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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APPROVAL

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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.

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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 <u>in situ</u> 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.

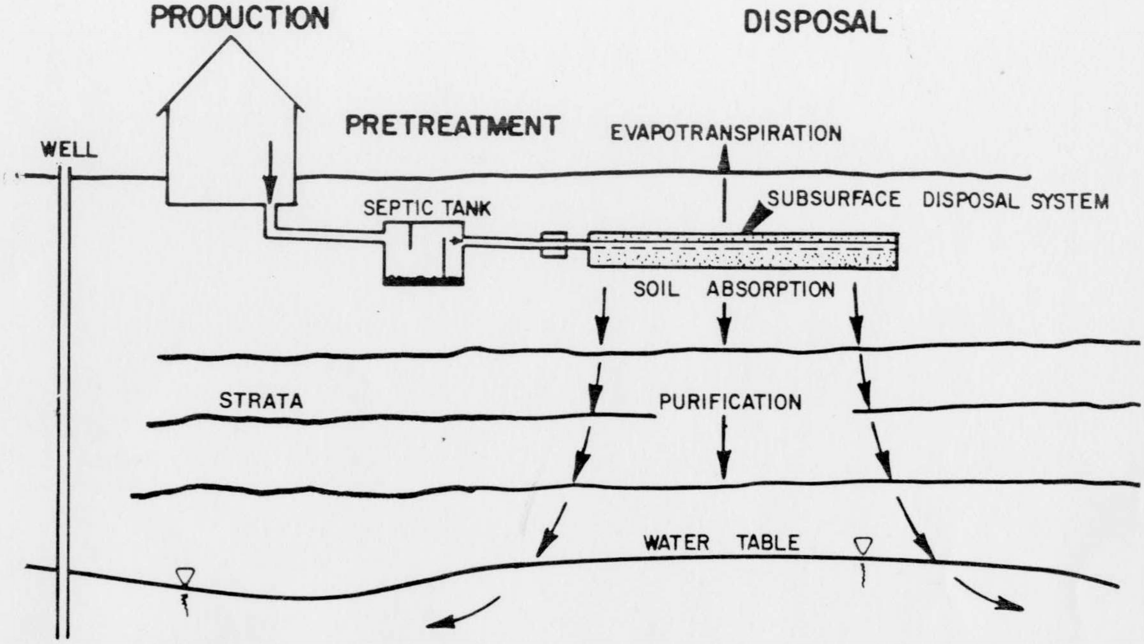


Figure 1. Soil treatment of wastewater by a typical septic system. (after U.S. Environmental Protection Agency, 1978).

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.

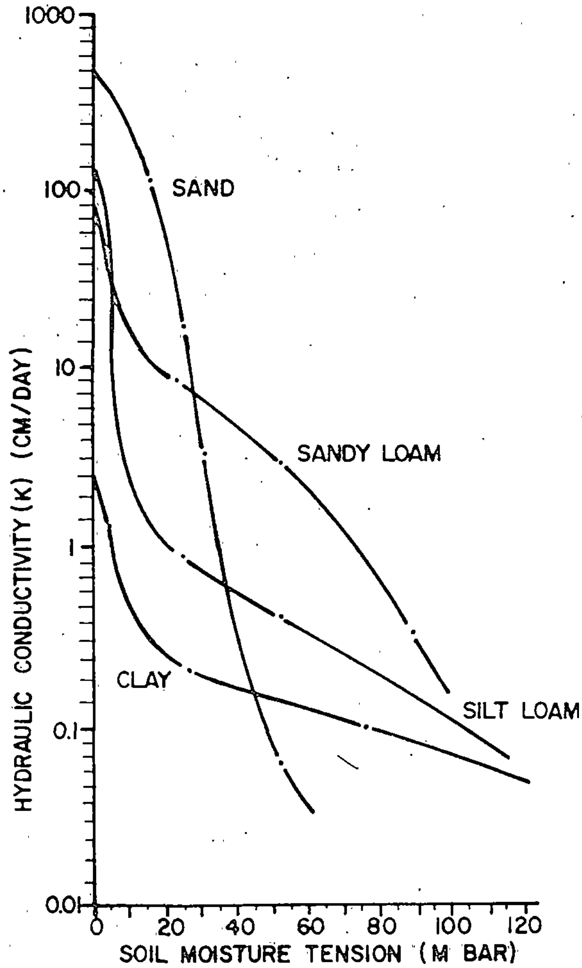


Figure 2. Relationship between hydraulic conductivity and soil matric tension for several soil textures (Bouma, 1975).

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

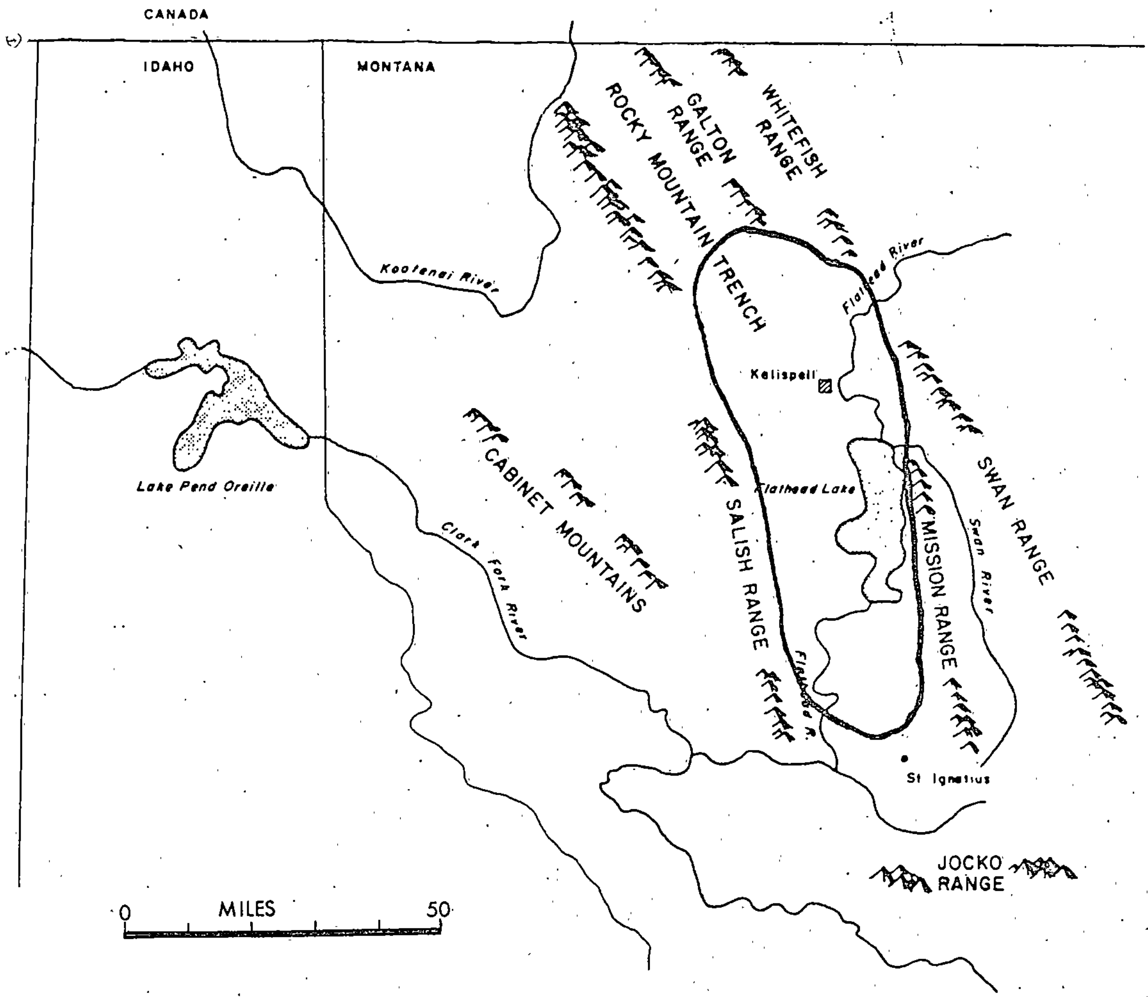


Figure 3. Map of northwestern Montana with the study area outlined (after Stoffel, 1980).

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.

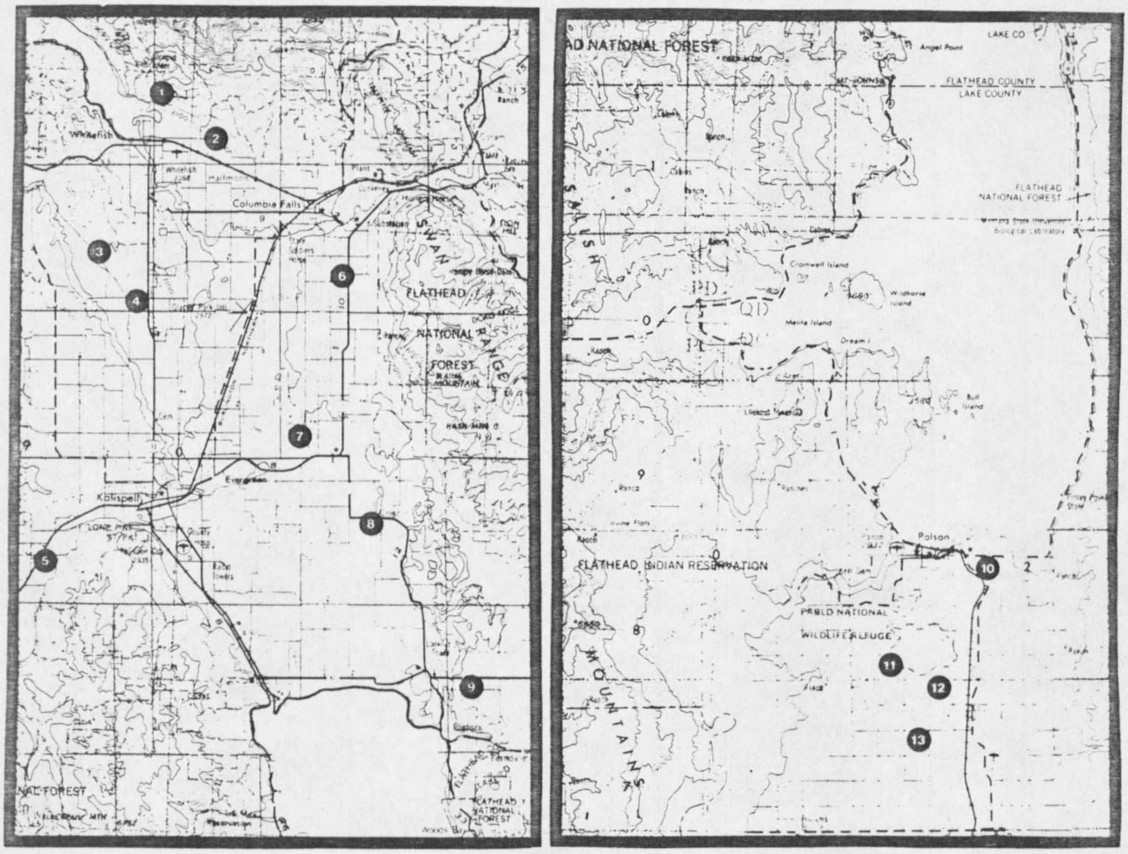
METHODS AND PROCEDURES

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

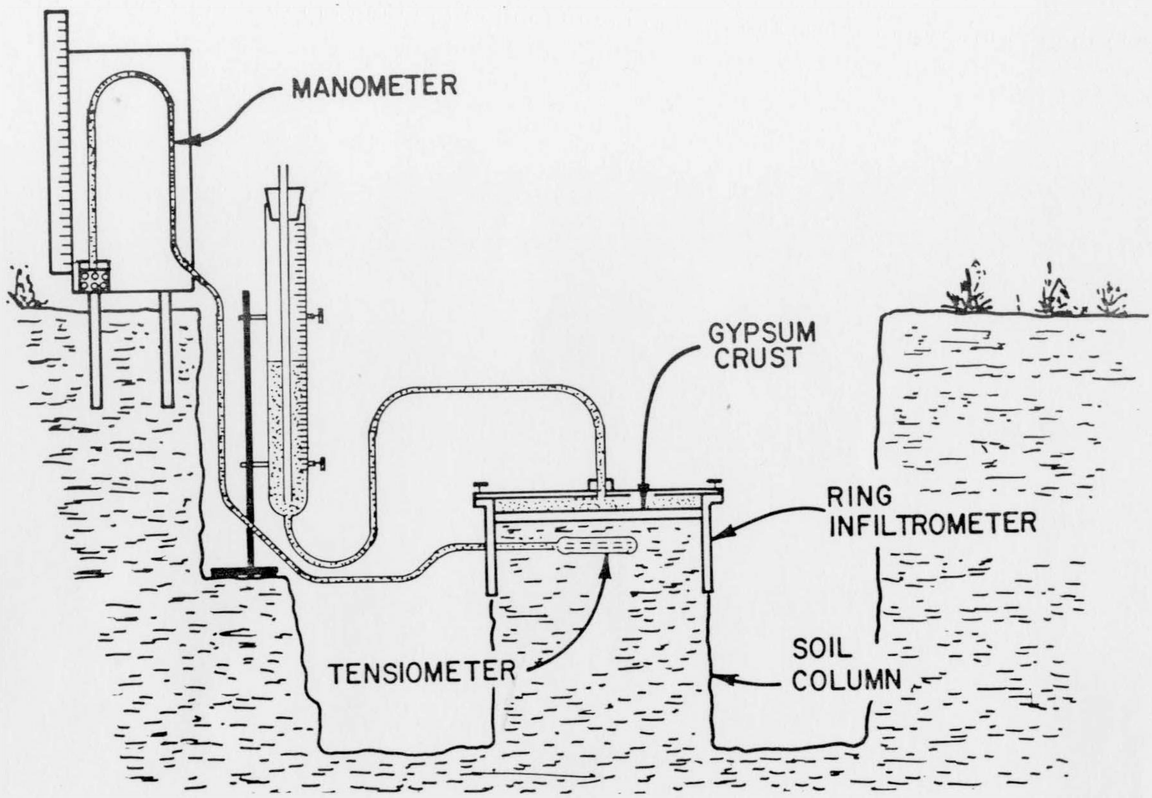


Figure 5. Schematic cross-section of the field set-up for the crust test.

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

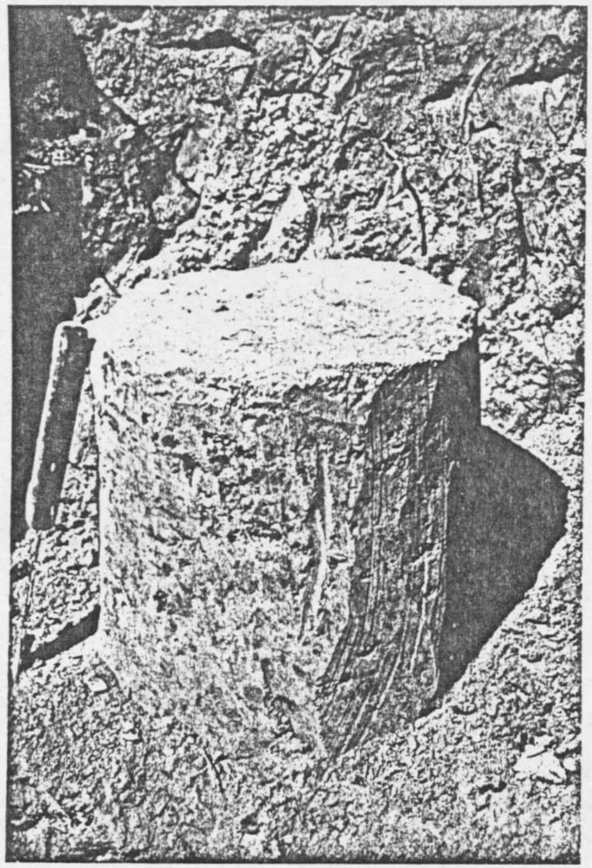


Figure 6. Soil column prepared for the crust test procedure.

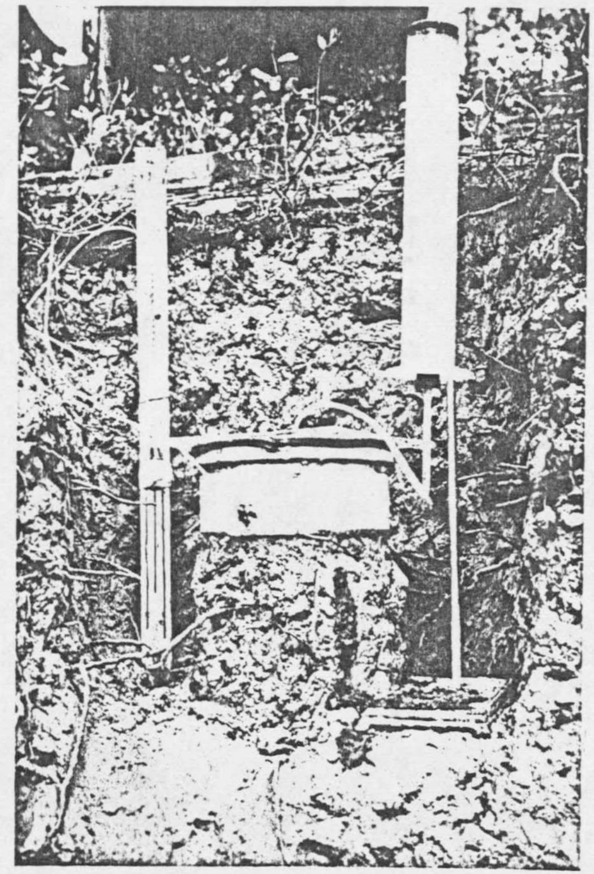


Figure 7. Field set-up of the crust test instrumentation

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

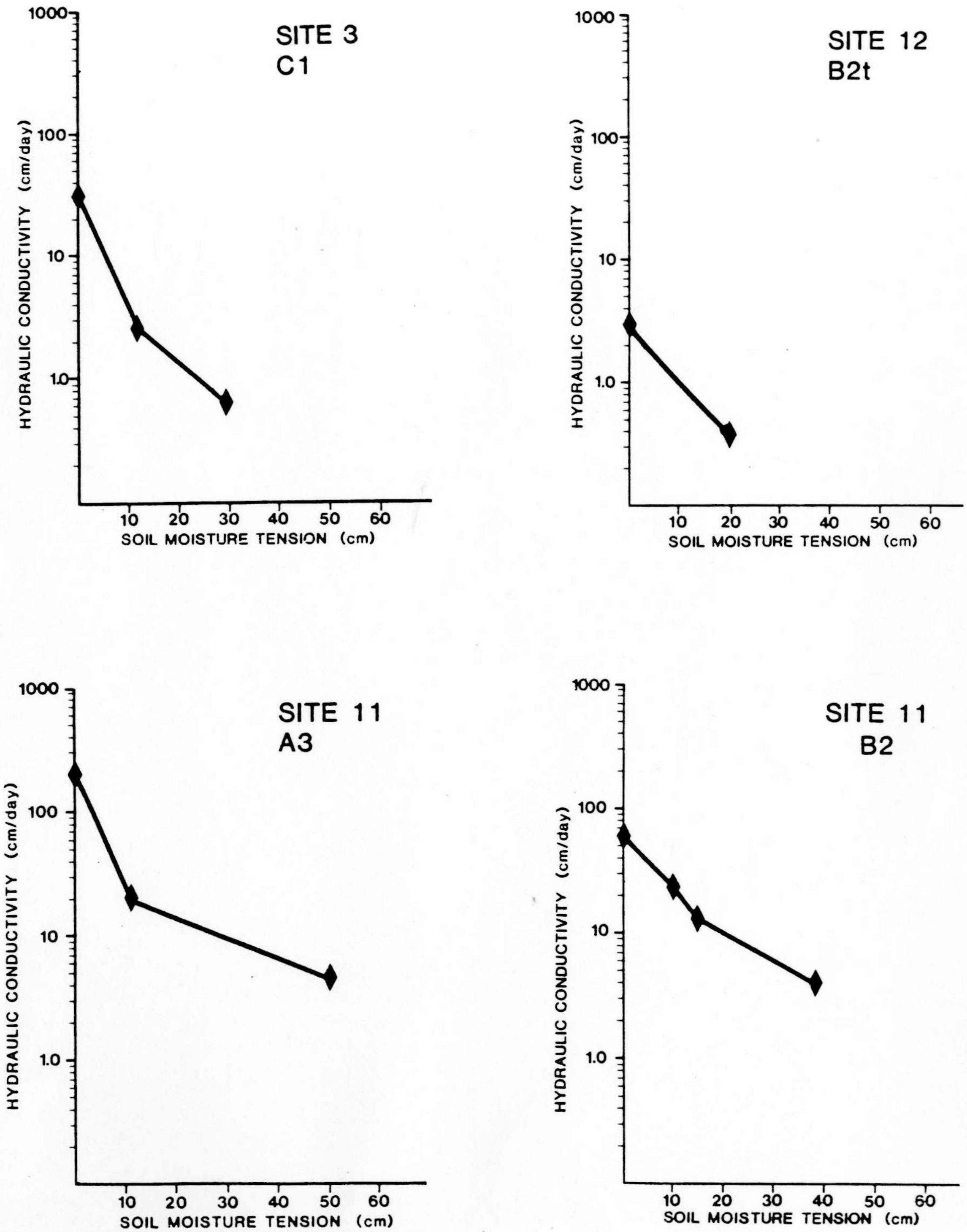


Figure 8. Hydraulic conductivity curves for soil horizons formed in lacustrine materials.