness and effective mixing thickness
- Background nitrate-nitrogen concentration of ground water
- Aquifer geology (e.g. unconsolidated sands, fractured bedrock, etc.)
- Potential for denitrification

EXTERNAL FACTORS

- Density of septic systems
- Present and potential use of aquifer
- Impact on downgradient users
- Nutrient status of surface waters in discharge areas
- Leakage to (i.e. contamination of) other aquifers
- Number of pumping wells in the aquifer and volume of water pumped
- Length of flow path to surface discharge area or downgradient users

Table 16 suggests that evaluation of potential ground-water impacts should include more than physical measurements or estimates of aquifer characteristics. In particular, it may be appropriate to appraise the relative importance of the receiving aquifer. To illustrate this point, two hypothetical cases may be compared. The first is a proposed high-density development (1-acre lots) that is underlain by a shallow (2 m deep), perched aquifer that has a saturated thickness of only 3 m, and which discharges to a local stream or wetlands area several kilometers away. It is unlikely that such an aquifer would ever serve as a drinking water source. Because the wetlands represent a preferred sink for the nutrients in the discharging ground water, a greater degree of degradation of this shallow aquifer may be acceptable (or even desirable if it decreases the potential for development that may affect other, more highly used aquifers). In such an example, it is possible that ground-water nitrate-N concentrations of even 20 mg/L or more would be unlikely to create health or water quality problems. Likewise, if discharge was to a stream, its dynamic environment might assimilate the added nitrogen load with little adverse effect.

By contrast, consider a similar development proposed above a deeper (10 m), thicker (50 m) aquifer that is heavily used for domestic water by an existing development down-gradient from the proposed one, or that discharges to a nearby lake. The potential for increased risk of drinking water contamination or nutrient enrichment of the lake is substantial. Accordingly, care should be exercised in determining an acceptable housing density, and/or alternative methods of sewage treatment should be investigated. Integrating the above information into the land-use planning process would result in a decision that development in the former area would be more desirable, other factors being equal.

Consideration of the criteria outlined in Table 16 represents a substantially more sophisticated approach to the site evaluation process than commonly employed. However, given the increased concern for ground-water quality, such sophistication is necessary and beneficial to insure that the potential adverse impacts of septic systems are minimized. A detailed field assessment of these factors will not be necessary for every situation, but even in those cases it is helpful to review these factors to obtain a better understanding of the potential impacts. Information of this nature will assist public officials in calculating the risks associated with a site (i.e. weighing the probability of contamination versus the health and environmental consequences of such contamination).

SUMMARY

This chapter has provided a discussion of the environmental consequences of on-site sewage treatment systems, primarily regarding impacts on ground-water quality. Recognizing the inherent difficulty in attempting to accurately quantify the parameters influencing ground-water quality, a simple model has been proposed to assist local authorities in the process of evaluation of potential impacts. Given the limitations in quantitative data available for most aquifers, such assessments are as much art as science, and their quality will reflect the acumen of the appraiser. The foregoing discussion is intended to improve both the reasoning power and scientific skills of the decision-maker. Further, this discussion indicates that evaluating the ground-water quality impacts of on-site sewage treatment systems is a four-step process. 1) The diluting capacity of the aquifer should be evaluated. 2) An estimate of nitrogen loading to the aquifer is needed. 3) The potential for denitrification within the system should be considered. 4) An assessment is needed of the relative importance of the receiving surface and ground waters.

CONCLUSIONS

The results of this field study of in situ soil hydraulic conductivity in the Flathead Valley of northwestern Montana suggest that soil water movement is strongly influenced by the vertical variability (textural stratification) often noted in soil profiles in the study area. Complex glacial and proglacial depositional environments are responsible for this variability, which is also strongly expressed in the horizontal plane (lateral variability across the landscape). Soils formed from similar parent materials (and/or with similar textural properties) generally exhibit similar hydraulic characteristics in the saturated and near-saturated range. However, substantial variability within these groups is not uncommon. This variability requires that determination of site/soil suitability for septic systems include on-site observations of soil profile characteristics. The implications of textural stratification within the soil profile need to be considered for proper design and long-term operation of individual on-site sewage treatment systems.

Principle component analysis was employed to reduce the large number of variables to a smaller set that would be easier to interpret, yet still account for most of the variance of the population. It was also used to graphically express the variability of physical and chemical soil properties with depth in the soil profile. Cluster analysis grouped the horizons from the study sites into coarse and fine-textured groups, and further subdivided these two groups into classes composed primarily of either A or C horizons. Discriminant analysis provided a two-dimensional grouping of these classes, and found that they were significantly different.

Concern with properly operating septic systems is based on potential degradation of surface and ground-water quality. Of the contaminants present in septic tank effluent, organic chemicals and nitrogen in the form of nitrate appears to present the greatest threat to the quality of ground-water resources. A simple model has been proposed that addresses the potential for nitrate contamination of ground water. It is designed to assist local regulatory officials in their efforts to minimize the environmental impacts of sewage treatment from suburban and rural housing developments. The model suggests that it is important to estimate the nitrogen load to the receiving aquifer (including the potential for denitrification), evaluate the diluting capacity of the aquifer, and also assess the relative importance of the particular ground-water system.

In the past decade, much progress has been made towards a greater comprehension of the principles governing the interaction of septic system effluent and ground-water systems. Preservation of the quality of our underground water reserves is an issue whose time has come, and it is imperative that problems regarding this resource be approached with a sufficient level of expertise. For that reason it is important that public officials involved in decision-making processes concerning the management of the ground-water resource be made aware of the type of analysis suggested in this report, and attempt to incorporate this knowledge into their evaluation procedures. The preceeding paragraphs suggest that as more is learned about the process of ground-water contamination by septic systems, an even greater level of sophistication and expertise will be required for effective management of the ground-water resource. As with other types of environmental issues, the key to effective management is the early recognition of potential problems, and the development of an appropriate strategy to mitigate or eliminate them. It is hoped that this thesis will contribute to improvements in the management of both on-site sewage treatment systems and ground-water resources in Montana.

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APPENDICES

APPENDIX 1

ON-SITE SEWAGE TREATMENT IN MONTANA

Given the insidious nature of ground-water contamination, it is especially important that regulatory authorities demonstrate concern regarding the continued growth in the number of septic systems in the State of Montana. For economic reasons, in most cases it is unlikely that septic systems will be replaced by central sewage treatment. The result will be an inexorable increase in individual on-site wastewater treatment systems, and a concomitant increase in nitrate loading of ground-water systems. For this reason, it is imperative that such growth be carefully monitored if future problems of ground-water pollution are to be avoided.

The discussion contained in the body of this thesis has demonstrated that most septic systems are point-source polluters of ground water, and that under certain conditions, the potential exists for septic systems to cause significant deterioration of ground-water quality. Such a threat implies a need for governmental regulation to help minimize this potential. The need for regulation becomes greater as the number of septic systems (and thus the potential for pollution) increases in any defined area. With this preface, it is the intent of the following discussion to outline recent trends in the growth of septic systems in Montana, examine the status of current regulatory efforts, and assess the environmental implications of these activities.

Recent Trends in Septic System Growth

Summary statistics for the state and each county regarding the changes in the number of housing units served by septic systems during the past two decades are presented in Table 17. They reveal that the number of housing units served by septic systems in Montana has grown from 70,018 in 1960, to 74,198 in 1970 (a 6 percent increase), to

Table 17. Statistics for housing units served by septic systems in Montana, 1960-1980.

	NUMBER OF SEPTIC SYSTEMS				PERCENT		
COUNTY	1960	1970	1980	CHANGE 1970-80	CHANGE 1970-80	UNITS ON SEPTIC	STATE TOTAL
BEAVERHEAD	1036	1066	1276	210	19.7	36.5	1.2
BIG HORN	720	1034	1451	417	40.3	39.4	1.4
BLAINE	717	726	983	257	35.4	38.9	0.9
BROADWATER	328	347	595	248	71.5	45.3	0.6
CARBON	1233	1025	1399	374	36.5	38.5	1.3
CARTER	287	397	377	-20	-4.9	48.5	0.4
CASCADE	2710	2980	4353	1373	46.1	13.6	4.1
CHOUTEAU	1189	1113	1128	15	1.3	43.7	1.1
CUSTER	706	652	935	283	43.4	17.2	0.9
DANIELS	425	472	443	-29	-6.0	35.7	0.4
DAWSON	739	764	1007	243	31.8	21.8	0.9
DEER LODGE	1026	1028	1152	124	12.1	23.1	1.1
FALLON	290	209	347	138	66.0	23.3	0.3
FERGUS	1437	1562	1797	235	15.0	34.1	1.7
FLATHEAD	6272	7179	12010	4831	67.3	57.7	11.2
GALLATIN	2809	3158	5497	2339	74.1	33.2	5.1
GARFIELD	232	316	397	81	25.6	55.9	0.4
GLACIER	561	857	1107	250	29.2	29.5	1.0
GOLDEN VALLEY	216	189	215	26	13.8	47.9	0.2
GRANITE	436	473	430	-43	-9.0	37.3	0.4
HILL	1124	1116	1459	343	30.7	20.9	1.4
JEFFERSON	735	674	1437	763	113.2	53.6	1.3
JUDITH BASIN	588	640	674	34	5.3	54.5	0.6
LAKE	2741	3096	4308	1212	39.1	57.5	4.0
LEWIS & CLARK	2130	2669	5275	2606	97.6	30.3	4.9

Table 17 (continued). Statistics for housing units served by septic systems in Montana, 1960-1980.

	NUMBER OF SEPTIC SYSTEMS				PERCENT		
COUNTY	1960	1970	1980	CHANGE 1970-80	CHANGE 1970-80	UNITS ON SEPTIC	STATE TOTAL
LIBERTY	312	283	265	-18	-6.3	26.3	0.2
LINCOLN	2376	4132	4750	618	15.0	69.6	4.4
MADISON	1437	1169	1413	244	20.9	57.0	1.3
MCCONE	479	471	617	146	31.0	57.7	0.6
MEAGHER	303	396	348	-48	-12.0	32.4	0.3
MINERAL	601	612	867	255	41.7	56.7	0.8
MISSOULA	8370	9148	12676	3528	38.6	42.4	11.8
MUSSELSHELL	499	457	744	287	62.8	37.2	0.7
PARK	1363	1451	1913	462	31.8	35.1	1.8
PETROLEUM	86	111	131	20	18.0	46.6	0.1
PHILLIPS	510	641	882	241	37.6	37.4	0.8
PONDERA	771	669	735	66	9.9	27.6	0.7
POWDER RIVER	403	443	476	33	7.4	44.4	0.4
POWELL	718	720	806	86	11.9	31.1	0.8
PRAIRIE	258	136	246	110	80.9	31.8	0.2
RAVALLI	3110	3344	6145	2801	83.8	69.9	5.7
RICHLAND	969	1083	1429	346	31.9	30.8	1.3
ROOSEVELT	654	723	755	32	4.4	19.9	0.7
ROSEBUD	426	580	870	290	50.0	23.4	0.8
SANDERS	1853	1815	2728	913	50.3	75.7	2.5
SHERIDAN	791	899	845	-54	-5.9	36.3	0.8
SILVER BOW	793	664	933	269	40.5	5.8	0.9
STILLWATER	770	845	1163	318	37.6	46.6	1.1
SWEET GRASS	425	424	525	101	23.8	38.0	0.5
TETON	997	1007	1134	127	12.6	43.6	1.1
TOOLE	608	603	506	-97	-16.0	21.0	0.5
TREASURE	119	180	187	7	3.9	46.2	0.2
VALLEY	1143	1048	1089	41	3.9	20.1	1.0
WHEATLAND	205	269	331	62	23.0	31.6	0.3
WIBAUX	229	203	243	40	19.7	35.9	0.2
YELLOWSTONE	7753	5930	11206	5276	89.0	26.2	10.5
TOTAL	70018	74198	107018	32820	44.2	34.0	

107,018 in 1980 (a 44 percent increase). This increase of 32,280 units served by septic systems, coupled with a statewide increase in housing units of 74,343, means that 44 percent of the new housing units constructed in Montana during the previous decade utilized septic systems for their domestic wastewater treatment, compared with the national average of 25 percent. This reflects a preference for low-density housing that is shared by many Montanans, and it is probable that this trend will continue in the years ahead.

This rapid increase was not spread evenly throughout the state, but was heavily concentrated in a few counties. Almost 78 percent of the new septic systems were built in the 9 counties listed in Table 18, and these counties contain over 60 percent of the septic systems in Montana. The top six counties account for 50 percent of the state's total. Figure 38 shows that few of the rest of the counties in Montana have appreciable numbers of systems (i.e. more than 900). Several summary statistics which emphasize this rapid growth for those counties are also presented in Table 18. Several of these counties (Ravalli, Lewis & Clark, Gallatin, and Flathead) experienced increases well in excess of 50 percent. Figure 39 shows the percent change in numbers of septic systems from 1970-1980 for those counties experiencing the greatest increases. The percent of housing units served by septic systems for those counties with the highest percentage of systems is shown in Figure 40.

That the nine counties in Table 18 have shown continued increases into the 1980's can be seen in Figure 41. All counties except Flathead reflect the drop in housing starts caused by the recession of the early 1980's. Data for the last several years indicate that rural homebuilding is rebounding, and unless there is a significant rise in interest rates, such growth can be expected to continue.

This information reveals that in a number of counties throughout the state substantial changes are occurring in the rural landscape that potentially could have adverse effects on environmental quality. Having established existing trends in the numbers of septic systems in Montana, it is of interest to review published information regarding documentation of water quality impacts from septic system effluent.

Table 18. Summary statistics for septic systems in selected Montana counties. (Source: U.S. Bureau of the Census, 1980)

			PERCENT		
COUNTY	TOTAL 1980	NET CHANGE 1970-1980	CHANGE 1970-1980	OF COUNTY ON SEPTIC	OF STATE SYSTEMS
MISSOULA	12676	3528	38.6	42.5	11.8
FLATHEAD	12010	4831	67.3	57.8	11.2
YELLOWSTONE	11206	5276	44.5	26.2	10.5
RAVALLI	6145	2801	83.8	69.9	5.7
GALLATIN	5497	2339	74.1	33.2	5.1
LEWIS & CLARK	5275	2606	97.6	30.3	4.9
LINCOLN	4750	618	15.0	69.7	4.4
CASCADE	4353	1373	46.1	13.7	4.1
LAKE	4316	1220	39.1	57.7	4.0

PERCENT OF STATE TOTAL -- 61.7

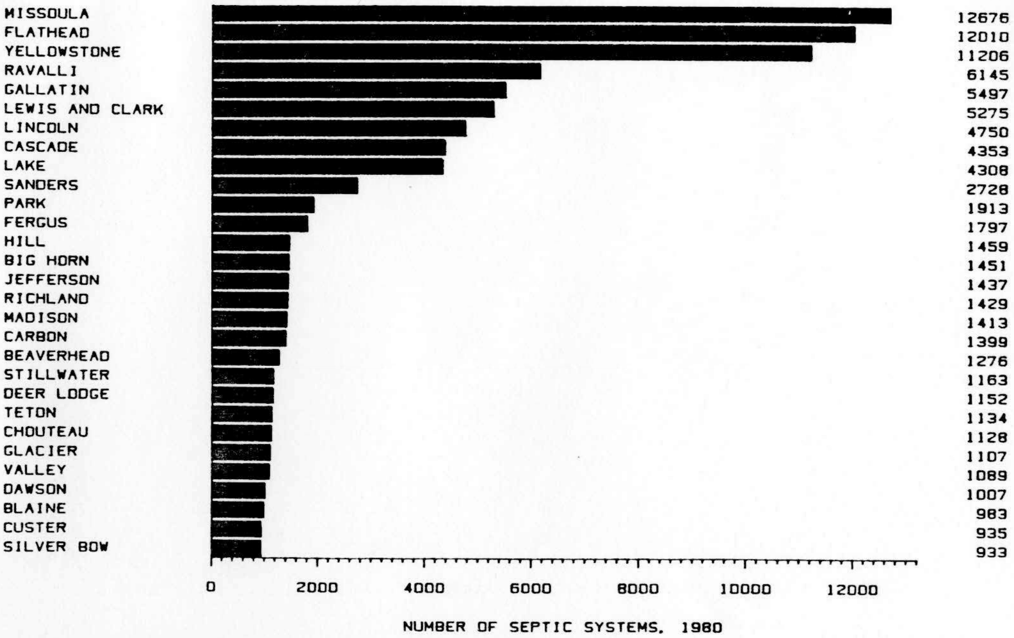

Figure 38. Montana counties with more than 900 housing units served by septic systems, 1980.

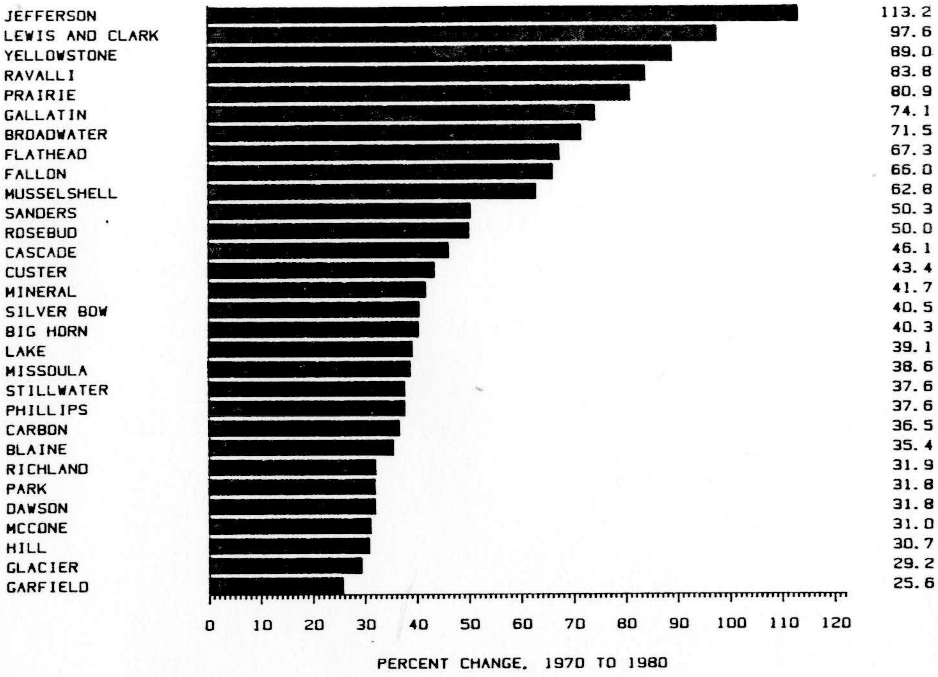

Figure 39. Montana counties experiencing an increase in excess of 25 percent of the number of housing units served by septic systems, 1970-1980.

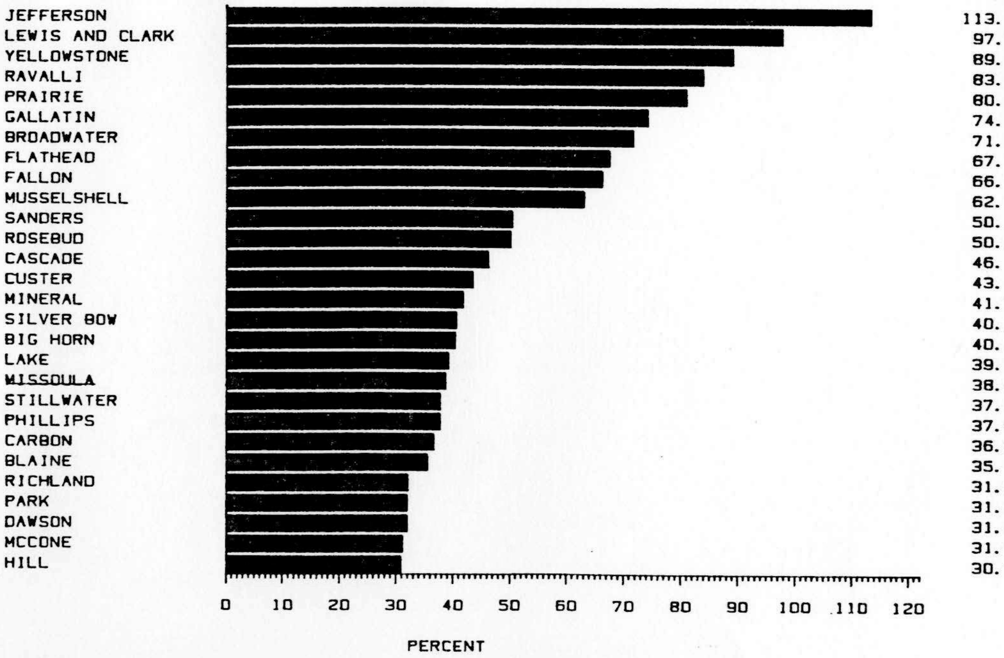

Figure 40. Montana counties with more than 30 percent of housing units served by septic systems.

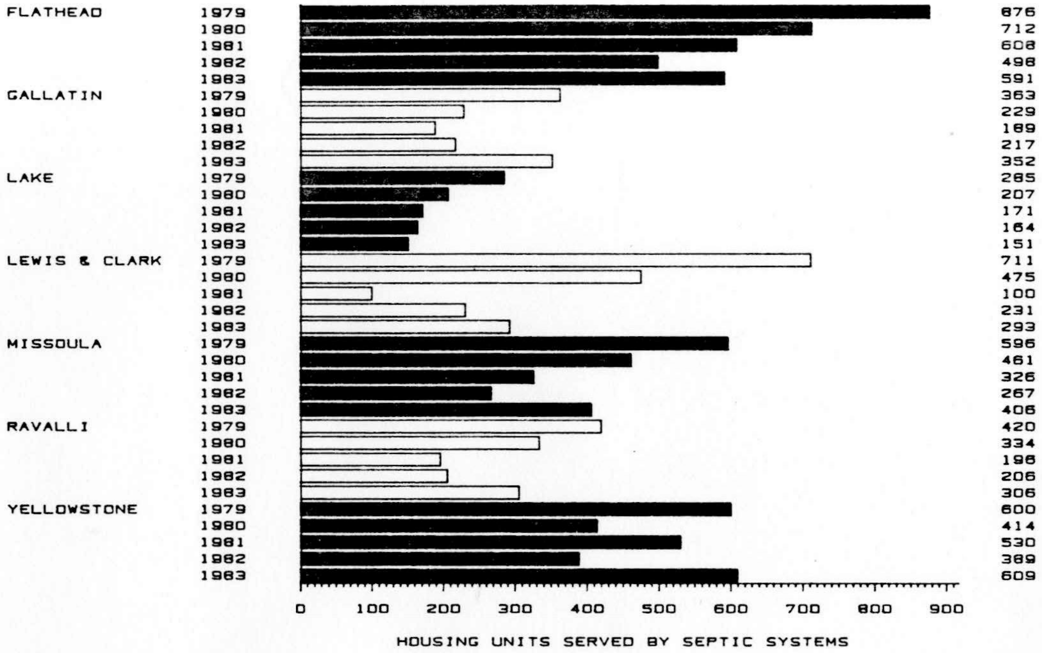

Figure 41. Yearly summary of septic system permits issued, 1979-1983.

Septic Systems and Water Quality in Montana

Konizeski et al. (1968) found four shallow wells in the upper Flathead Valley with nitrate nitrogen levels in excess of 22 mg/L, with a high of 65 mg/L. Elevated concentrations were noted in several other wells in the area, including four domestic wells with values greater than the recommended drinking water limit of 10 mg/L. One of the possible sources of contamination mentioned was domestic sewage.

Peavy and Groves (1978) looked at ground-water quality in the vicinity of two septic systems in the Bozeman area. They concluded that the nitrate nitrogen content of ground water beneath a 1 acre site could increase by 0.5 mg/L assuming a nitrate-N concentration of 16.6

mg/L beneath a 1500 sq. ft. drainfield. This increase would be cumulative downgradient from the site, and could lead to significant contamination in high density situations (Blue Ribbons of the Big Sky, 1979).

The Subdivision Bureau of the Montana Dept. of Health and Environmental Sciences (Montana Dept. of Health and Environ. Sci., 1979) prepared a report which prioritized the potential for ground-water contamination at 32 subdivisions, based on housing density, soil properties, and hydrologic conditions. Five of these subdivisions were studied by Peavy et al. (1980), by analyzing water samples from shallow driven wells and household wells. No significant levels of contamination were found, although the investigators noted that limited data was collected, and the prospect of continued development at these subdivisions increased the potential for future problems.

Potential pollution at five sites was noted in a ground-water quality assessment performed by the Montana Dept. of Health and Environmental Science (1978). Work in the Missoula area by Juday and Keller (1978) showed that wells in the areas with highest population and septic system densities had nitrate nitrogen concentrations 10-15 times higher than lesser developed areas. Recent work in the Flathead Valley (Spratt, 1982; Newman, 1982) outlined septic system nitrate contamination of a shallow floodplain aquifer in the Evergreen area, and of wells in a fractured limestone aquifer in the Somers area.

Several other studies in the 1970's evaluated citizen's concerns regarding water quality in general. Seastedt and Tibbs (1974) in a report on land use and water quality in the Flathead drainage noted that there was a need for understanding the effects of subdivision development on ground-water quality. Ruffato (1980) in a study of water quality in the Five-Valleys region of western Montana noted most problems of ground-water contamination in that area were from septic systems. He recommended that the long-term impact of continued use of septic systems should receive mandatory state review that would prohibit developments that display any likelihood of ground-water contamination.

A ground-water quality assessment (Montana Dept. of Health and Environ. Sci., 1978b) by the Water Quality Bureau prioritized existing and future ground-water quality problems in Montana. It found that on-site domestic sewage treatment ranked fifth, behind dryland farming, irrigation, oil production, and transport and storage of petroleum wastes. It recommended that studies be undertaken to determine the fate of septic system nitrogen in ground water, and suggested monitoring programs to evaluate the effectiveness of sewage treatment.

A similar assessment of both surface and ground-water quality (Montana Dept. of Health and Environ. Sci., 1978a) listed nutrient and pathogenic contamination of ground-water from subdivisions as sixth on a list of state problems. It ranked only behind saline seep as a ground-water pollution problem. Management alternatives to deal with this problem included:

> Development of more comprehensive statewide guidelines to facilitate selection and installation of suitable subsurface disposal systems.
>
> Modification or development of county regulations to control design, location, and installation of septic systems.

Development of ground-water quality standards to include impacts of septic systems.

Development of a statewide ground-water monitoring network to document the impact of septic systems.

Virtually all of the above-mentioned projects were the result of funding from the U.S. Environmental Protection Agency's 208 Water Quality Program, an outgrowth of the Federal Water Pollution Control Amendment of 1972. This funding source is no longer available. As a consequence, its termination has signaled an end to research activities. In the opinion of the author, it also marked the end of general State concern regarding on-site sewage treatment and water quality.

Septic System Regulation in Montana

From this flurry of attention given to water quality problems in the late 1970's, it is clear that there was considerable concern regarding the present and potential impacts of septic systems. In the years that have followed, however, it appears that while there have been some improvements in the approaches taken toward regulation of septic systems on both the county and state level (e.g. changes in regulations), overall there has been little substantive action taken toward addressing the issues raised by these previous studies.

On the positive side, conversations with sanitarians from the populous counties of the state reveal that counties with larger numbers of septic systems have stiffened their regulations, and the state has recently done the same. The problem here is that there is little opportunity for proper enforcement of these regulations. From direct contact and conversations with county sanitarians during the course of this study, it appears that while they are the regulators responsible for most of the verification of site suitability for septic systems, they commonly lack the technical background needed for this type of work. Basically they are asked to determine the inter-relationships of the soil resource, wastewater treatment, and the ground-water resource, yet the vast majority of sanitarians have had little if any training in either soil science or hydrogeology. This in spite of the fact that some sanitarians in the larger counties may spend 40-50 percent or more of their time during part of the year on site evaluation for septic systems.

From the experiences of the author during the past four years, it appears that most sanitarians develop their expertise on-the-job. Some take a great interest in learning about soil and hydrological properties, and develop acceptable levels of proficiency. Others may not have the time, resources, or interest to develop such skills, with the result being less-than-adequate evaluations of site suitability for septic systems. This should not be interpreted as a blanket condemnation of the skills of county sanitarians. It is more a recognition of the fact that this group is asked to perform a wide variety of environmental health-related inspections, from food service establishments to groceries to laundries to motels to schools to septic systems. Given the fact that generally they receive little training in natural resource evaluation during their college years, it is not surprising that they lack the technical skills which would allow them to better characterize soil/site suitability for septic systems.

Further complicating the process of making a rational evaluation of site suitability is the pressure under which some of the more important decisions must be made. Because waste treatment is frequently the only limiting site constraint to development, the viability of developing a parcel of land often is determined by the sanitarian's decision on site suitability. A decision that a site is unsuitable may result in the loss of county revenues in the form of taxes on developed property, which might not please the sanitarian's supervisors, the county commissioners. It may also cost the developer tens of thousands of dollars in unrealized profits, and he may decide to pursue the matter in court, where the sanitarian may not be able to adequately justify his evaluation versus one by the developer's professional specialist (engineer, soil scientist, hydrologist, etc.). Such additional pressures complicate the decision-making process, and in situations like these the sanitarian could benefit from authoritative technical support, which presumably should be available at the state level.

However, despite the call for increased state action (by the studies cited earlier) regarding the potential problems associated with rural subdivisions and septic systems, and the need to provide technical support for county personnel, there has in fact been a decrease. This is reflected in the gradual demise of the the Subdivision Review Bureau, the principle state agency dealing with septic systems, from a staff of eight technical positions, to its present status as the Subdivision Review Section of the Water Quality Bureau, with a technical staff of two. Thus, during a period of time when the public was calling for increased state action, and during a period of rapid increase in subdivision activity, state participation has significantly decreased.

In the author's opinion, there are several reasons for this decline, a stormy relationship with the Legislature, especially the Senate, being perhaps the central problem. The present staff is limited to primarily office examination of plans for subdivision sanitation and water supply, with little opportunity for on-site inspections of proposed subdivisions, and even less for monitoring of subdivisions already approved. Further, there is insufficient staffing to allow for planning of in-service training sessions for county personnel.

Despite recommendations for ground-water monitoring programs, none has been established for septic systems (Jim McCauley, Subdivision Bureau, DHES, personal communication). In isolated instances, generally for larger, multi-family systems, some ground-water quality monitoring is taking place, but not on the scale which is necessary to help answer some of the questions raised by the reports of the late 1970's (Montana Dept. of Health and Environ. Sci., 1978; Judy and Keller, 1978; Peavy et al., 1980). It is revealing to note the comparatively large amount of ground-water monitoring for such activities as municipal sewage treatment plants, saline seep, and coal strip-mining (Loren Bahls, Water Quality Bureau, personal communication). While not to suggest that any of this monitoring is unnecessary, it is difficult to come up with a good reason why a potential problem of the magnitude posed by septic systems (in some areas) is not deserving of considerably more attention than it has received as of late.

If there is any reason, in the opinion of the author, it probably is money. Both municipal treatment plants and the coal mines are required by state agencies to conduct monitoring programs to determine the impact of their activities on water quality, and the state programs which keep tabs on this monitoring receive considerable federal funding (Joe Steiner, Water Quality Bureau, personal communication). There is no similar source of outside funding for septic systems, and it is up to the state or local government to develop programs to manage such problems. One suggestion would be to require that those responsible for the development of rural subdivisions using septic systems be required to include a ground-water monitoring program, just as they are asked to insure proper roads, storm drainage, and domestic water supply.

Again, it is funding that is the major obstacle to increased state and local activity in regulating and monitoring septic systems. The present Subdivision Review Section (SRS) is the principle state agency responsible for overseeing on-site sewage treatment activities. It is funded solely on the basis of fees charged for review of subdivision applications. During the past several years, the SRS has experienced several periods of financial difficulties, with resultant staff reductions, and warnings of potential layoffs for current staff (Jim McCauley, personal communication). With the present reduced staff (two full-time technical positions) the situation appears to have stabilized, but a strong argument can be made that this is an inadequate level of staffing. This is especially true given the recent increases in the number of septic systems. The author feels that the present level of staffing provides for a minimal review process, with little potential for on-site investigation, for post-application monitoring to insure that the subdivision is being developed in accordance with state standards, for educational/training support for county sanitarians, septic system installers, etc. Additional staff support would go a long way towards improving the quality of state regulation of on-site domestic sewage treatment.

Regarding this problem with funding, it is informative to look at the financial support provided for municipal sewage treatment systems. Between 1972-1982, capital investments in municipal wastewater facilities totaled $138.6 million, or an average yearly expenditure of $13.86 million for improving the quality of municipal wastewater treatment (Joe Steiner, Water Quality Bureau, personal communication). Of this ten year total, $103.1 million came from the EPA, $33.9 million from local governments, and $1.6 million from the State. A recent news release (Billings Gazette, June 27, 1984) from Montana Dept. of Health and Environ. Sci. states that between June, 1984, and October, 1985, a total of more than $35 million will be awarded ($24.5 million in federal money) for new construction and/or improvements in wastewater treatment facilities in 14 Montana communities.

As noted earlier, about 34 percent of the household sewage in Montana is treated by septic systems. A better estimate of the relative amount of sewage treated by both municipal systems versus on-site systems can be made using information from a recent state report

(Montana Dept. of Health and Environ. Sci., 1983). From 1980 U.S. Bureau of Census figures, Montana is shown to have 459,705 people (58 percent of the state population) served by municipal systems, and 326,985 (42 percent) served by septic systems. Using standard values of 100-125 gal/day/capita for municipal systems, and 50 gal/day/capita for on-site systems, it can be estimated that 75-80 percent of the total sewage generated in Montana is treated by municipal plants, and 20-25 percent by septic systems.

The large investment of federal dollars to improve municipal sewage treatment in Montana is evidence of a genuine concern of the water quality problems such centralized plants can create. However, the preceeding arguments have shown that septic systems, too, can adversely impact surface and ground-water quality. Given that 20-25 percent of the state's sewage is treated by septic systems, it would seem that there is a need for increased funding of efforts to better define existing and potential problem associated with this method of sewage treatment. This is not to suggest that a multi-million dollar program is necessary, but to emphasize that presently there is insufficient concern devoted to a process responsible for the treatment and disposal of a significant proportion of wastewater generated in Montana, and which may have some substantial environmental impacts.

To illustrate this point, an analogy with air pollution problems is helpful. In some areas, both in Montana and elsewhere, industries have had to spend considerable amounts of money to reduce air-borne pollutants. During this same period of reducing degradation of air quality by major polluters, there was a gradual but steady increase in the use of wood stoves. That is, while there was a major effort to control pollution by focusing on the prominent polluters, by not taking note of the increase in wood stoves, another serious air pollution problem was allowed to develop unchecked. Perhaps now is the time to pay a bit more attention to the potential problems associated with septic systems.

Aside from specific environmental concerns, there is another important aspect of this issue, that of consumer protection. A reasonable estimate is that 4000 new septic systems per year are installed in Montana, at an average cost of about $2000, for an estimated expenditure of $8 million. To perform satisfactorily, it is essential that a septic system be properly sited, designed, installed, and maintained. A recent study in Maine, a state with a septic system review program considerably more comprehensive than Montana's, found that over half of the systems constructed in the last seven years had not been sited, designed, or installed properly (Struchtemeyer and Black, 1981). Sometimes this is the result of conscious efforts to avoid regulations and save some money, but often it occurs because of a lack of understanding of the best way to perform the job. It is most likely that a similar situation exists in Montana.

Such incorrectly constructed systems frequently do not perform properly, or may fail prematurely. The homeowner, faced with a substantial financial outlay to correct the problem, is often tempted to circumvent sanitary regulations and jury-rig a simple solution to the problem, perhaps direct-piping of septic tank effluent to a cesspool, drainage ditch, or other convenient disposal source. The result is the creation of an unacceptable public health hazard, and environmental degradation.

An associated problem develops when a consumer purchases a parcel of land on which to build his home, finds out later that it is not suitable for a conventional septic system, and is required to spend thousands of extra dollars on an alternative septic system such as a mound. This added cost may pose a substantial burden to the prospective homebuilder.

Closer review of the entire septic system process, from more detailed site evaluation procedures to training/education programs for installers and homeowners, should decrease the potential for such incidents. Septic systems may cost from $1500-7000 or more, and as such represent a major consumer expenditure, one about which the typical consumer is woefully ignorant. It does not seem unreasonable for the state to take an active role in insuring that all septic systems be installed in a responsible manner, thus protecting both the consumer and the environment. In the past it has been difficult for a variety of reasons to obtain additional funding to support such activities. It is hoped that many of the arguments proposed in this document will serve to promote increased awareness of the need for supplemental funding to more adequately address the topic of on-site sewage treatment in Montana.

SUMMARY AND CONCLUSIONS

The intent of the preceeding discussion was not to advance the hypothesis that septic systems pose an imminent threat to water quality in Montana. Rather, it was to document recent state and county trends in the growth of these sewage treatment systems, and examine the current status of their regulation. Several points should be emphasized:

- -- almost every septic system will contribute to an increase in the nitrate concentration of ground water;
- -- any ground-water system has a limited ability to satisfactorily dilute such nitrate contamination;
- -- there have been several cases in Montana where ground-water contamination has been attributed to septic systems;
- -- recent localized surges in the numbers of septic systems increase the potential that new cases of nitrate contamination may develop;
- -- despite this greater risk for ground-water degradation, efforts at the state and county level do not sufficiently address the severity of the problem;
- — improvements in the site evaluation process could contribute towards lessening these potential impacts;
- — there is a need for greater State awareness of and involvement in the problems associated with on-site sewage treatment systems.

The following recommendations are proposed to facilitate a better understanding of the present and future impacts of septic systems in Montana, and of their role in the process of wastewater treatment and disposal.

1) Increased state funding is needed to bolster the staff of the Subdivision Review Section. A need exists for an individual with technical expertise in the area of soil science/geohydrology. Additional staffing and funding would provide needed technical support of and training for county sanitarians, by allowing more travel for on-site inspections of proposed developments.

2) Formal training programs for sanitarians and other public health officials should be established. Such programs would emphasize the areas of soils, geohydrology, and other pertinent aspects of septic system regulation. These could be offered through an annual or biennial short course offered through the University system, and through regional seminars. Students pursuing degrees in Environmental Health should be encouraged to incorporate coursework from the natural sciences in their curriculum.

3) More detailed inventory of soil and hydrological characteristics of proposed major subdivisions should be required. This should include collection of existing information on soil and hydrological parameters in the area of interest, and, if such information is insufficient, field collection of additional data. This information should be included in a discussion of the potential cumulative impact of the development on water quality, especially on existing users of local ground-water sources. A water quality monitoring program should be required during and after development of the subdivision to help assess these impacts.

4) Educational programs for others involved in the various aspects of on-site waste treatment, e.g. homeowners, contractors, engineers,

realtors, developers, etc., should be developed and promoted. Such programs would increase public awareness of the benefits and potential hazards of septic systems, and help in the responsible management of this method of waste treatment and disposal.

5) A ground-water monitoring program should be established which would assess the impacts of rural subdivisions water quality. A good base from which to build such a program already exists. The list of subdivisions evaluated for potential ground-water quality impacts (Montana Dept. of Health and Environ. Sci., 1979) should be reviewed, and new developments added. Those subdivisions monitored during the study by Peavy et al. (1980) should be re-evaluated to examine changes in the last 5 years, and to determine the influence of density on water quality in such areas. Yearly or biennial testing of domestic wells should be encouraged through public service announcements or other advertising, especially in those areas of higher septic system density.

6) A central computer record-keeping system should be instituted, one that is capable of map generation, to assist in the evaluation of summary statistics, e.g. density of systems in any given area, number and location of new systems each year, ground-water nitrate concentrations, etc. This is especially needed for monitoring trends in those counties experiencing rapid growth.

7) The use of on-site treatment systems that are most likely to reduce nitrogen loading, e.g. mounds, dosing systems, composting toilets should be encouraged.

8) The State should encourage, facilitate, and provide funding for research activities of various problems associated with septic systems, e.g. effect of system density on ground-water quality, possible methods for decreasing the nitrogen loading from septic systems, etc. The best way to develop rules for the future management of septic systems is to observe and define how current systems are working and changing with time.

9) The use of centralized, large-scale on-site systems as an alternative to individual septic systems should be evaluated. Such larger systems may allow the utilization of more sophisticated technology, (e.g. for increasing denitrification) and would be easier to monitor. They could serve as viable alternatives for those higher density areas where ground-water contamination exists or has a high potential for developing.

To believe that even a fraction of these suggestions may actually be instituted is to reveal a penchant for quixotism. While such ideas may result in many heads nodding in agreement, the bottom line will be: Where can we get the money to accomplish these suggestions? Excluding the possibility of federal funding, there are two logical sources to tap. One would be to increase the rates currently charged for the review of proposed subdivisions. Unless fees are increased substantially (e.g. perhaps doubled), it is unlikely that enough money could be collected to fully address the problems. Also, an assessment of this nature in effect is asking future users to subsidize a program which would manage problems for which they are not solely responsible, and from which they will not solely benefit. They share such potential responsibility with thousands of other owners of septic systems.

It would seem that perhaps the most equitable answer to this funding dilemma would be an annual tax levied on housing units or commercial buildings served by septic systems. Given the 107,000 units served by septic systems, a tax of only $5-10 would generate $500,000-1,000,000. If desired, the tax could be scaled on the volume of wastewater generated by the owner, with larger users paying more. This would appear to be a generous enough sum to address many if not all of the concerns stated in this discussion. The potential benefits of such a tax in protecting public health, preventing environmental degradation, and generally improving the state of on-site sewage treatment in Montana contribute a rather persuasive argument for pursuing a levy of this sort. A possible alternative to a statewide tax would be to allow a county option, i.e., only impose the tax in those counties where high numbers of septic systems increase the probability for problems to develop. This recognizes the fact that many counties in the state have so few systems that water quality problems are unlikely to develop.

In the past decade, many states have initiated substanitial programs to deal with the problems caused by widespread use of septic systems. Such problems did not develop overnight, but rather were the result of many years of gradual change. Because of the diffuse nature of septic systems, once a problem is created, it is difficult to manage, as it may require dealing with several hundreds or thousands of individual owners of septic systems. This is far more complicated than dealing with a single entity that is responsible for a source of contamination. Further, ground-water contamination is not easily reversed. Once significant contamination has occurred, it may take many years for water quality to return to acceptable levels. Prevention of such problems is imperative.

Numerous other states have learned their lessons the hard way, because of delayed recognition of problems that slowly developed over a period of many years. By learning from those mistakes, and by putting forth a genuine effort to characterize the current situation, Montana has the opportunity to avoid the water quality problems that can be caused by septic systems. Taking action now to forestall potential problems of ground-water degradation from septic systems will pay back many dividends to both society and the environment in the years to come.

APPENDIX 2

SOIL PROFILE DESCRIPTIONS

Table 19. Soil profile description for site 1.

```
                                   SITE DESCRIPTION
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
Soil Series:WHITEFISH        Site Number: 1                County:Flathead
Location: NE1/4, NW1/4, NW1/4 Section 21 Township 31 , Range 21
Classification: Fine-loamy, mixed typic Cryoboralf

Date Sampled:  7/30/81       Elevation:  3450ft, 1051m     Precipitation:  28in, 711 mm
Site Codes/Co:07/PM:04/Veg:05/LU:03/Drain:05/Perm:05/Ersn:02/Postn:04/LF:09/
Material: glacial till       Vegetation: larch-fir         Land use: forest
Drainage: well               Permeability: medium to rapid Erosion: slight
Slope:   12%,   7degrees     Aspect: SSW                   Position: midslope
Soil temp.(50cm)  19C, 66F   Number of Horizons:7          Landform: terrace


                                 PROFILE DESCRIPTION
:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
|          DEPTH      COLOR                         STR CONS RT  PR                     |
|HOR. NO.   (cm)   MOIST      DRY          TEXT  CF gsk dmsp asl ask  pH EFF BND  *     |
:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::


01      1    8-0          /          /                                .          1
B2ir    2    0-24    10YR 4/6   10YR 5/6 09 sil  36 111 2212 632      7.3 1  22
C11     3   24-67    10YR 7/1   10YR 8/2 05 sl   53 111 1111 532      7.3 1  55
C12     4   67-102   10YR 7/1   10YR 8/2 05 sl   51 111 1111 332      7.3 1  22
IIC2    5  102-125   10YR 5/2   10YR 6/4 05 sl   28 111 1111 232      7.3 1  22
IIIC3   6  125-143   10YR 4/2   10YR 6/4 05 sl   29 111 1111 232      7.3 1  12   2
IVC4    7  143-162   10YR 5/3   10YR 6/5 09 sil  22 111 3322 232      8.0 1  66   3
              -           /          /                                .

:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
CF=coarse fragment(%)    STR=structure grade,size,kind
CONS=moist,dry,sticky, plastic consistence   RT=root amount, size, location
PR=pore amount, size, kind   EFF=effervesence   BND=boundary
COMMENTS (*): 1-DID NOT DESCRIBE OR SAMPLE
2-ROOT MAT AT BASE OF IIIC3
3-UPPER 5 CM HAS BANDS OF ORGANICALLY STAINED CLAY
```

Table 20. Soil profile description for site 2.

```
                                  SITE DESCRIPTION
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
Soil Series:WHITEFISH          Site Number:2                 County:Flathead
Location: NW1/4, SE1/4, NW1/4 Section 34 Township 31N , Range 21W
Classification: Fine-loamy, mixed typic Cryoboralf

Date Sampled:  8/10/81         Elevation:  3090ft,  941m     Precipitation:  24in, 609 mm
Site Codes/Co:07/PM:04/Veg:22/LU:09/Drain:04/Perm:03/Ersn:02/Postn:04/LF:07/
Material: glacial till         Vegetation: tame pasture      Land use: pasture
Drainage: moderate             Permeability: slow to medium  Erosion: slight
Slope:    3%,   2degrees       Aspect: SSE                   Position: midslope
Soil temp.(50cm)  16C, 60F     Number of Horizons:7          Landform: ground moraine

                                PROFILE DESCRIPTION
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
|           DEPTH      COLOR                      STR CONS RT  PR                      |
|HOR. NO.    (cm)   MOIST      DRY       TEXT   CF gsk dmsp asl ask   pH EFF BND  *    |
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

A1      8    0-15   10YR 3/3  10YR 6/3 09 sil  <5 324 3312 732       6.5 1  22
B2t     9   15-35   10YR 4/4  10YR 6/6 09 sil  26 434 3322 632       6.0 1  32
C1     10   35-76   10YR 6/3  10YR 7/2 09 sil  32 434 3322 433       6.0 1  22
C12    11   76-95   10YR 6/4  10YR 7/4 09 sil  31 433 3322 334       6.2 1  22
C2     12   95-130  10YR 7/4  10YR 8/4 08 l    74 544 4433 334       6.0 1  11
IIC3   13  130-145  10YR 3/1  10YR 5/2 15 sic  27 635 4533 334       8.0 4  22    1
IIIC4  14  145-160  10YR 5/2  10YR 6/2 09 sil  08 111 4423 334       8.0 4  66    1
             -          /         /                                  .

::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
CF=coarse fragment(%)   STR=structure grade,size,kind
CONS=moist,dry,sticky, plastic consistence   RT=root amount, size, location
PR=pore amount, size, kind   EFF=effervesence   BND=boundary
COMMENTS (*): 1-EFFERVESCES VIOLENTLY BETWEEN PEDS, NONE TO SLIGHT ON BROKEN PED FACE
```

Table 21. Soil profile description for site 3.

```
                                  SITE DESCRIPTION
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
Soil Series:DEPEW              Site Number:3                 County:Flathead
Location: NW1/4, SE1/4, SE1/4 Section 22 Township 30N , Range 22W
Classification: Fine, mixed typic Eutroboralf

Date Sampled:  8/21/81         Elevation:  3010ft,  917m     Precipitation:  16in, 406 mm
Site Codes/Co:07/PM:05/Veg:21/LU:09/Drain:04/Perm:04/Ersn:01/Postn:07/LF:10/
Material:  lacustrine          Vegetation: perennial forage  Land use: pasture
Drainage: moderate             Permeability: medium          Erosion: none
Slope:    1%,   0degrees       Aspect: SSE                   Position: level slope
Soil temp.(50cm)  20C, 68F     Number of Horizons:7          Landform: floodplain

                                PROFILE DESCRIPTION
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
|           DEPTH      COLOR                      STR CONS RT  PR                      |
|HOR. NO.    (cm)   MOIST      DRY       TEXT   CF gsk dmsp asl ask   pH EFF BND  *    |
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

Ap     15    0-18   10YR 5/2  10YR 7/1 12 sicl 00 652 4423 742       7.8 1  11
B21t   16   18-48   10YR 5/2  10YR 7/3 11 cl   00 646 4423 533       8.0 1  21    1
B22t   17   48-64   10YR 5/2  10YR 7/3 11 cl   00 646 4423 333       8.0 3  21    1
C1     18   64-91   10YR 6/3  10YR 8/3 11 cl   00 646 4423 534       8.2 3  11
C2     19   91-97   10YR 4/3 7.5YR 6/4 08 l    00 111 3311 434       8.0 1  11    2
C3     20   97-127  10YR 6/3  10YR 7/4 11 cl   00 652 4423 334       8.2 3  55    3
C4     21  127-152  10YR 6/3  10YR 7/4 11 cl   00 652 4423 334       8.2 3  66    3
             -          /         /                                  .

::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
CF=coarse fragment(%)   STR=structure grade,size,kind
CONS=moist,dry,sticky, plastic consistence   RT=root amount, size, location
PR=pore amount, size, kind   EFF=effervesence   BND=boundary
COMMENTS (*): 1-HAS MOTTLED APPEARANCE FROM IN SITU WEATHERING OF VARVES
2-THICK REDDISH VARVE
3-CUTANS EXTEND TO BOTTOM OF PIT ALONG  LONG CONTINUOUS CRACKS (3-4' LONG), FEWER CUTANS
ALONG HORIZONTAL PLANE.  PORES AND ROOTS ARE BOTH ORIENTED PRIMARILY HORIZONTALLY IN THE
C HORIZONS
```

Table 22. Soil profile description for site 4.

SITE DESCRIPTION

Soil Series:WHITEFISH Site Number:4 County:Flathead
Location: SW1/4, NE1/4, NW1/4 Section 1 Township 29N , Range 22W
Classification: Fine-loamy, mixed typic Cryoboralf

Date Sampled: 7/28/81 Elevation: 3040ft, 926m Precipitation: 16in, 406 mm
Site Codes/Co:07/PM:04/Veg:05/LU:03/Drain:05/Perm:04/Ersn:01/Postn:04/LF:07/
Material: glacial till Vegetation: larch-fir Land use: forest
Drainage: well Permeability: medium Erosion: none
Slope: 10%, 6degrees Aspect: ESE Position: midslope
Soil temp.(50cm) 15C, 59F Number of Horizons:7 Landform: ground moraine

PROFILE DESCRIPTION

HOR.	NO.	DEPTH (cm)	COLOR MOIST	COLOR DRY	TEXT	CF	STR gsk	CONS dmsp	RT asl	PR ask	pH	EFF	BND	*
O2	22	2-0	/	/							.			3
A1	23	0-16	10YR 4/2	10YR 6/2	09 sil	19	234	3312	732		7.8	1	22	
A2	24	16-32	10YR 5/3	10YR 6/4	09 sil	31	234	2212	532		7.6	1	22	
B2t	25	32-49	10YR 5/3	10YR 8/3	09 sil	21	234	2322	532		8.0	4	22	
C1	26	49-77	10YR 6/3	10YR 7/2	09 sil	14	111	3312	342		8.2	4	32	1
C2	27	77-107	10YR 6/4	10YR 7/3	09 sil	33	111	3322	235		8.2	4	22	1
IIC3	28	107-174	2.5Y 6/4	2.5Y 7/4	09 sil	43	111	3323	111		8.2	4	66	2
		-	/	/							.			

CF=coarse fragment(%) STR=structure grade,size,kind
CONS=moist,dry,sticky, plastic consistence RT=root amount, size, location
PR=pore amount, size, kind EFF=effervesence BND=boundary
COMMENTS (*): 1-THESE HORIZONS HAVE ROCK FRAGMENTS WEATHERED IN PLACE (COLORFUL SILTSTONE S)
2-MASSIVE IN PLACE, BREAKS OUT INTO FINE ANGULAR BLOCKY FRAGMENTS.
3-DID NOT SAMPLE

Table 23. Soil profile description for site 5.

SITE DESCRIPTION

Soil Series:PROSPECT Site Number:5 County:Flathead
Location: NE1/4, SE1/4, NW1/4 Section 29 Township 28N , Range 22W
Classification: Fine-loamy, mixed udic Haploboroll

Date Sampled: 7/27/81 Elevation: 3140ft, 957m Precipitation: 16in, 406 mm
Site Codes/Co:07/PM:04/Veg:22/LU:08/Drain:05/Perm:03/Ersn:01/Postn:07/LF:07/
Material: glacial till Vegetation: tame pasture Land use: dryland hay
Drainage: well Permeability: slow to medium Erosion: none
Slope: 1%, 0degrees Aspect: EAST Position: level slope
Soil temp.(50cm) 21C, 69F Number of Horizons:6 Landform: ground moraine

PROFILE DESCRIPTION

HOR.	NO.	DEPTH (cm)	COLOR MOIST	COLOR DRY	TEXT	CF	STR gsk	CONS dmsp	RT asl	PR ask	pH	EFF	BND	*
Ap	29	0-17	10YR 3/2	10YR 4/2	09 sil	12	473	2223	752	358	7.5	1	11	
B2t	30	17-44	10YR 6/3	10YR 7/3	12 sicl	28	444	4433	543	754	8.5	4	22	
B3t	31	44-62	10YR 6/3	10YR 7/3	12 sicl	07	444	4433	543	754	8.5	4	23	
C1	32	62-85	10YR 6/3	10YR 8/2	09 sil	05	261	4423	343	554	8.0	4	12	
IIC2	33	85-174	10YR 6/3	10YR 7/3	09 sil	00	281	4923	243	111	8.0	3	66	1
IIC2	34	85-174	10YR 5/4	10YR 6/4	14 c	00	281	4443	111	111	8.5	2	55	1
		-	/	/							.			
		-	/	/							.			

CF=coarse fragment(%) STR=structure grade,size,kind
CONS=moist,dry,sticky, plastic consistence RT=root amount, size, location
PR=pore amount, size, kind EFF=effervesence BND=boundary
COMMENTS (*): 1-THESE TWO "HORIZONS" ARE THE SILTY AND CLAYEY LAYERS RESPECTIVELY, OF THE VARVED SEDIMENTS

Table 24. Soil profile description for site 6.

SITE DESCRIPTION

Soil Series:BLANCHARD　Site Number:6　County:Flathead
Location: NW1/4, NW1/4, SE1/4 Section 28 Township 30N , Range 20W
Classification: Mixed, frigid typic Ustipsamment

Date Sampled: 7/28/81　Elevation: 3070ft, 935m　Precipitation: 18in, 457 mm
Site Codes/Co:07/PM:03/Veg:22/LU:09/Drain:05/Perm:05/Ersn:02/Postn:07/LF:06/
Material: glacial outwash　Vegetation: tame pasture　Land use: pasture
Drainage: well　Permeability: medium to rapid　Erosion: slight
Slope: 1%, 0degrees　Aspect: SSW　Position: level slope
Soil temp.(50cm) 19C, 66F　Number of Horizons:7　Landform: glacial outwas

PROFILE DESCRIPTION

HOR.	NO.	DEPTH (cm)	COLOR MOIST	COLOR DRY	TEXT	CF	STR gsk	CONS dmsp	RT asl	PR ask	pH	EFF	BND	*
Ap	35	0-18	10YR 2/1	10YR 3/1	05 sl	00	224	2211	732		7.6	1	11	
A3	36	18-33	10YR 2/2	10YR 3/2	05 sl	00	334	2211	622		7.6	1	22	
B21	37	33-52	10YR 4/3	10YR 5/4	02 ls	00	444	2211	522		7.6	1	22	
B22	38	52-68	10YR 3/3	10YR 4/4	02 ls	05	234	2211	342		7.6	1	22	
C1	39	68-93	7.5YR 4/4	7.5YR 5/5	05 sl	03	234	2211	342		8.0	2	12	
IIC2	40	93-118	10YR 4/2	10YR 5/3	02 ls	47	111	1111	424		7.8	4	11	1
IIIC3	41	118-160	7.5YR 4/2	7.5YR 5/2	02 ls	00	111	1111	422		7.0	2	66	2
		-	/	/							.			

CF=coarse fragment(%)　STR=structure grade,size,kind
CONS=moist,dry,sticky, plastic consistence　RT=root amount, size, location
PR=pore amount, size, kind　EFF=effervesence　BND=boundary
COMMENTS (*): 1-THICK 2-4mm CaCO3 COATINGS ON BOTTOM SIDES OF GRAVEL.
2-"BRANCHING FINGERS" OF CARBONATE START IN THIS HORIZON AND CONTINUE TO BOTTOM OF IIC2.
WATER TABLE AT ~180cm.

Table 25. Soil profile description for site 7.

SITE DESCRIPTION

Soil Series:FLATHEAD　Site Number:7　County:Flathead
Location: NE1/4, SE1/4, NE1/4 Section 31 Township 29N , Range 20W
Classification: Coarse-loamy, mixed udic Haploboroll

Date Sampled: 8/13/81　Elevation: 2980ft, 908m　Precipitation: 18in, 457 mm
Site Codes/Co:07/PM:03/Veg:22/LU:09/Drain:04/Perm:03/Ersn:02/Postn:07/LF:09/
Material: glacial outwash　Vegetation: tame pasture　Land use: pasture
Drainage: moderate　Permeability: slow to medium　Erosion: slight
Slope: 1%, 0degrees　Aspect: SSE　Position: level slope
Soil temp.(50cm) 20C, 68F　Number of Horizons:6　Landform: terrace

PROFILE DESCRIPTION

HOR.	NO.	DEPTH (cm)	COLOR MOIST	COLOR DRY	TEXT	CF	STR gsk	CONS dmsp	RT asl	PR ask	pH	EFF	BND	*
Ap	42	0-10	10YR 3/2	10YR 5/3	09 sil	00	433	2211	752		7.8	1	11	
A3	43	10-39	10YR 3/2	10YR 5/3	10 scl	00	343	4411	742		8.0	1	22	
B2	44	39-66	10YR 3/3	10YR 5/3	09 sil	00	343	3322	742		8.0	2	12	
C1ca	45	66-97	10YR 5/3	10YR 7/3	09 sil	00	111	4422	542		8.2	4	12	1
C2	46	97-118	10YR 6/4	10YR 7/4	08 l	00	111	3311	442		8.0	4	32	1
C3	47	118-165	10YR 6/4	10YR 7/4	09 sil	00	111	3311	332		8.0	4	66	2
		-	/	/							.			
		-	/	/							.			

CF=coarse fragment(%)　STR=structure grade,size,kind
CONS=moist,dry,sticky, plastic consistence　RT=root amount, size, location
PR=pore amount, size, kind　EFF=effervesence　BND=boundary
COMMENTS (*): 1-C HORIZONS ARE COMPOSED OF THINLY (2-5cm) STRATIFIED FINE SANDS AND SILTS
2-MOTTLES COMMON, MEDIUM IN SIZE, AND PROMINENT. 10YR 5/8 TO 5/6, MIXED ARE 4/4. THESE EXTEND AT LEAST TWO METERS DEEPER THAN THE BOTTOM OF PIT AS DETERMINED BY AUGERING.

Table 26. Soil profile description for site 8.

```
                                   SITE DESCRIPTION
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
Soil Series:CRESTON            Site Number:8                County:Flathead
Location: NE1/4, NE1/4, SE1/4 Section 16 Township 28N , Range 20W
Classification: Coarse-silty, mixed udic Haploboroll

Date Sampled:  7/29/81         Elevation:  2950ft,  899m    Precipitation:  18in, 457 mm
Site Codes/Co:07/PM:05/Veg:21/LU:07/Drain:04/Perm:04/Ersn:01/Postn:07/LF:09/
Material:  lacustrine          Vegetation: perennial forage Land use:  irrigated hay
Drainage: moderate             Permeability: medium         Erosion: none
Slope:    2%,   1degrees       Aspect: ESE                  Position: level slope
Soil temp.(50cm)  18C, 64F     Number of Horizons:5         Landform: terrace

                                 PROFILE DESCRIPTION
:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
|           DEPTH       COLOR                       STR CONS RT  PR                    |
|HOR. NO.    (cm)    MOIST      DRY        TEXT   CF gsk dmsp asl ask   pH EFF BND  *  |
:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

A11     48     0-20    10YR 3/2   10YR 3/1 08 l    00 334 2211 732 658  7.5 1  21
A12     49    20-37    10YR 3/2   10YR 4/3 08 l    00 334 2211 732 658  7.8 1  22
B2      50    37-57    10YR 3/3   10YR 4/3 08 l    00 235 3221 532 558  8.0 2  32
C1ca    51    57-108   10YR 5/4   10YR 6/4 09 sil  00 135 4321 532 553  8.2 3  32    1
C2      52   108-170   10YR 6/3   10YR 7/4 09 sil  00 135 4321 532 553  8.2 3  66    1
                -          /          /                                  .
                -          /          /                                  .
                -          /          /                                  .

:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
CF=coarse fragment(%)   STR=structure grade,size,kind
CONS=moist,dry,sticky, plastic consistence   RT=root amount, size, location
PR=pore amount, size, kind   EFF=effervesence   BND=boundary
COMMENTS (*): 1-MOTTLES PRESENT, COMMON, MEDIUM TO LARGE, PROMINENT, 10YR 5/8
BEDROCK AT ~200cm
```

Table 27. Soil profile description for site 9.

```
                                   SITE DESCRIPTION
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
Soil Series:BLANCHARD          Site Number:9                County:Flathead
Location: NW1/4, NE1/4, NW1/4 Section 19 Township 27N , Range 19W
Classification: Mixed, frigid typic Ustipsamment

Date Sampled:  8/14/81         Elevation:  3060ft,  932m    Precipitation:  18in, 457 mm
Site Codes/Co:07/PM:03/Veg:22/LU:09/Drain:05/Perm:05/Ersn:02/Postn:04/LF:05/
Material: glacial outwash      Vegetation: tame pasture     Land use: pasture
Drainage: well                 Permeability: medium to rapid Erosion: slight
Slope:    5%,   3degrees       Aspect: NNE                  Position: midslope
Soil temp.(50cm)  21C, 69F     Number of Horizons:6         Landform:  sand dune

                                 PROFILE DESCRIPTION
:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
|           DEPTH       COLOR                       STR CONS RT  PR                    |
|HOR. NO.    (cm)    MOIST      DRY        TEXT   CF gsk dmsp asl ask   pH EFF BND  *  |
:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

A1      53     0-5         /          /                                  .          1
C1      54     5-35    10YR 5/4   10YR 7/3 01 s    00 111 1111 352      7.3 1  55   2
C2      55    35-65    10YR 5/4   10YR 7/3 01 s    00 111 1111 352      7.3 1  55   2
C3      56    65-95    10YR 5/4   10YR 7/3 01 s    00 111 1111 352      7.3 1  55   2
C4      57    95-125   10YR 5/4   10YR 7/3 01 s    00 111 1111 352      7.3 1  55   2
C5      58   125-155   10YR 5/4   10YR 7/3 01 s    00 111 1111 352      7.3 1  66   2
                -          /          /                                  .
                -          /          /                                  .

:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
CF=coarse fragment(%)   STR=structure grade,size,kind
CONS=moist,dry,sticky, plastic consistence   RT=root amount, size, location
PR=pore amount, size, kind   EFF=effervesence   BND=boundary
COMMENTS (*): 1-DID NOT DESCRIBE OR SAMPLE
2-THIN (2-3cm) CLAY LAMELLAE ARE PRESENT THROUGHOUT PROFILE,  APPROXIMATELY EVERY 15-25
cm VERTICALLY.  COLOR IS 7.5YR 5/8, CONSISTENCE, 4411, pH = 8.0.  ARE WAVY IN NATURE AND
COALESCE AND BRANCH OUT AT RANDOM.
```

Table 28. Soil profile description for site 10.

SITE DESCRIPTION

Soil Series:KRAUSE   Site Number:10   County:Lake
Location: SW1/4, SE1/4, NE1/4 Section 11 Township 22N , Range 20W
Classification: Sandy-skeletal, mixed, frigid andic Ustochrept

Date Sampled: 8/20/81   Elevation: 3120ft, 950m   Precipitation: 15in, 381 mm
Site Codes/Co:15/PM:04/Veg:22/LU:09/Drain:05/Perm:04/Ersn:02/Postn:03/LF:07/
Material: glacial till   Vegetation: tame pasture   Land use: pasture
Drainage: well   Permeability: medium   Erosion: slight
Slope: 6%, 3degrees   Aspect: NNE   Position: upper midslope
Soil temp.(50cm) 20C, 68F   Number of Horizons:6   Landform: ground moraine

PROFILE DESCRIPTION

HOR.	NO.	DEPTH (cm)	COLOR MOIST	DRY	TEXT	CF	STR gsk	CONS dmsp	RT asl	PR ask	pH	EFF	BND	*
Ap	59	0-15	10YR 3/2	10YR 3/1	09 sil	17	534	3322	752		6.5	1	11	
A21	60	15-24	/	/							.			1
A22	61	24-46	10YR 5/3	10YR 7/3	09 sil	45	434	4422	542		8.0	1	32	
B21t	62	46-79	10YR 6/3	10YR 7/3	12 sicl	31	434	3322	342		8.5	4	22	
B22	63	79-110	10YR 5/3	10YR 6/3	09 sil	50	635	3322	242		8.8	4	55	
B3	64	110-138	10YR 5/3	10YR 6/3	09 sil	35	635	3322	111		8.7	4	12	
C	65	138-188	10YR 5/3	10YR 6/3	09 sil	05	111	3311	111		8.6	4	66	2
		-	/	/							.			

CF=coarse fragment(%)   STR=structure grade,size,kind
CONS=moist,dry,sticky, plastic consistence   RT=root amount, size, location
PR=pore amount, size, kind   EFF=effervesence   BND=boundary
COMMENTS (*): 1-DID NOT DESCRIBE OR SAMPLE, APPEARS TO BE A REMANT A2 OR A3
2-C HORIZON IS VARVED

Table 29. Soil profile description for site 11.

SITE DESCRIPTION

Soil Series:QUIGLEY   Site Number:11   County:Lake
Location: SW1/4, NW1/4, NE1/4 Section 32 Township 22N , Range 20W
Classification: Fine-loamy, mixed typic Haploboroll

Date Sampled: 8/25/81   Elevation: 3220ft, 981m   Precipitation: 15in, 381 mm
Site Codes/Co:15/PM:05/Veg:11/LU:05/Drain:05/Perm:03/Ersn:02/Postn:07/LF:07/
Material: lacustrine   Vegetation: dryland crop   Land use: dryland crop
Drainage: well   Permeability: slow to medium   Erosion: slight
Slope: 1%, 0degrees   Aspect: South   Position: level slope
Soil temp.(50cm) 17C, 62F   Number of Horizons:7   Landform: ground moraine

PROFILE DESCRIPTION

HOR.	NO.	DEPTH (cm)	COLOR MOIST	DRY	TEXT	CF	STR gsk	CONS dmsp	RT asl	PR ask	pH	EFF	BND	*
Ap	66	0-28	10YR 3/2	10YR 5/2	09 sil	00	434	3322	732		6.5	1	11	
A3	67	28-42	10YR 5/4	10YR 6/4	09 sil	00	234	3322	632		7.2	1	22	
B21	68	42-64	10YR 5/4	10YR 6/4	09 sil	00	234	3322	432		7.8	1	55	
B22	69	64-84	10YR 5/4	10YR 6/4	09 sil	00	234	3322	322		8.5	1	11	
C1ca	70	84-116	10YR 6/3	10YR 7/3	09 sil	00	111	4322	111		8.5	4	11	
IIC2	71	116-124	10YR 7/3	10YR 8/4	09 sil	00	111	3322	111		8.5	4	11	1
IIIC3	72	124-185	10YR 6/3	10YR 7/4	09 sil	00	111	3322	111		8.5	4	66	
		-	/	/							.			

CF=coarse fragment(%)   STR=structure grade,size,kind
CONS=moist,dry,sticky, plastic consistence   RT=root amount, size, location
PR=pore amount, size, kind   EFF=effervesence   BND=boundary
COMMENTS (*): 1-THIS HORIZON IS A LIGHTER COLORED BAND OF HIGH SILT CONTENT.

Table 30. Soil profile description for site 12.

SITE DESCRIPTION

Soil Series:POLSON Site Number:12 County:Lake
Location: NW1/4, NW1/4, NW1/4 Section 3 Township 21N , Range 20W
Classification: Fine-silty, mixed glossic Natriboroll

Date Sampled: 8/24/81 Elevation: 3190ft, 972m Precipitation: 15in, 381 mm.
Site Codes/Co:15/PM:05/Veg:22/LU:09/Drain:04/Perm:03/Ersn:02/Postn:07/LF:07/
Material: lacustrine Vegetation: tame pasture Land use: pasture
Drainage: moderate Permeability: slow to medium Erosion: slight
Slope: 1%, 0degrees Aspect: SOUTH Position: level slope
Soil temp.(50cm) 22C, 71F Number of Horizons:7 Landform: ground moraine

PROFILE DESCRIPTION

HOR.	NO.	DEPTH (cm)	COLOR MOIST	DRY	TEXT	CF	STR gsk	CONS dmsp	RT asl	PR ask	pH	EFF	BND	*
Ap	73	0-22	10YR 3/1	10YR 4/2	02 ls	03	434	4422	732		6.8	1	11	
A2	74	22-39	10YR 4/3	10YR 7/2	08 l	25	434	3322	732		7.5	1	21	
B2t	75	39-51	10YR 4/3	10YR 6/4	12 sicl	05	237	4433	532		8.4	1	22	
C1ca	76	51-64	10YR 5/3	10YR 6/3	14 c	02	534	4433	542		8.3	4	55	1
C2	77	64-101	/	/							.			1
C3	78	101-140	10YR 5/4	10YR 6/4	09 sil	03	434	4422	342		8.3	4	55	2
C4	79	140-193	10YR 5/3	10YR 6/4	09 sil	09	434	4422	342		8.3	4	66	2
		-	/	/							.			

CF=coarse fragment(%) STR=structure grade,size,kind
CONS=moist,dry,sticky, plastic consistence RT=root amount, size, location
PR=pore amount, size, kind EFF=effervesence BND=boundary
COMMENTS (*): 1-SAMPLED AND DESCRIBED AS ONE HORIZON
2-THESE HORIZONS APPEAR TO BE VARVES ORIENTED AT ~30 DEGREES FORM THE VERTICAL. ARE VERY THINLY BEDDED.

Table 31. Soil profile description for site 13.

SITE DESCRIPTION

Soil Series:GIRD Site Number:13 County:Lake
Location: NE1/4, SE1/4, NE1/4 Section 16 Township 21N , Range 20W
Classification: Coarse-silty, mixed typic Haploboroll

Date Sampled: 8/24/81 Elevation: 3090ft, 941m Precipitation: 15in, 381 mm
Site Codes/Co:15/PM:03/Veg:22/LU:09/Drain:05/Perm:05/Ersn:02/Postn:01/LF:05/
Material: glacial outwash Vegetation: tame pasture Land use: pasture
Drainage: well Permeability: medium to rapid Erosion: slight
Slope: 6%, 3degrees Aspect: NNW Position: crest
Soil temp.(50cm) 22C, 71F Number of Horizons:5 Landform: sand dune

PROFILE DESCRIPTION

HOR.	NO.	DEPTH (cm)	COLOR MOIST	DRY	TEXT	CF	STR gsk	CONS dmsp	RT asl	PR ask	pH	EFF	BND	*
Ap	80	0-19	10YR 2/2	10YR 5/2	06 fsl	00	243	3211	732		6.8	1	12	
B2	81	19-38	10YR 2/2	10YR 5/3	06 fsl	00	443	3211	732		6.8	1	32	
C1	82	38-61	10YR 4/4	10YR 6/4	06 fsl	00	111	3211	532		7.8	1	32	
C2	83	61-104	10YR 4/4	10YR 6/4	06 fsl	00	111	2111	332		7.8	1	55	
C3	84	104-170	10YR 4/3	10YR 6/3	06 fsl	00	111	2111	332		8.0	1	66	
		-	/	/							.			
		-	/	/							.			
		-	/	/							.			

CF=coarse fragment(%) STR=structure grade,size,kind
CONS=moist,dry,sticky, plastic consistence RT=root amount, size, location
PR=pore amount, size, kind EFF=effervesence BND=boundary
COMMENTS (*):

APPENDIX 3

LABORATORY DATA

Table 32. Physical and chemical data for site 1.

Horizon	Depth (cm)	Thick (cm)	Mechanical analysis sand (%)	silt	clay	vcos	cos	ms	fs	vfs	Water content 15bar (%)	.3bar	.1bar	0bar	Avail H_2O	Atterberg Limits Liq.	Plast.	Proctor Test
A1	0-15	15	31.0	61.0	8.0	.	.	.	.	.	13.1	34.4	43.2	61.9	21.3			
B2t	15-35	20	26.0	61.0	13.0	.	.	.	.	.	6.8	23.1	30.9	35.5	16.3			
C1	35-76	41	30.0	61.0	9.0	.	.	.	.	.	3.4	16.7	19.1	20.1	13.3			
C12	76-95	19	24.0	51.0	25.0	.	.	.	.	.	8.1	22.4	25.2	33.4	14.3			
C2	95-130	35	45.0	34.0	21.0	.	.	.	.	.	7.7	13.3	14.8	27.1	5.6			
IIC3	130-145	15	12.0	46.0	42.0	.	.	.	.	.	18.0	32.0	36.8	59.9	14.0			
IIIC4	145-160	15	13.0	62.0	25.0	.	.	.	.	.	10.3	29.2	30.5	46.8	18.9			

Horizon	Depth (cm)	Bulk Density .3bar (g/cm^3)	OD	COLE	Particle density (g/cm^3)	CEC (meq/ 100g)	15bar/ clay ratio	CEC/ clay ratio	Sample Number
A1	0-15	.	1.3	.	.	12.4	1.63	1.55	8
B2t	15-35	.	.	.	.	7.8	0.52	0.60	9
C1	35-76	.	.	.	.	5.4	0.37	0.60	10
C12	76-95	.	.	.	.	15.2	0.32	0.60	11
C2	95-130	.	.	.	.	12.6	0.36	0.60	12
IIC3	130-145	.	1.9	.	.	26.1	0.42	0.62	13
IIIC4	145-160	.	1.9	.	.	14.5	0.41	0.58	14

Comments:

Horizon	Depth (cm)	Thick (cm)	Org. Carbon (%)	Total N (%)	C/N ratio	pH 1:1 H_2O	pH 1:2 $CaCl_2$	saturation extract H_2O (%)	paste pH	EC (mmho/cm)	Ca (meq/l)	Mg	Na	K	HCO_3	SO_4	SAR
A1	0-15	15	6.0	0.22	27.2	5.1	4.7	61.9	5.4	0.4	2.1	3.1	0.2	.	36		0.1
B2t	15-35	20	2.0	0.07	28.5	5.1	4.5	35.5	5.7	0.2	1.2	0.3	0.3	.	60		0.3
C1	35-76	41	0.2	0.02	10.0	5.0	4.5	20.1	6.0	0.1	0.7	0.2	0.4	.	107		0.5
C12	76-95	19	0.5	0.03	16.6	5.7	5.1	33.4	6.2	0.1	0.8	0.2	0.3	.	72		0.4
C2	95-130	35	0.2	0.02	10.0	6.9	6.4	27.1	7.0	0.4	0.5	1.4	0.6	.	459		0.6
IIC3	130-145	15	0.5	0.07	7.1	7.2	6.5	59.9	7.4	0.2	1.9	0.5	0.3	.	181		0.2
IIIC3	145-160	15	3.2	0.02	.	7.8	7.2	46.8	8.1	0.4	1.9	0.5	0.3	.	250		0.2

Horizon	Depth (cm)	NH_4OAc extract Ca (meq/100g)	Mg	Na	K	CEC-sum	$BaCl_2$ Acid.	Base satn. (%)	ESP (%)	NaOAc CEC meq/100g	$CaCO_3$ (%)	Sample Number
A1	0-15.	8.7	1.2	0.1	.	12.4	2.4	80.	0.8	12.4	.	8
B2t	15-35	4.8	0.8	0.2	.	7.8	2.0	74.	5.1	7.8	.	9
C1	35-76	4.2	0.7	0.1	.	5.4	0.4	92.	1.8	5.4	.	10
C12	76-95	9.8	2.1	0.1	.	15.2	3.2	78.	0.6	15.2	.	11
C2	95-130	10.9	1.9	0.1	.	12.9	.	100.	0.7	12.6	.	12
IIC3	130-145	25.5	4.3	0.0	.	29.8	.	100.	0.0	26.1	.	13
IIIC3	145-160	33.8	2.5	0.1	.	36.4	.	100.	0.2	14.5	.	14

Comments: $BaCl_2$ ACIDITY CALCULATED AS THE DIFFERENCE BETWEEN NAOAc CEC AND CEC SUM.

Table 33. Physical and chemical data for site 2.

Horizon	Depth (cm)	Thick (cm)	Mechanical analysis (%)								Water content (%)				Avail H_2O	Atterberg Limits		Proctor Test
			sand	silt	clay	vcos	cos	ms	fs	vfs	15bar	.3bar	.1bar	0bar		Liq.	Plast.	
Ap	0-18	18	11.0	53.0	36.0	.	.	.	.	.	18.9	34.8	37.4	48.0	15.9			
B21t	18-48	30	1.0	34.0	65.0	.	.	.	.	.	25.0	35.7	39.8	56.9	10.7			
B22t	48-64	16	0.0	32.0	68.0	.	.	.	.	.	19.0	35.6	38.3	57.1	16.6			
C1	64-91	27	2.0	35.0	63.0	0.0	0.0	0.0	0.0	2.0	19.2	38.0	41.4	63.7	18.8			
C2	91-97	6	17.0	65.0	18.0	.	.	.	.	.	.	.	.	.	.			
C3	97-127	30	0.0	20.0	80.0	.	.	.	.	.	23.2	39.9	42.4	70.4	16.7			
C4 *	127-152	25	.	.	.	.	.	.	.	.	.	.	.	.	.			

Horizon	Depth (cm)	Bulk Density (g/cm^3)			Particle density (g/cm^3)	CEC (meq/100g)	15bar/clay ratio	CEC/clay ratio	Sample Number
		.3bar	OD	COLE					
Ap	0-18	.	1.6	.	.	15.2	0.52	0.42	15
B21t	18-48	.	1.7	.	.	16.1	0.38	0.24	16
B22t	48-64	.	1.7	.	.	14.4	0.27	0.21	17
C1	64-91	.	1.7	.	.	14.8	0.25	0.19	18
C2	91-97	.	.	.	.	.	0.00	0.00	19
C3	97-127	.	1.7	.	.	13.5	0.29	0.16	20
C4 *	127-152	.	.	.	.	..	.	.	21

Comments: * Did not sample

Horizon	Depth (cm)	Thick (cm)	Org. Carbon (%)	Total N (%)	C/N ratio	pH 1:1 H_2O	pH 1:2 $CaCl_2$	saturation extract H_2O (%)	paste pH	EC (mmho/cm)	Ca (meq/l)	Mg (meq/l)	Na (meq/l)	K (meq/l)	HCO_3 (meq/l)	SO_4 (meq/l)	SAR
Ap	0-18	18	3.8	0.13	29.2	6.8	6.6	48.0	6.9	0.6	6.8	5.9	1.4	.	392		0.5
B21t	18-48	30	1.0	0.05	20.0	7.8	7.2	56.9	7.9	0.6	2.5	2.0	1.2	.	248		0.8
B22t	48-64	16	0.6	0.04	15.0	8.1	7.4	57.1	8.3	0.6	1.6	1.4	1.0	.			0.8
C1	64-91	27	0.4	0.03	13.3	8.3	7.5	63.7	8.5	0.6	0.8	1.2	1.2	.	217		1.2
C2	91-97	6	.	.	.	.	.	.	.	.	.	.	.	.			0.0
C3	97-127	30	0.4	0.03	13.3	8.5	7.5	70.4	8.4	0.8	0.6	1.3	1.2	.	308		1.2
C4	127-152	25	.	.	.	.	.	.	.	.	.	.	.	.			0.0

Horizon	Depth (cm)	NH_4OAc extract (meq/100g)					$BaCl_2$ Acid. (meq/100g)	Base satn. (%)	ESP (%)	NaOAc CEC meq/100g	$CaCO_3$ (%)	Sample Number
		Ca	Mg	Na	K	CEC-sum						
Ap	0-18	10.5	5.1	0.5	.	16.1	.	100.	3.1	15.2	.	15
B21t	18-48	44.4	7.7	0.6	.	52.7	.	100.	1.8	16.1	.	16
B22t	48-64	42.4	7.1	0.6	.	50.1	.	100.	1.1	14.4	.	17
C1	64-91	42.6	9.6	0.8	.	53.0	.	100.	1.5	14.8	.	18
C2	91-97	.	.	.	.	.	.	.	.	.	.	19
C3	97-127	42.6	11.3	0.8	.	54.7	.	100.	1.4	13.5	.	20
C4	127-152	.	.	.	.	.	.	.	.	.	.	21

Comments: DID NOT SAMPLE C4.

$BaCl_2$ ACIDITY CALCULATED AS THE DIFFERENCE BETWEEN NAOAc CEC AND CEC SUM.

Table 34. Physical and chemical data for site 3.

Horizon	Depth (cm)	Thick (cm)	Mechanical analysis (%) sand	silt	clay	vcos	cos	ms	fs	vfs	Water content (%) 15bar	.3bar	.1bar	0bar	Avail H_2O	Atterberg Limits Liq.	Plast.	Proctor Test
O2	2-0	-2	.	.	.	.	.	.	.	.	.	.	.	.	.			
A1	0-16	16	23.0	64.0	13.0	.	.	.	.	.	8.8	26.6	37.7	45.9	17.8			
A2	16-32	16	23.0	66.0	11.0	.	.	.	.	.	7.5	21.7	33.3	36.2	14.2			
B2t	32-49	17	18.0	74.0	8.0	3.0	3.0	2.0	4.0	6.0	6.6	25.3	33.7	35.4	18.7			
C1	49-77	28	16.0	68.0	16.0	3.0	1.0	4.0	3.0	5.0	5.6	32.4	39.3	40.0	26.8			
C2	77-107	30	20.0	73.0	7.0	.	.	.	.	.	4.5	26.7	32.7	35.5	22.2			
IIC3	107-174	67	32.0	56.0	12.0	.	.	.	.	.	3.4	16.7	18.3	21.0	13.3			

Horizon	Depth (cm)	Bulk Density (g/cm^3) .3bar	OD	COLE	Particle density (g/cm^3)	CEC (meq/100g)	15bar/clay ratio	CEC/clay ratio	Sample Number
O2	2-0	.	.	.	.	.	.	.	22
A1	0-16	.	1.3	.	.	14.6	0.67	1.12	23
A2	16-32	.	1.4	.	.	13.5	0.68	1.22	24
B2t	32-49	.	1.3	.	.	9.1	0.47	0.65	25
C1	49-77	.	1.4	.	.	7.4	0.35	0.46	26
C2	77-107	.	1.5	.	.	5.6	0.64	0.80	27
IIC3	107-174	.	.	.	.	3.5	0.28	0.29	28

Comments:

Horizon	Depth (cm)	Thick (cm)	Org. Carbon (%)	Total N (%)	C/N ratio	pH 1:1 H_2O	pH 1:2 $CaCl_2$	saturation extract H_2O (%)	paste pH	EC (mmho/cm)	Ca (meq/l)	Mg	Na	K	HCO_3	SO_4	SAR
O2	2-0	-2	.	.	.	.	.	.	.	.	.	.	.	.			0.0
A1	0-16	16	2.5	0.08	31.2	7.1	6.8	45.9	7.1	0.4	5.5	1.4	0.2	.	35		0.1
A2	16-32	16	1.1	0.05	22.0	7.5	7.0	36.2	7.6	0.4	5.3	1.1	0.2	.	278		0.1
B2t	32-49	17	1.2	0.04	30.0	7.9	7.5	35.4	8.0	0.4	5.0	1.2	0.4	.	332		0.2
C1	49-77	28	1.0	0.03	33.3	8.4	7.8	40.0	8.6	0.5	1.8	1.5	2.2	.	362		1.7
C2	77-107	30	0.4	0.02	20.0	8.6	8.0	35.5	8.7	00.4	0.9	2.4	1.1	.	296		0.8
IIC3	107-174	67	0.3	0.01	30.0	8.9	7.9	21.0	9.0	0.4	0.5	1.6	2.7	.	254		2.6

Horizon	Depth (cm)	NH_4OAc extract (meq/100g) Ca	Mg	Na	K	CEC-sum	$BaCl_2$ Acid.	Base satn. (%)	ESP (%)	NaOAc CEC meq/100g	$CaCO_3$ (%)	Sample Number
O2	2-0	.	.	.	.	.	.	.	.	.	.	22
A1	0-16	15.7	1.7	0.1	.	17.5	.	100.	1.1	14.6	.	23
A2	16-32	17.7	1.6	0.1	.	19.4	.	100.	0.5	13.5	.	24
B2t	32-49	46.4	1.9	0.1	.	48.4	.	100.	0.2	9.1	.	25
C1	49-77	44.4	3.1	0.2	.	47.7	.	100.	0.4	7.4	.	26
C2	77-107	42.4	6.4	0.1	.	48.9	.	100.	0.2	5.6	.	27
IIC3	107-174	36.4	3.1	0.2	.	39.7	.	100.	0.5	3.5	.	28

Comments: $BaCl_2$ ACIDITY CALCULATED AS THE DIFFERENCE BETWEEN NAOAc CEC AND CEC SUM.

Table 35. Physical and chemical data for site 4.

Horizon	Depth (cm)	Thick (cm)	Mechanical analysis sand	silt	clay	vcos	cos	ms	fs	vfs	Water content 15bar	.3bar	.1bar	0bar	Avail H_2O	Atterberg Limits Liq.	Plast.	Proctor Test
			---- (%) ----								---- (%) ----							
Ap	0-17	17	21.0	67.0	12.0	.	.	.	.	.	12.4	30.8	34.5	43.2	18.4			
B2t	17-44	27	15.0	52.0	33.0	.	.	.	.	.	10.4	27.3	28.4	40.2	16.9			
B3t	44-62	18	19.0	51.0	30.0	.	.	.	.	.	7.5	25.0	25.7	48.9	17.5			
C1	62-85	23	10.0	68.0	22.0	.	.	.	.	.	4.9	28.0	29.3	34.1	23.1			
IIC2*	85-174	89	1.0	87.0	12.0	.	.	.	.	.	2.9	28.0	30.4	35.9	25.1			
IIC2*	85-174	89	1.0	28.0	71.0	.	.	.	.	.	21.0	39.4	.	.	18.4			
	-		.	.	.	.	.	..	.	.	.	.	.	.	.			

Horizon	Depth (cm)	Bulk Density .3bar	OD	COLE	Particle density	CEC (meq/100g)	15bar/clay ratio	CEC/clay ratio	Sample Number
		--- (g/cm^3) ---			(g/cm^3)				
Ap	0-17	.	1.5	.	.	17.4	1.03	1.45	29
B2t	17-44	.	1.8	.	.	7.0	0.31	0.21	30
B3t	44-62	.	1.7	.	.	4.3	0.25	0.14	31
C1	62-85	.	1.8	.	.	3.9	0.22	0.17	32
IIC2*	85-174	.	1.6	.	.	2.6	0.24	0.21	33
IIC2*	85-174	.	.	.	.	16.5	0.29	0.23	34
	-	.	.	.	.	.	.	.	

Comments:* SILTY AND CLAYEY MEMBERS OF A SINGLE VARVE, EACH ~3 CM THICK

Horizon	Depth (cm)	Thick (cm)	Org. Carbon	Total N	C/N ratio	pH 1:1 H_2O	1:2 $CaCl_2$	saturation extract H_2O (%)	paste pH	EC (mmho/cm)	Ca	Mg	Na	K	HCO_3	SO_4	SAR
			--- (%) ---								---- (meq/l) ----						
Ap	0-17	17	3.5	0.15	23.3	8.5	7.6	43.2	8.8	12.0	2.1	2.3	19.1	.	918		12.8
B2t	17-44	27	1.0	0.04	25.0	9.8	8.8	40.2	10.0	28.0	0.4	1.2	54.0	.	640		60.3
B3t	44-62	18	0.3	0.02	15.0	9.8	8.9	48.9	10.0	7.0	0.3	1.0	52.0	.	356		64.4
C1	62-85	23	0.3	0.01	30.0	9.8	8.4	34.1	9.8	1.6	0.2	0.4	26.0	.	453		47.4
IIC2#	85-174	89	0.1	0.01	10.0	9.8	8.6	35.9	9.9	2.8	0.4	1.4	42.0	.	211		44.2
IIC2*	85-174	89	0.5	0.02	25.0	.	.	.	.	.	.	.	.	.			0.0
	-		.	.	.	.	.	.	.	.	.	.	.	.			0.0

Horizon	Depth (cm)	NH_4OAc extract Ca	Mg	Na	K	CEC-sum	$BaCl_2$ Acid.	Base satn.	ESP (%)	NaOAc CEC	$CaCO_3$ (%)	Sample Number
		---- (meq/100g) ----						(%)		meq/100g		
Ap	0-17	14.7	5.4	3.2	.	23.3	.	100.	13.7	17.4	.	29
B2t	17-44	44.4	6.7	5.7	.	56.8	.	100.	91.5	7.0	.	30
B3t	44-62	42.4	4.5	6.2	.	53.1	.	100.	11.6	4.3	.	31
C1	62-85	40.4	3.0	2.9	.	46.3	.	100.	6.2	3.9	.	32
IIC2#	85-174	38.5	2.1	3.0	.	43.6	.	100.	6.8	2.6	.	33
IIC2*	85-174	38.5	10.9	10.7	.	60.1	.	100.	17.8	16.5	.	34
	-	.	.	.	.	.	.	.	.	.	.	

Comments: IIC2# IS THE SILTY COMPONENT OF THE VARVED COUPLETS, IIC2* IS THE CLAYEY COMPONENT
$BaCl_2$ ACIDITY CALCULATED AS THE DIFFERENCE BETWEEN NAOAc CEC AND CEC SUM.

Table 36. Physical and chemical data for site 5.

Horizon	Depth (cm)	Thick (cm)	Mechanical analysis sand	silt	clay	vcos	cos	ms	fs	vfs	Water content 15bar	.3bar	.1bar	0bar	Avail H_2O	Atterberg Limits Liq.	Plast.	Proctor Test
			---- (%) ----								---- (%) ----							
Ap	0-18	18	73.0	21.0	6.0	.	.	.	.	.	7.8	11.0	16.7	30.4	3.2			
A3	18-33	15	67.0	23.0	10.0	.	.	.	.	.	8.1	11.5	17.2	27.8	3.4			
B21	33-52	19	83.0	12.0	5.0	8.0	30.0	23.0	19.0	3.0	5.0	6.4	9.1	24.4	1.4			
B22	52-68	16	77.0	15.0	8.0	.	.	.	.	.	4.1	4.9	8.4	23.6	0.8			
C1	68-93	25	75.0	17.0	8.0	.	.	.	.	.	2.3	4.7	6.1	23.3	2.4			
IIC2	93-118	25	79.0	15.0	6.0	.	.	.	.	.	1.4	3.6	5.5	23.5	2.2			
IIIC3	118-160	42	94.0	4.0	2.0	1.0	50.0	36.0	6.0	1.0	1.1	2.1	3.0	28.6	1.0			

Horizon	Depth (cm)	Bulk Density .3bar	OD	COLE	Particle density (g/cm^3)	CEC (meq/ 100g)	15bar/ clay ratio	CEC/ clay ratio	Sample Number
		--- (g/cm^3) ---							
Ap	0-18	.	1.6	.	.	12.2	1.30	2.03	35
A3	18-33	.	1.6	.	.	12.0	0.81	1.20	36
B21	33-52	.	1.6	.	.	7.8	0.62	0.97	37
B22	52-68	.	1.7	.	.	5.9	0.51	0.73	38
C1	68-93	.	1.6	.	.	3.9	0.28	0.48	39
IIC2	93-118	.	1.6	.	.	2.8	0.23	0.46	40
IIIC3	118-160	.	1.6	.	.	2.0	0.18	0.33	41

Comments:

Horizon	Depth (cm)	Thick (cm)	Org. Carbon	Total N	C/N ratio	pH 1:1 H_2O	1:2 $CaCl_2$	saturation extract H_2O (%)	paste pH	EC (mmho/cm)	Ca	Mg	Na	K	HCO_3	SO_4	SAR
			--- (%) ---								---- (meq/l) ----						
Ap	0-18	18	3.2	0.13	24.6	6.8	6.3	30.4	7.1	0.2	2.4	0.6	0.2	.	97		0.1
A3	18-33	15	2.4	0.10	24.0	7.0	6.3	27.8	7.2	0.2	1.9	0.5	0.2	.	121		0.1
B21	33-52	19	0.5	0.03	16.6	7.2	6.4	24.4	7.4	0.1	0.8	0.2	0.2	.	133		0.2
B22	52-68	16	0.3	0.02	15.0	7.9	7.3	23.6	8.4	0.2	2.0	0.4	0.3	.	211		0.2
C1	68-93	25	0.1	0.02	5.0	8.2	7.3	23.3	8.5	0.2	1.9	0.3	0.4	.	254		0.3
IIC2	93-118	25	0.1	0.01	10.0	8.4	7.7	23.5	8.8	0.2	2.1	0.3	0.2	.	205		0.1
IIIC3	118-160	42	0.1	0.01	10.0	8.3	7.5	28.6	9.0	0.2	1.8	0.2	0.2	.			0.2

Horizon	Depth (cm)	NH_4OAc extract Ca	Mg	Na	K	CEC-sum	$BaCl_2$ Acid.	Base satn. (%)	ESP (%)	NaOAc CEC meq/100g	$CaCO_3$ (%)	Sample Number
		---- (meq/100g) ----										
Ap	0-18	10.5	1.2	0.1	.	12.2	0.4	96.	0.8	12.2	.	35
A3	18-33	10.9	1.3	0.1	.	12.3	.	100.	1.6	12.0	.	36
B21	33-52	6.5	1.0	0.1	.	7.8	0.2	97.	1.2	7.8	.	37
B22	52-68	15.2	0.8	0.1	.	16.1	.	100.	0.6	5.9	.	38
C1	68-93	42.1	0.7	0.0	.	42.8	.	100.	0.0	3.9	.	39
IIC2	93-118	42.1	0.9	0.0	.	43.0	.	100.	0.0	2.8	.	40
IIIC3	118-160	31.7	0.6	0.1	.	32.4	.	100.	0.3	2.0	.	41

Comments: $BaCl_2$ ACIDITY CALCULATED AS THE DIFFERENCE BETWEEN NAOAc CEC AND CEC SUM.

Table 37. Physical and chemical data for site 6.

Horizon	Depth (cm)	Thick (cm)	Mechanical analysis								Water content				Avail H_2O	Atterberg Limits		Proctor Test
			sand	silt	clay	vcos	cos	ms	fs	vfs	15bar	.3bar	.1bar	0bar		Liq.	Plast.	
			(%)								(%)							
O1	8-0	-8	.	.	.	.	.	.	.	.	.	.	.	.	.			
B2ir	0-24	24	39.0	57.0	4.0	.	.	.	.	.	9.5	29.4	45.4	55.4	19.9			
C11	24-67	43	56.0	38.0	6.0	12.0	10.0	10.0	14.0	10.0	2.7	9.5	11.8	17.3	6.8			
C12	67-102	35	51.0	43.0	6.0	.	.	.	.	.	2.5	7.8	12.4	17.8	5.3			
IIC2	102-125	23	65.0	29.0	6.0	.	.	.	.	.	2.4	7.3	13.8	20.9	4.9			
IIIC3	125-143	18	65.0	31.0	4.0	.	.	.	.	.	2.5	5.8	7.4	18.2	3.3			
IVC4	143-162	19	22.0	74.0	4.0	.	.	.	.	.	2.2	19.8	25.1	27.4	17.6			

Horizon	Depth (cm)	Bulk Density			Particle density (g/cm^3)	CEC (meq/ 100g)	15bar/ clay ratio	CEC/ clay ratio	Sample Number
		.3bar	OD	COLE					
		(g/cm^3)							
O1	8-0	.	.	.	.	.	.	.	1
B2ir	0-24	.	1.2	.	.	10.9	2.37	2.72	2
C11	24-67	.	.	.	.	4.8	0.45	0.80	3
C12	67-102	.	.	.	.	4.4	0.41	0.73	4
IIC2	102-125	.	.	.	.	4.3	0.40	0.71	5
IIIC3	125-143	.	.	.	.	4.1	0.62	1.02	6
IVC4	143-162	.	1.7	.	.	4.8	0.55	1.20	7

Comments:01 HORIZON WAS NOT SAMPLED

Horizon	Depth (cm)	Thick (cm)	Org. Carbon	Total N	C/N ratio	pH		saturation extract									
						1:1 H_2O	1:2 $CaCl_2$	H_2O (%)	paste pH	EC (mmho/cm)	Ca	Mg	Na	K	HCO_3	SO_4	SAR
			(%)								(meq/l)						
O1	8-0	-8	.	.	.	.	.	.	.	.	.	.	.	.			0.0
B2ir	0-24	24	1.6	0.05	32.0	6.4	5.8	55.4	7.1	0.2	0.6	0.2	0.3	.	66		0.4
C11	24-67	43	.1	0.01	10.0	7.7	7.3	17.3	8.1	0.1	0.8	0.3	0.4	.	78		0.5
C12	67-102	35	0.1	0.08	1.2	7.1	6.5	17.8	7.7	0.1	0.8	0.3	0.4	.	97		0.5
IIC2	102-125	23	0.1	0.01	10.0	7.3	6.7	20.9	7.6	0.1	0.9	0.4	0.3	.	199		0.3
IIIC3	125-143	18	0.1	0.09	1.1	7.2	6.6	18.2	7.3	0.1	0.6	2.6	0.3	.	84		0.2
IVC4	143-162	19	0.1	0.01	10.0	8.0	7.4	27.4	8.5	0.2	1.8	0.5	0.3	.	205		0.2

Horizon	Depth (cm)	NH_4OAc extract					$BaCL_2$ Acid.	Base satn.	ESP (%)	NaOAc CEC meq/100g	$CaCO_3$ (%)	Sample Number
		Ca	Mg	Na	K	CEC-sum						
		(meq/100g)						(%)				
O1	8-0	.	.	.	.	.	.	.	.	.	.	1
B2ir	0-24	5.3	0.6	0.0	.	6.7	0.8	88.	6.9	10.9	.	2
C11	24-67	0.8	0.3	0.4	.	4.8	3.3	31.	8.3	4.8	.	3
C12	67-102	0.8	0.3	0.4	.	4.4	2.9	34.	9.0	4.4	.	4
IIC2	102-125	0.9	0.4	0.3	.	4.3	2.7	37.	6.9	4.3	.	5
IIIC3	125-143	0.6	2.6	0.3	.	4.1	0.6	85.	7.3	4.1	.	6
IVC4	143-162	1.8	0.5	0.3	.	2.6	.	100.	11.5	4.8	.	7

Comments: THE 01 HORIZON WAS NOT SAMPLED.

$BaCl_2$ ACIDITY CALCULATED FROM THE DIFFERENCE BETWEEN NH_4OAc CEC and CEC SUM.

Table 38. Physical and chemical data for site 7.

Horizon	Depth (cm)	Thick (cm)	sand	silt	clay	vcos	cos	ms	fs	vfs	15bar	.3bar	.1bar	0bar	Avail H_2O	Atterberg Limits Liq.	Plast.	Proctor Test
			Mechanical analysis (%)								Water content (%)							
Ap *	0-10	10	.	.	.	.	.	.	.	.	.	.	.	.	.			
A3	10-39	29	45.0	27.0	28.0	.	.	.	.	.	9.2	20.9	33.5	47.5	11.7			
B2t	39-66	27	33.0	51.0	16.0	.	.	.	.	.	8.4	22.5	36.3	46.6	14.1			
C1ca	66-97	31	11.0	69.0	20.0	0.0	0.0	0.0	1.0	10.0	8.8	29.7	34.7	41.3	20.9			
C2	97-118	21	50.0	43.0	7.0	0.0	1.0	0.0	4.0	45.0	3.4	11.5	21.4	31.4	8.1			
C3	118-165	47	32.0	58.0	10.0	.	.	.	.	.	2.9	11.4	24.6	32.8	8.5			
	-		.	.	.	.	.	.	.	.	.	.	.	.	.			

Horizon	Depth (cm)	Bulk Density .3bar	OD	COLE	Particle density (g/cm^3)	CEC (meq/ 100g)	15bar/ clay ratio	CEC/ clay ratio	Sample Number
		--- (g/cm^3) ---							
Ap *	0-10	.	.	.	.	.	.	.	42
A3	10-39	.	1.3	.	.	23.9	0.32	0.85	43
B2t	39-66	.	1.1	.	.	14.1	0.52	0.88	44
C1ca	66-97	.	1.5	.	.	8.8	0.38	0.38	45
C2	97-118	.	1.4	.	.	5.2	0.34	0.52	46
C3	118-165	.	1.5	.	.	4.1	0.29	0.41	47
	-	. .	.	.	.	.	.	.	

Comments: * Did not sample

Horizon	Depth (cm)	Thick (cm)	Org. Carbon	Total N	C/N ratio	pH 1:1 H_2O	pH 1:2 $CaCl_2$	H_2O (%)	paste pH	EC (mmho/cm)	Ca	Mg	Na	K	HCO_3	SO_4	SAR
			--- (%) ---					saturation extract			(meq/l)						
Ap	0-10	10	.	.	.	.	.	.	.	.	.	.	.	.			0.0
A3	10-39	29	3.4	0.14	24.2	8.1	7.3	47.5	7.9	0.6	2.9	0.8	0.3	.	374		0.2
B2	39-66	27	2.2	0.09	24.4	8.4	7.7	46.6	8.7	0.8	2.0	0.9	0.5	.	399		0.4
C1ca	66-97	31	0.6	0.03	20.0	8.8	8.2	41.3	9.1	0.8	0.7	5.8	2.9	.	344		1.6
C2	97-118	21	0.3	0.02	15.0	8.7	8.1	31.4	9.1	0.5	0.5	4.3	2.7	.	362		1.7
C3	118-165	47	0.2	0.01	20.0	8.7	7.9	32.8	9.1	0.4	0.5	0.3	1.9	.	272		3.0
	-		.	.	.	.	.	.	.	.	.	.	.	.			0.0

Horizon	Depth (cm)	Ca	Mg	Na	K	CEC-sum	$BaCl_2$ Acid.	Base satn. (%)	ESP (%)	NaOAc CEC meq/100g	$CaCO_3$ (%)	Sample Number
		NH_4OAc extract (meq/100g)										
Ap	0-10	.	.	.	.	.	.	.	.	.	.	42
A3	10-39	4.8	2.6	0.2	.	23.9	16.3	31.	2.0	23.9	.	43
B2	39-66	46.3	5.3	0.1	.	51.7	.	100.	0.1	14.1	.	44
C1ca	66-97	46.3	9.5	0.3	.	56.1	.	100.	0.5	8.8	.	45
C2	97-118	42.1	7.3	0.2	.	49.6	.	100.	0.4	5.2	.	46
C3	118-165	44.2	5.6	0.1	.	49.9	.	100.	0.2	4.1	.	47
	-	.	.	.	.	.	.	.	.	.	.	

Comments: $BaCl_2$ ACIDITY CALCULATED AS THE DIFFERENCE BETWEEN NAOAc CEC AND CEC SUM.

Table 39. Physical and chemical data for site 8.

Horizon	Depth (cm)	Thick (cm)	Mechanical analysis								Water content				Avail	Atterberg Limits		Proctor Test
			sand	silt	clay	vcos	cos	ms	fs	vfs	15bar	.3bar	.1bar	0bar	H_2O	Liq.	Plast.	
			(%)								(%)							
A11	0-20	20	43.0	45.0	12.0	.	.	.	.	.	11.1	23.9	35.9	49.1	12.8			
A12	20-37	17	45.0	46.0	9.0	.	.	.	.	.	10.9	22.2	35.7	46.6	11.3			
B2	37-57	20	41.0	47.0	12.0	.	.	.	.	.	5.5	15.6	21.5	35.0	10.1			
C1ca	57-108	51	18.0	64.0	18.0	.	.	.	.	.	6.4	22.4	31.3	39.4	16.0			
C2	108-170	62	5.0	70.0	25.0	.	.	.	.	.	7.6	30.1	33.1	37.9	22.5			
	-		.	.	.	.	.	.	.	.	.	.	.	.	.			
	-		.	.	.	.	.	.	.	.	.	.	.	.	.			

Horizon	Depth (cm)	Bulk Density			Particle density	CEC (meq/ 100g)	15bar/ clay ratio	CEC/ clay ratio	Sample Number
		.3bar	OD	COLE					
		(g/cm^3)			(g/cm^3)				
A11	0-20	.	1.3	.	.	19.6	0.92	1.63	48
A12	20-37	.	1.3	.	.	16.5	1.21	1.83	49
B2	37-57	.	1.3	.	.	9.8	0.45	0.81	50
C1ca	57-108	.	1.5	.	.	6.1	0.35	0.33	51
C2	108-170	.	1.5	.	.	8.3	0.30	0.33	52
	-	.	.	.	.	.	.	.	
	-	.	.	.	.	.	.	.	

Comments:

Horizon	Depth (cm)	Thick (cm)	Org. Carbon	Total N	C/N ratio	pH 1:1 H_2O	pH 1:2 $CaCl_2$	saturation extract									
			(%)					H_2O (%)	paste pH	EC (mmho/cm)	Ca	Mg	Na	K	HCO_3	SO_4	SAR
											(meq/l)						
A11	0-20	20	3.1	0.28	11.0	6.5	5.9	49.1	6.6	0.3	2.1	0.6	0.3	.	121		0.2
A12	20-37	17	5.0	0.18	27.7	6.6	5.9	46.6	6.9	0.1	1.3	0.4	0.2	.	97		0.2
B2	37-57	20	1.3	0.06	21.6	7.5	7.2	35.0	7.4	0.4	3.1	1.1	0.4	.	332		0.2
C1ca	57-108	51	0.6	0.03	20.0	8.2	7.6	39.4	8.6	0.4	1.9	0.6	0.4	.	242		0.3
C2	108-170	62	0.4	0.01	40.0	8.2	7.5	37.9	8.4	0.4	1.5	0.5	1.6	.	223		1.6
	-		.	.	.	.	.	.	.	.	.	.	.	.			0.0
	-		.	.	.	.	.	.	.	.	.	.	.	.			0.0

Horizon	Depth (cm)	NH_4OAc extract					$BaCl_2$ Acid.	Base satn.	ESP (%)	NaOAc CEC	$CaCO_3$ (%)	Sample Number
		Ca	Mg	Na	K	CEC-sum						
		(meq/100g)						(%)		meq/100g		
A11	0-20	17.2	1.9	0.1	.	19.6	0.4	97.	0.5	19.6	.	48
A12	20-37	14.0	2.0	0.1	.	16.5	0.4	97.	2.4	16.5	.	49
B2	37-57	10.5	1.6	0.1	.	12.2	.	100.	0.8	9.8	.	50
C1ca	57-108	50.4	2.2	0.1	.	52.7	.	100.	0.1	6.1	.	51
C2	108-170	48.4	2.7	0.3	.	51.4	.	100.	0.5	8.3	.	52
	-	.	.	.	.	.	.	.	.	.	.	
	-	.	.	.	.	.	.	.	.	.	.	

Comments: $BaCl_2$ ACIDITY CALCULATED AS THE DIFFERENCE BETWEEN NAOAc CEC AND CEC SUM.

Table 40. Physical and chemical data for site 9.

Horizon	Depth (cm)	Thick (cm)	Mechanical analysis sand (%)	silt	clay	vcos	cos	ms	fs	vfs	Water content 15bar (%)	.3bar	.1bar	0bar	Avail H_2O	Atterberg Limits Liq.	Plast.	Proctor Test
A1 *	0-5	5	.	.	.	.	.	.	.	.	.	.	.	.	.			
C1	5-35	30	88.0	10.0	2.0	0.0	11.0	36.0	34.0	7.0	3.2	5.7	8.1	25.4	2.5			
C2	35-65	30	89.0	11.0	0.0	.	.	.	.	.	2.9	4.9	7.7	25.3	2.0			
C3	65-95	30	91.0	7.0	2.0	.	.	.	.	.	2.7	5.0	7.1	28.0	2.3			
C4	95-125	30	88.0	10.0	2.0	.	.	.	.	.	3.1	5.7	7.9	27.1	2.6			
C5	125-155	30	90.0	10.0	0.0	.	.	.	.	.	2.7	4.8	6.7	28.8	2.1			
LM **	-		81.0	9.0	10.0	.	.	.	.	.	.	.	11.2	.	.			

Horizon	Depth (cm)	Bulk Density .3bar (g/cm³)	OD	COLE	Particle density (g/cm³)	CEC (meq/100g)	15bar/clay ratio	CEC/clay ratio	Sample Number
A1 *	0-5	.	.	.	.	.	.	.	53
C1	5-35	.	1.6	.	.	4.6	.	.	54
C2	35-65	.	1.6	.	.	5.0	.	.	55
C3	65-95	.	1.6	.	.	4.4	1.35	2.20	56
C4	95-125	.	1.6	.	.	4.6	1.55	2.30	57
C5	125-155	.	1.6	.	.	4.1	.	.	58
LM **	-	.	1.7	.	.	.	0.00	0.00	

Comments: * Did not sample. LM * = clay lamellae

Horizon	Depth (cm)	Thick (cm)	Org. Carbon (%)	Total N (%)	C/N ratio	pH 1:1 H_2O	pH 1:2 $CaCl_2$	saturation extract H_2O (%)	paste pH	EC (mmho/cm)	Ca (meq/l)	Mg	Na	K	HCO_3	SO_4	SAR
A1	0-5	5	.	.	.	.	.	.	.	.	.	.	.	.			0.0
C1	5-35	30	0.1	0.01	10.0	7.4	7.1	25.4	7.5	0.2	0.9	0.6	0.7	.	34		0.8
C2	35-65	30	0.1	0.01	10.0	7.2	6.7	25.3	7.3	0.1	0.5	0.4	0.7	.	103		1.0
C3	65-95	30	0.1	0.01	10.0	7.4	6.8	28.0	7.4	0.2	0.9	0.7	1.1	.	91		1.2
C4	95-125	30	0.1	0.01	10.0	7.2	6.6	27.1	7.2	0.2	1.0	1.2	1.0	.	91		0.9
C5	125-155	30	0.1	0.01	10.0	6.7	6.2	28.8	6.8	0.2	1.2	1.6	0.5	.	48		0.4
	-		.	.	.	.	.	.	.	.	.	.	.	.			0.0

Horizon	Depth (cm)	NH_4OAc extract Ca (meq/100g)	Mg	Na	K	CEC-sum	$BaCl_2$ Acid.	Base satn. (%)	ESP (%)	NaOAc CEC meq/100g	$CaCO_3$ (%)	Sample Number
A1	0-5	.	.	.	.	.	.	.	.	.	.	53
C1	5-35	3.1	1.3	0.1	.	4.6	0.1	97.	15.2	4.6	.	54
C2	35-65	2.7	1.3	0.1	.	5.0	0.9	82.	2.0	5.0	.	55
C3	65-95	2.7	1.5	0.1	.	4.4	0.1	97.	2.2	4.4	.	56
C4	95-125	2.9	1.8	0.2	.	4.9	.	100.	4.0	4.6	.	57
C5	125-155	2.1	1.8	0.1	.	4.1	0.1	97.	2.4	4.1	.	58
	-	.	.	.	.	.	.	.	.	.	.	

Comments: $BaCl_2$ ACIDITY CALCULATED AS THE DIFFERENCE BETWEEN NAOAc CEC AND CEC SUM.

Table 41. Physical and chemical data for site 10.

Horizon	Depth (cm)	Thick (cm)	Mechanical analysis sand (%)	silt	clay	vcos	cos	ms	fs	vfs	Water content 15bar (%)	.3bar	.1bar	0bar	Avail H$_2$O	Atterberg Limits Liq.	Plast.	Proctor Test
Ap	0-15	15	27.0	59.0	14.0	.	.	.	.	.	14.9	37.5	50.2	67.0	22.6			
A21 *	15-24	9	.	.	.	.	.	.	.	.	.	.	.	.	.			
A22	24-46	22	24.0	53.0	23.0	.	.	.	.	.	4.3	20.3	23.9	28.7	16.0			
B21t	46-79	33	19.0	51.0	30.0	.	.	.	.	.	6.5	24.5	27.2	37.0	18.0			
B22	79-110	31	21.0	59.0	20.0	.	.	.	.	.	4.0	20.4	20.8	25.8	16.4			
B23	110-138	28	30.0	54.0	16.0	4.0	4.0	4.0	9.0	9.0	6.2	23.0	24.0	31.3	16.8			
C	138-188	50	4.0	74.0	22.0	.	.	.	.	.	4.9	27.8	30.1	33.7	22.9			

Horizon	Depth (cm)	Bulk Density .3bar (g/cm^3)	OD	COLE	Particle density (g/cm^3)	CEC (meq/100g)	15bar/clay ratio	CEC/clay ratio	Sample Number
Ap	0-15	.	1.1	.	.	20.4	1.06	1.45	59
A21 *	15-24	.	.	.	.	.	.	.	60
A22	24-46	.	.	.	.	5.9	0.18	0.25	61
B21t	46-79	.	1.8	.	.	5.4	0.21	0.18	62
B22	79-110	.	1.9	.	.	3.9	0.20	0.19	63
B23	110-138	.	1.7	.	.	4.8	0.28	0.21	64
C	138-188	.	1.6	.	.	4.4	0.22	0.20	65

Comments: * DID NOT SAMPLE

Horizon	Depth (cm)	Thick (cm)	Org. Carbon (%)	Total N (%)	C/N ratio	pH 1:1 H$_2$O	pH 1:2 CaCl$_2$	saturation extract H$_2$O (%)	paste pH	EC (mmho/cm)	Ca (meq/l)	Mg	Na	K	HCO$_3$	SO$_4$	SAR
Ap	0-15	15	6.0	0.24	25.0	6.7	6.0	67.0	6.5	0.4	3.7	1.6	0.2	.	495		0.1
A21 *	15-24	9	.	.	.	.	.	.	.	.	.	.	.	.			0.0
A22	24-46	22	0.8	0.07	11.4	8.0	7.4	28.7	8.0	0.4	2.9	2.3	0.6	.	308		0.3
B21t	46-79	33	0.4	0.02	20.0	8.4	7.8	37.0	8.5	0.4	1.5	1.6	0.8	.	272		0.6
B22	79-110	31	0.3	0.01	30.0	8.6	7.8	25.8	8.8	0.3	0.7	0.9	1.6	.	205		1.7
B23	110-138	28	0.7	0.01	70.0	8.5	7.7	31.3	8.7	0.4	0.9	0.9	1.2	.	205		1.2
C	138-188	50	0.4	0.05	8.0	8.4	7.7	33.7	8.6	0.3	0.9	0.6	0.6	.	182		0.6

Horizon	Depth (cm)	NH$_4$OAc extract Ca (meq/100g)	Mg	Na	K	CEC-sum	BaCl$_2$ Acid.	Base satn. (%)	ESP (%)	NaOAc CEC meq/100g	CaCO$_3$ (%)	Sample Number
Ap	0-15	14.8	4.0	0.4	.	20.0	0.8	96.	2.0	20.4	.	59
A21 *	15-24	.	.	.	.	.	.	.	.	.	.	60
A22	24-46	21.3	2.9	0.5	.	24.7	.	100.	2.0	5.9	.	61
B21t	46-79	46.3	4.7	0.4	.	51.4	.	100.	0.7	5.4	.	62
B22	79-110	46.3	3.1	0.5	.	49.9	.	100.	1.0	3.9	.	63
B23	110-138	38.5	3.2	0.2	.	41.9	.	100.	0.4	4.8	.	64
C	138-188	38.5	2.4	0.1	.	41.0	.	100.	0.2	4.4	.	65

Comments: * DID NOT SAMPLE, THIN HORIZON.
$BaCl_2$ ACIDITY CALCULATED AS THE DIFFERENCE BETWEEN NAOAc CEC AND CEC SUM.

Table 42. Physical and chemical data for site 11.

Horizon	Depth (cm)	Thick (cm)	Mechanical analysis (%)								Water content (%)					Atterberg Limits		Proctor Test
			sand	silt	clay	vcos	cos	ms	fs	vfs	15bar	.3bar	.1bar	0bar	Avail H_2O	Liq.	Plast.	
Ap	0-28	28	4.0	74.0	22.0	.	.	.	.	.	12.9	39.2	43.6	50.7	26.3			
A3	28-42	14	5.0	80.0	15.0	0.0	0.0	0.0	1.0	4.0	11.6	32.2	36.7	42.7	20.6			
B21	42-64	22	4.0	83.0	13.0	.	.	.	.	.	6.6	31.7	34.2	38.8	25.1			
B22	64-84	20	2.0	76.0	22.0	0.0	0.0	0.0	0.0	2.0	5.4	33.1	36.0	37.9	27.7			
C1ca	84-116	32	1.0	75.0	24.0	.	.	.	.	.	4.3	35.9	37.3	39.2	31.6			
IIC2	116-124	8	0.0	84.0	16.0	.	.	.	.	.	2.8	30.2	31.0	36.9	27.4			
IIIC3	124-160	36	4.0	80.0	16.0	.	.	.	.	.	4.2	27.9	29.1	30.8	23.7			

Horizon	Depth (cm)	Bulk Density (g/cm^3)			Particle density (g/cm^3)	CEC (meq/ 100g)	15bar/ clay ratio	CEC/ clay ratio	Sample Number
		.3bar	OD	COLE					
Ap	0-28	.	1.3	.	.	17.0	0.58	0.77	66
A3	28-42	.	1.2	.	.	11.1	0.77	0.74	67
B21	42-64	.	1.4	.	.	8.7	0.50	0.66	68
B22	64-84	.	1.3	.	.	9.4	0.31	0.55	69
C1ca	84-116	.	1.4	.	.	7.2	0.17	0.30	70
IIC2	116-124	.	1.5	.	.	3.9	0.17	0.24	71
IIIC3	124-160	.	1.7	.	.	3.3	0.26	0.20	72

Comments:

Horizon	Depth (cm)	Thick (cm)	Org. Carbon (%)	Total N (%)	C/N ratio	pH		saturation extract									
						1:1 H_2O	1:2 $CaCl_2$	H_2O (%)	paste pH	EC (mmho/cm)	Ca (meq/l)	Mg (meq/l)	Na (meq/l)	K (meq/l)	HCO_3 (meq/l)	SO_4 (meq/l)	SAR
Ap	0-28	28	5.0	0.18	27.7	6.2	5.9	50.7	6.2	0.3	2.0	0.5	0.3	.	84		0.2
A3	28-42	14	1.5	0.07	21.4	7.5	6.7	42.7	7.3	0.2	2.0	0.7	0.7	.	169		0.6
B21	42-64	22	0.8	0.04	20.0	8.1	7.3	38.8	8.1	0.4	1.6	0.6	2.3	.	211		2.1
B22	64-84	20	0.6	0.04	15.0	8.5	7.7	37.9	8.8	0.5	0.8	0.4	4.6	.	230		5.9
C1ca	84-116	32	0.6	0.02	30.0	9.2	7.9	39.2	9.5	1.0	0.5	0.2	6.7	.	344		11.3
IIC2	116-124	8	0.2	0.01	20.0	9.2	8.1	36.9	9.6	0.8	0.5	0.3	6.1	.	344		9.6
IIIC3	124-160	36	0.1	0.02	5.0	8.9	8.0	30.8	9.3	0.7	0.5	0.4	6.4	.	223		9.5

Horizon	Depth (cm)	NH_4OAc extract (meq/100g)					$BaCl_2$ Acid. (meq/100g)	Base satn. (%)	ESP (%)	NaOAc CEC meq/100g	$CaCO_3$ (%)	Sample Number
		Ca	Mg	Na	K	CEC-sum						
Ap	0-28	13.0	1.6	0.1	.	17.0	2.3	86.	0.5	17.0	.	66
A3	28-42	9.6	1.8	0.1	.	11.5	.	100.	20.0	11.1	.	67
B21	42-64	8.4	1.7	0.3	.	10.4	.	100.	2.8	8.7	.	68
B22	64-84	10.2	2.2	1.0	.	13.4	.	100.	7.4	9.4	.	69
C1ca	84-116	42.4	2.3	2.3	.	47.0	.	100.	4.8	7.2	.	70
IIC2	116-124	34.5	1.6	1.3	.	37.4	.	100.	3.4	3.9	.	71
IIIC3	124-160	36.5	2.1	1.1	.	39.7	.	100.	2.7	3.3	.	72

Comments: $BaCl_2$ ACIDITY CALCULATED AS THE DIFFERENCE BETWEEN NAOAc CEC AND CEC SUM.

Table 43. Physical and chemical data for site 12.

Horizon	Depth (cm)	Thick (cm)	Mechanical analysis sand (%)	silt	clay	vcos	cos	ms	fs	vfs	Water content 15bar (%)	.3bar	.1bar	0bar	Avail H_2O	Atterberg Limits Liq.	Plast.	Proctor Test
Ap	0-22	22	91.0	0.0	9.0	.	.	.	.	.	18.8	33.6	40.2	48.6	14.8			
A2	22-39	17	12.0	79.0	9.0	.	.	.	.	.	5.2	22.9	25.6	30.4	17.7			
B2t	39-51	12	6.0	46.0	48.0	0.0	0.0	1.0	1.0	4.0	16.4	30.6	34.5	60.0	14.2			
C1ca *	51-64	13	.	.	.	.	.	.	.	.	.	.	.	.	.			
C2 *	64-101	37	2.0	38.0	60.0	.	.	.	.	.	17.8	32.3	34.8	68.1	14.5			
C3	101-140	39	10.0	68.0	22.0	.	.	.	.	.	14.0	28.9	30.8	63.0	14.9			
C4	140-193	53	12.0	65.0	23.0	.	.	.	.	.	7.7	26.3	27.8	53.8	18.6			

Horizon	Depth (cm)	Bulk Density .3bar (g/cm^3)	OD	COLE	Particle density (g/cm^3)	CEC (meq/100g)	15bar/clay ratio	CEC/clay ratio	Sample Number
Ap	0-22	.	1.5	.	.	14.8	2.08	1.64	73
A2	22-39	.	1.7	.	.	4.8	0.57	0.53	74
B2t	39-51	.	1.8	.	.	25.2	0.37	0.57	75
C1ca *	51-64	.	.	.	.	.	.	.	76
C2 *	64-101	.	1.8	.	.	32.2	0.29	0.53	77
C3	101-140	.	1.8	.	.	9.1	0.63	0.41	78
C4	140-193	.	1.8	.	.	11.7	0.33	0.50	79

Comments: * SAMPLED AS ONE HORIZON

Horizon	Depth (cm)	Thick (cm)	Org. Carbon (%)	Total N (%)	C/N ratio	pH 1:1 H_2O	pH 1:2 $CaCl_2$	saturation extract H_2O (%)	paste pH	EC (mmho/cm)	Ca (meq/l)	Mg	Na	K	HCO_3	SO_4	SAR
Ap	0-22	22	5.3	0.19	27.8	5.8	5.0	48.6	5.8	0.3	2.1	1.5	0.8	.	60		0.5
A2	22-39	17	1.5	0.06	25.0	7.3	6.5	30.4	7.3	0.8	1.2	2.1	15.7	.	248		12.2
B2t	39-51	12	1.7	0.05	34.0	8.3	7.8	60.0	8.6	3.4	1.9	9.5	35.7	.	223		14.9
C1ca*	51-64	13	.	.	.	.	.	.	.	.	.	.	.	.			0.0
C2ca*	64-101	37	1.1	0.02	55.0	8.6	8.1	68.1	8.8	3.2	1.6	7.9	31.3	.	133		14.3
C3	101-140	39	0.6	0.07	8.5	8.5	8.1	63.0	9.0	2.8	2.0	9.9	35.7	.	151		14.6
C4	140-193	53	0.6	0.07	8.5	8.6	8.1	53.8	9.0	3.1	2.0	8.6	32.2	.	127		13.9

Horizon	Depth (cm)	NH_4OAc extract Ca (meq/100g)	Mg	Na	K	CEC-sum	$BaCl_2$ Acid.	Base satn. (%)	ESP (%)	NaOAc CEC meq/100g	$CaCO_3$ (%)	Sample Number
Ap	0-22	8.4	2.3	3.4	.	14.8	0.7	95.	22.9	14.8	.	73
A2	22-39	2.9	2.5	1.4	.	6.8	.	100.	.	4.8	.	74
B2t	39-51	30.5	9.3	5.0	.	44.8	.	100.	11.1	25.2	.	75
C1ca*	51-64	.	.	.	.	.	.	.	.	.	.	76
C2ca*	64-101	40.5	9.6	5.7	.	55.8	.	100.	10.2	32.2	.	77
C3	101-140	@.	@.	@.	.	.	.	.	.	9.1	.	78
C4	140-193	36.5	4.5	3.2	.	44.2	.	100.	7.2	11.7	.	79

Comments: * SAMPLED AND DESCRIBED AS ONE HORIZON. @ = NO ANALYSIS PERFORMED
$BaCl_2$ ACIDITY CALCULATED AS THE DIFFERENCE BETWEEN NAOAc CEC AND CEC SUM.

Table 44. Physical and chemical data for site 13.

Horizon	Depth (cm)	Thick (cm)	Mechanical analysis sand	silt	clay	vcos	cos	ms	fs	vfs	Water content 15bar	.3bar	.1bar	0bar	Avail H_2O	Atterberg Limits Liq.	Plast.	Proctor Test
			----	----	(%)	----	----	----	----	----	----	----	(%)	----	----			
Ap	0-19	19	52.0	48.0	0.0	0.1	.	.	.	.	5.2	8.8	16.2	38.7	3.6			
B2	19-38	19	52.0	48.0	0.0	.	.	.	.	.	4.0	7.2	10.1	33.8	3.2			
C1	38-61	23	72.0	26.0	2.0	0.0	0.0	0.0	8.0	64.0	3.0	5.3	9.6	35.1	2.3			
C2	61-104	43	56.0	39.0	5.0	.	.	.	.	.	2.4	4.0	9.5	33.8	1.6			
C3	104-170	66	68.0	27.0	5.0	.	.	.	.	.	1.5	4.1	7.8	36.4	2.6			
	-		.	.	.	.	.	.	.	.	.	.	.	.	.			
	-		.	.	.	.	.	.	.	.	.	.	.	.	.			

Horizon	Depth (cm)	Bulk Density .3bar	OD	COLE	Particle density (g/cm^3)	CEC (meq/100g)	15bar/clay ratio	CEC/clay ratio	Sample Number
		---	(g/cm^3)	---					
Ap	0-19	.	1.5	.	.	7.2	.	.	80
B2	19-38	.	1.5	.	.	5.4	.	.	81
C1	38-61	.	1.5	.	.	4.6	0.75	1.15	82
C2	61-104	.	1.4	.	.	3.3	0.48	0.66	83
C3	104-170	.	1.5	.	.	2.0	0.30	0.40	84
	-	.	.	.	.	.	.	.	
	-	.	.	.	.	.	.	.	

Comments:

Horizon	Depth (cm)	Thick (cm)	Org. Carbon (%)	Total N (%)	C/N ratio	pH 1:1 H_2O	pH 1:2 $CaCl_2$	saturation extract H_2O (%)	paste pH	EC (mmho/cm)	Ca	Mg	Na	K	HCO_3	SO_4	SAR
											----	----	(meq/l)	----	----		
Ap	0-19	19	2.1	0.09	23.3	6.8	6.0	38.7	6.8	0.3	1.4	0.5	0.3	.	151		0.3
B2	19-38	19	0.8	0.05	16.0	6.6	5.7	33.8	6.7	0.2	0.9	0.3	0.3	.	91		0.3
C1	38-61	23	0.3	0.03	10.0	7.5	6.5	35.1	7.4	0.2	1.6	0.5	0.6	.	374		0.5
C2	61-104	43	0.1	0.01	10.0	7.9	7.2	33.8	8.1	0.2	1.8	0.5	0.5	.	175		0.4
C3	104-170	66	0.1	0.01	10.0	8.3	7.5	36.4	8.8	0.2	2.4	0.3	0.4	.	332		0.3
	-		.	.	.	.	.	.	.	.	.	.	.	.			0.0
	-		.	.	.	.	.	.	.	.	.	.	.	.			0.0

Horizon	Depth (cm)	NH_4OAc extract Ca	Mg	Na	K	CEC-sum	$BaCl_2$ Acid.	Base satn. (%)	ESP (%)	NaOAc CEC meq/100g	$CaCO_3$ (%)	Sample Number
		----	----	(meq/100g)	----	----	----					
Ap	0-19	4.4	0.8	0.1	.	7.2	1.9	73.	1.3	7.2	.	80
B2	19-38	3.5	0.5	0.0	.	5.4	1.4	74.	11.1	5.4	.	81
C1	38-61	3.5	0.5	0.1	.	4.5	0.4	91.	2.2	4.5	.	82
C2	61-104	7.2	0.5	0.1	.	7.8	.	100.	1.2	3.3	.	83
C3	104-170	34.5	0.7	0.1	.	35.3	.	100.	0.2	2.0	.	84
	-	.	.	.	.	.	.	.	.	.	.	
	-	.	.	.	.	.	.	.	.	.	.	

Comments: $BaCl_2$ ACIDITY CALCULATED AS THE DIFFERENCE BETWEEN NAOAc CEC AND CEC SUM.

APPENDIX 4

KEY TO CODES USED IN THE PEDFORM SYSTEM

Table 45. Index for county codes in the PEDFORM system.

Code	County	Code	County	Code	County
01	Silver Bow	19	Chouteau	37	Daniels
02	Cascade	20	Valley	38	Glacier
03	Yellowstone	21	Toole	39	Fallon
04	Missoula	22	Big Horn	40	Sweet Grass
05	Lewis & Clark	23	Musselshell	41	McCone
06	Gallatin	24	Blaine	42	Carter
07	Flathead	25	Madison	43	Broadwater
08	Fergus	26	Pondera	44	Wheatland
09	Powder River	27	Richland	45	Prairie
10	Carbon	28	Powell	46	Granite
11	Phillips	29	Rosebud	47	Meagher
12	Hill	30	Deer Lodge	48	Liberty
13	Ravalli	31	Teton	49	Park
14	Custer	32	Stillwater	50	Garfield
15	Lake	33	Treasure	51	Jefferson
16	Dawson	34	Sheridan	52	Wibaux
17	Roosevelt	35	Sanders	53	Golden Valley
18	Beaverhead	36	Judith Basin	54	Mineral
				55	Petroleum
				56	Lincoln

Table 46. Index for parent material, vegetation, and land use codes in the PEDFORM system.

Code	Parent Material	Code	Vegetation	Code	Land Use
01	volcanic ash	01	mixed coniferous	01	commercial forest
02	loess	02	ponderosa pine	02	non-commercial "
03	glacial outwash	03	lodgepole pine	03	forest
04	glacial till	04	spruce-fir	04	range
05	lacustrine	05	larch-fir	05	dryland crop
06	peat	06	Douglas-fir	06	irrigated crop
07	muck	07	mixed deciduous	07	irrigated hay
08	residual sandst.	08	cottonwood	08	dryland hay
09	residual shale	09	aspen	09	pasture
10	residual siltst.	10	trees	10	residential
11	residual limest.	11	dryland crop	11	urban
12	resid. crystalline	12	irrig. field crop	12	disturbed land
13	mixed alluvium	13	row crops	13	strip mine
14	alluvial	14	horticultural crop	14	mill tailings
15	colluvial	15	riparian	15	mine dump
16	soliflucate	16	mixed shortgrass	16	wildland
17	sandst. alluvium	17	mixed midgrass	17	landfill
18	shale alluvium	18	shrubs & grasses		
19	siltst. alluvium	19	halophytic		
20	crystalline alluv.	20	sedges & rushes		
21	limestone alluv.	21	perennial forage		
		22	tame pasture		

Table 47. Index codes for drainage, permeability, erosion, landscape position, and landform type in the PEDFORM system.

Code	Drainage	Code	Permeability	Code	Erosion
01	very poor	01	very slow	01	none
02	poor	02	slow	02	slight
03	poor to moderate	03	slow to medium	03	moderate
04	moderate	04	medium	04	severe
05	well	05	medium to rapid	05	slight-wind
06	well to excessive	06	rapid	06	moderate-wind
07	excessive	07	very rapid	07	severe-wind
08	'altered, drained'				
09	'altered, wetted'				

Table 48. Index for landscape position and landform codes in the PEDFORM SYSTEM.

Code	Landscape Position	Code	Landform
01	crest	01	sedimentary upland
02	ridge	02	mountains
03	upper midslope	03	playa
04	midslope	04	alluvial fan
05	lower midslope	05	sand dune
06	footslope	06	glacial outwash
07	level slope	07	ground moraine
		08	alpine till
		09	terrace
		10	floodplain
		11	plateau
		12	solifluction lobe
		13	patterned ground
		14	backswamp
		15	landslide
		16	badlands
		17	disturbed land
		18	talus

Table 49. Index for effervescence in HCl, and horizon boundary in the PEDFORM system.

Code	Effervescence	Lower Horizon Boundary			
		Code	Distinctness	Code	Shape
01	noncalcareous	01	abrupt <1in.)	01	smooth
02	slight	02	clear (1-2.5in.)	02	wavy
03	moderate	03	gradual (2.5-5in.)	03	irregular
04	violent	04	diffuse (>5in.)	04	broken
		05	arbitrary	05	arbitrary
		06	not reached	06	not reached

Table 50. Index for soil consistence in the PEDFORM system.

Code	Dry consistence	Code	Moist consistence
01	loose	01	loose
02	soft: easily crushes to powder	02	very friable: crushes under gentle pressure
03	slightly hard: easily broken between thumb and finger	03	friable: crushes easily under moderate pressure between thumb and finger
04	hard: easily broken in hand	04	firm: crushes under moderate pressure between thumb and finger
05	very hard: broken in hands with difficulty	05	very firm: barely crushable between thumb and finger
06	extremely hard: cannot be broken in hands	06	extremely firm: crushes under strong pressure in hand
07	indurated	07	indurated

Code	Wet stickiness	Code	Wet plasticity
01	nonsticky: no adherence	01	nonplastic: no wire formed
02	slightly sticky: adheres to thumb and finger but comes off one cleanly	02	slightly plastic: wire forms but easily deformed
03	sticky: soil adheres and stretches before pulling apart	03	plastic: wire forms, moderate pressure required to deform
04	very sticky: soil adheres to both fingers	04	very plastic: wire forms, much pressure required to deform

Table 51. Index for structure grade, size, and kind used in the PEDFORM system.

Code	Structure grade	Code	Structure kind
01	massive	01	massive
02	weak: peds barely observable in place; peds undefinable when disturbed	02	platy
03	weak to moderate	03	granular
04	moderate: peds easily observable; when disturbed most of material consists of peds.	04	subangular blocky
05	moderate to strong	05	angular blocky
06	strong: peds distinctly visible; when disturbed entire soil mass is aggregated	06	prismatic
		07	columnar
		08	wedge

Code	Size Class	Diameter of granules	Thickness of plates	Diameter of blocks	Diameter of prisms
		(mm)			
01	very fine	<1	<1	<5	<10
02	fine	1-2	1-2	5-10	10-20
03	medium	2-5	2-5	10-20	20-50
04	coarse	5-10	5-10	20-50	50-100
05	very coarse	>10	>10	>50	>100

Table 52. Index for pore size and kind in the PEDFORM system.

Code	Size	Code	Kind
01	none	01	none
02	micro and very fine	02	irregular and tubular
03	very fine (.1-.5mm)	03	tubular
04	fine and very fine	04	tubular continuous
05	fine (.5-2mm)	05	tubular discontinuous
06	medium and fine	06	vesicular
07	medium (2-5mm)	07	vesicular and tubular
08	coarse and medium	08	interstitial voids between peds
09	coarse (>5mm)	09	interstitial voids between rocks

Table 53. Index for root abundance, size, and location in the PEDFORM system.

Code	Size	Code	Location
01	none	01	none
02	very fine (0.1-1mm)	02	throughout horizon
03	fine and very fine	03	between peds
04	fine (1-2mm)	04	flattened in cracks
05	medium and fine	05	flattened around rocks
06	medium (2-5mm)	06	mat at top of horizon
07	coarse and medium		
08	coarse (>5mm)		
09	fine and coarse		

Code	Abundance CLASS	Very fine	Fine	Medium	Coarse
		(NUMBER/DM**2)			
01	none				
02	trace				
03	few	<10	<10	<1	<1
04	few to common				
05	common	10-100	10-100	1-10	1-5
06	common to many				
07	many	>100	>100	>10	>5