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SOIL GENESIS IN RELATION TO GROUNDWATER AND SOIL MOISTURE REGIMES NEAR VEGREVILLE, ALBERTA

by

ADRIAN HENRY MACLEAN, B.Sc.(Hons.), M.S.A.

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

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EDMONTON, ALBERTA

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "Soil genesis in relation to groundwater and soil moisture regimes near Vegreville, Alberta." submitted by Adrian Henry MacLean in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

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ABSTRACT

The study was designed to obtain information on groundwater flow, and moisture above the water table, at selected sites in the Vegreville area and to relate this information to features of soil genesis revealed by detailed soil mapping and analysis.

It was concluded that while deep groundwater flow is predominantly downward throughout the study area, numerous shallow flow systems are superimposed on this flow which in part owe their complexity to permeability contrasts within both bedrock and surficial materials. Under these conditions, tensiometers were particularly useful, in combination with piezometers, in providing information on flow close to the water table at individua sites. At high elevation where groundwater recharge predominates, soils ranged from Eluviated Black Chernozem through Humic Eluviated Gleysol to Orthic Humic Gleysol with decreasing depth to the water table. At low elevations where groundwater discharge occurs, gypsum and salt accumulation zones existed above the water table in all soils studied. Soils ranged from Alkaline Solonetz or Saline Black Solonetz where the water table was within 0.5 m of the surface through Black Solonetz where depth to the water table was between 0.5 and 3.0 m, while an Orthic Black Chernozem occurred where the water table was around 2.5 m below the surface and the ratio of sodium to divalent cations in the discharging groundwater was less than at other sites.

Groundwater is undoubtedly a contributing factor in soil

genesis in the Vegreville area, but effects of other factors, such as lateral flow above the water table in the more permeable surface horizons and rooting depths cannot be ignored.

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INTRODUCTION

INTRODUCTION

Theories concerning relationships between soils and groundwater flow have existed for some time, but relatively few studies have been made to confirm them (Pawluk et al. 1969). An area of 100 square kilometres (38.5 sq. miles) was chosen by Dr. J. Toth of the Alberta Research Council and Dr. S. Pawluk of the University of Alberta for the purpose of investigating groundwater in relation to the genesis of Solonetzic soils. Proximity to the Agriculture Canada Research Station, presence of salinity and solonetzic soils and a physiography fairly typical of the region as a whole, were among reasons for location of the area to the northeast of Vegreville. Leskiw (1971) related soils within the chosen area to the apparent groundwater flow as indicated by surface features, such as vegetation, seepages, salt crusts, and moist depressions (sloughs), and also by analyses from existing wells. Deep piezometers were installed by the Water Resources Division of the Department of Environment, but full information from these could not be obtained before completion of Leskiw's study. The present study was designed to obtain detailed information of groundwater flow at a few selected sites within the same area, using piezometers. Information was also to be obtained on moisture regimes above the water table using a neutron probe, tensiometers and psychrometers, and on ground temperatures using buried thermocouples. This information was to be related to the soil characteristics around each site revealed by detailed soil mapping and by physical and chemical analyses, so as to evaluate the influence of groundwater flow upon soil genesis.

LITERATURE REVIEW

LITERATURE REVIEW

I - GROUNDWATER FLOW

Several different approaches have been used in studies of groundwater flow. The first of these, the mathematical or theoretical approach, is based on dependance of groundwater flow on well-defined physical laws. A second approach, piezometric analysis, involves actual measurement of potentials in the field, ~~from which flow directions can be derived. A third approach uses~~ surface features as indicators of groundwater characteristics. A fourth approach is the hydrogeochemical approach which makes use of the chemical composition of groundwater in the interpretation of groundwater flow patterns. A fifth and final approach involves use of stream hydrographs to calculate groundwater discharge but since this is useful mainly in humid areas where a high proportion of the discharge reaches the stream, and even then only on a regional scale, it will not be considered here. The first four approaches are however discussed in detail below.

Mathematical or theoretical approach

Hubbert (1940) developed the concept of fluid potential as analogous to electrical potential. He defined it as: the amount of work that would be required to transport a unit mass of fluid from some arbitrary chosen standard position and state to the position and state considered. Fluid potential includes a component from work against gravity and a component from work against pressure and can be expressed in the form:

$$\phi = \int_{Po}^{P} \frac{dP}{\rho} + gZ$$

P is pressure exerted by a column of water; Po is atmospheric pressure; ρ is fluid density; g is acceleration of gravity; Z is the height above datum of the potential in question.

Tóth (1962), 1963) applied the work of Hubbert to an idealized case of the small drainange basin in the Prairie environment. Such a basin, he defined as: 'An area bounded by topographic highs, its lowest parts being occupied by an impounded body of surface water or by the outlet of a relatively low order stream, and having similar physiographic conditions over the whole of its surface'. He suggested that such a basin would not exceed an area of several hundred square miles. He showed that in such basins, river valleys are not cut into the landscape sufficiently to act as line sinks, and therefore groundwater discharge occurs throughout the lower half of the basin and is separated from groundwater recharge on the upper slopes by a theoretical midline. Tóth showed that topographic irregularities within such a basin produced their own groundwater flow systems which were superimposed on the main (regional) flow system of the basin. For convenience, he classified the flow systems as Regional, Intermediate and Local (Figure 1), though there is no theoretical upper limit to the number of flow systems possible.

Mathematical solutions to groundwater flow problems involve application of the steady-state form of Richards equation (Richards 1931) to find the fluid potential at various points within a theoretical model of a basin. The equation is valid for

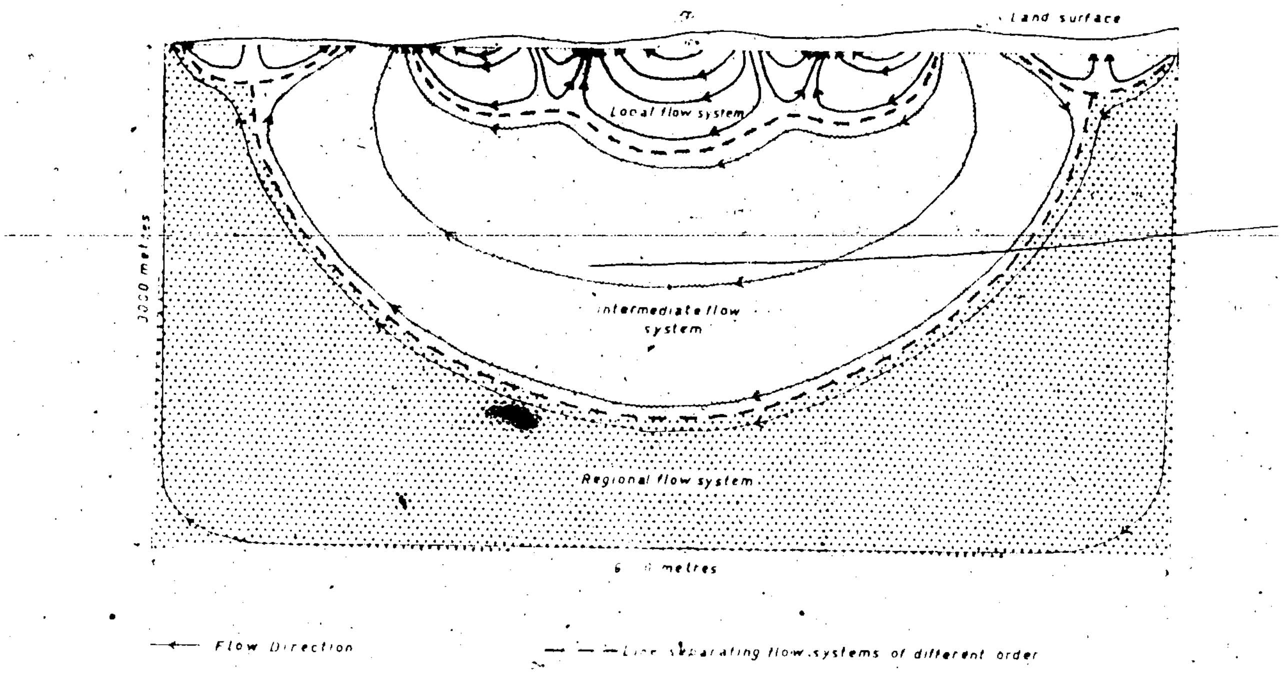


Figure 1. Vertical cross-section showing Local, Intermediate and Regional flow systems in a theoretical small drainage basin (After Tóth, 1962).

isotropic media, and for anisotropic media where the principle directions of anisotropy coincide with the co-ordinate axes (Childs 1957). It can be written in the form:

$$\frac{\partial}{\partial x}\left[K x \frac{\partial \phi}{\partial x}\right]+\frac{\partial}{\partial y}\left[K y \frac{\partial \phi}{\partial y}\right]+\frac{\partial}{\partial z}\left[K z \frac{\partial \phi}{\partial z}\right]=-\frac{\partial \theta}{\partial t}=0$$

x, y and z are the co-ordinate axes; Kx, Ky, Kz are hydraulic conductivities in the x, y and z direction respectively; ϕ is potential; θ is volumetric moisture content; t is time.

Even with simplified flow systems and boundary conditions, mathematical solutions using this equation were impractical prior to the development of modern computers. Instead, two dimensional laboratory water-flow models or electric analogues were used, and these are still considered useful for solving groundwater flow problems. Freeze and Witherspoon (1966) have however succeeded in using computers to solve both two and three dimensional flow problems, even where several materials of contrasting permeability, and anisotropy have been included. The programs involve solution of an extremely large set of simultaneous equations by an iterative procedure, for every point within the basin for which the fluid potential is required. Although of considerable value, such mathematical solutions are all dependant on simplification of the natural situation, and can never be a complete substitute for field measurements.

Piezometric analysis

Fluid potential can be expressed as total head, which at a given point is the height of a column of water that can be supported at that point (pressure component) plus the height of that point above standard datum (elevation component). It follows that the water level in a tightly cased well (or piezometer) expressed as height above sea level, is a direct measure of groundwater potential within the flow system, at the point where the well or piezometer terminates. Normally several piezometers are installed at a single site, constituting a nest, as this allows vertical hydraulic gradients to be measured. Nests are usually situated in a line at right angles to a river, because flow parallel to the river is normally small compared to flow towards the river, and can be neglected in the construction of equipotential lines in a simplified two dimensional diagram. If the assumption can be made that the geology is homogeneous and isotropic, then flow lines simply intersect equipotential lines at right angles. However, in non-homogeneous materials, refraction of equipotential lines and flow lines occurs at the lithological contacts according to the tangent law of refraction (Hubbert 1940):

$$\frac{\text{Tan } \theta_1}{\text{Tan } \theta_2} = \frac{K_1}{K_2}$$

K_1 and K_2 are the hydraulic conductivities of the materials and θ is the angle between the equipotential line and the lithological boundary or in the case of a flowline, the angle between the flowline and the normal to the boundary.

Provided the degree of anisotropy can be estimated, and it is usually very pronounced in sedimentary materials, then angles of intersection of flowlines with equipotential lines can be calculated for a diagram with no vertical exaggeration as described by Maasland (1957) and Liakopoulos (1965). Where vertical exaggeration is desired, its effects on angles of intersection must also be taken into account (Van Everdingen 1963).

Unfortunately, water movement into and out of a well or piezometer results in a time lag in registering changes in fluid potential, which can be significant in poorly permeable materials. The lag may be minimized by reducing the diameter of the upper piezometer pipe stem. Usually however, corrections are made for time lag using the method of Hvorslev (1951). Piezometer time lags may at the same time be used to estimate hydraulic conductivities which in combination with hydraulic gradients provide an estimate of rates of flow, using Darcy's law. The procedures are explained in greater detail under 'analytical methods'.

Surface features

Surface features have been shown to be reliable indicators of groundwater conditions. Tóth (1966) presented the following classification of such features observed in the Trochu area of Alberta:

1. Features pertaining to environment:
    a) Climate, b) Relief, c) Geology.
2. Features pertaining to water:
    a) Aspects of the actual presence or absence of water and its physical and chemical properties.
    Examples: springs, seepages, groundwater levels, flowing wells, and chemical and physical properties of the water.

b) Aspects associated with presence or absence of water and with its chemical and physical properties. Examples: natural vegetation, salt precipitates, "burnt crops", "soap holes", moist depressions, dry depressions, and man-made objects.

Meyboom (1966, 1967a) emphasized the importance of vegetation as an indicator of groundwater conditions in south-central Saskatchewan. Willow-ringed sloughs for example indicated the presence of non-saline groundwater and while local discharge occurred into them in late spring and summer, they acted as a source of regional recharge during the period when the willow (*Salix* spp.) was dormant. Meyboom (1967a) listed various other shrubs besides willow which were found to be phreatophytic, that is capable of utilizing groundwater, and some of these could facilitate discharge from depths up to two metres. Halophytes, particularly Western sea-blite (*Suaeda depressa* (Pursh) S. Wats), Red Samphire (*Salicornia rubra*, A. Nesl) and Salt grass (*Distichlis stricta* (Torr.) Rydb) together with an absence of willows around sloughs indicated saline groundwater discharge.

Lissey (1968) used plant communities as indicators of groundwater quality in his classification of sloughs in the Oak River basin in S.W. Manitoba. The presence or absence of the following plant zones were considered diagnostic: 1) permanent open water zone, 2) intermittent saline zone, 3) deep marsh zone, 4) shallow marsh zone, 5) wet meadow zone, and 6) low prairie zone. Sloughs were classified into: 1) fast recharge, 2) slow recharge, 3) fast fresh discharge, 4) slow fresh discharge, 5) fast saline discharge, and 6) slow saline discharge. Piezometers however indicated that many of the fresh water discharge sloughs were really transitional between recharge and discharge.

Leskiw (1971) used the surface features employed by Tóth, Meyboom, and Lissey, in his mapping of groundwater in the Vegreville study area (Figure 2). He classified sloughs into four categories: fast recharge, slow recharge, discharge, and indefinite. The area as a whole was separated into five groundwater categories: i) recharge, ii) discharge, iii) indefinite, iv) discharge with island recharge, and v) recharge with island discharge.

Hydrogeochemistry

Schoeller (1959) noted three forms of zonation which are reflected in the chemical composition of groundwater: 1) geological zonation, 2) climatic zonation, and 3) vertical zonation.

Geological zonation is the most obvious. Chemical composition is controlled by minerals present and their solubility and tendency for chemical reactions. Amount of solution or reaction is influenced by time of contact between water and formation, which in turn is influenced by permeability, hydraulic gradient and length of flow path. It has been noted (Chebotarev 1955, Schoeller 1959) that as the flow path increases there is an increase in the amount of dissolved solids and a tendency for the dominant cation to change from Ca^{++} to Mg^{++} to Na^{+} and for the dominant anion to change from HCO_3^{-} to SO_4^{--} to Cl^{-}. The changes are mainly brought about as a result of exchange reactions which

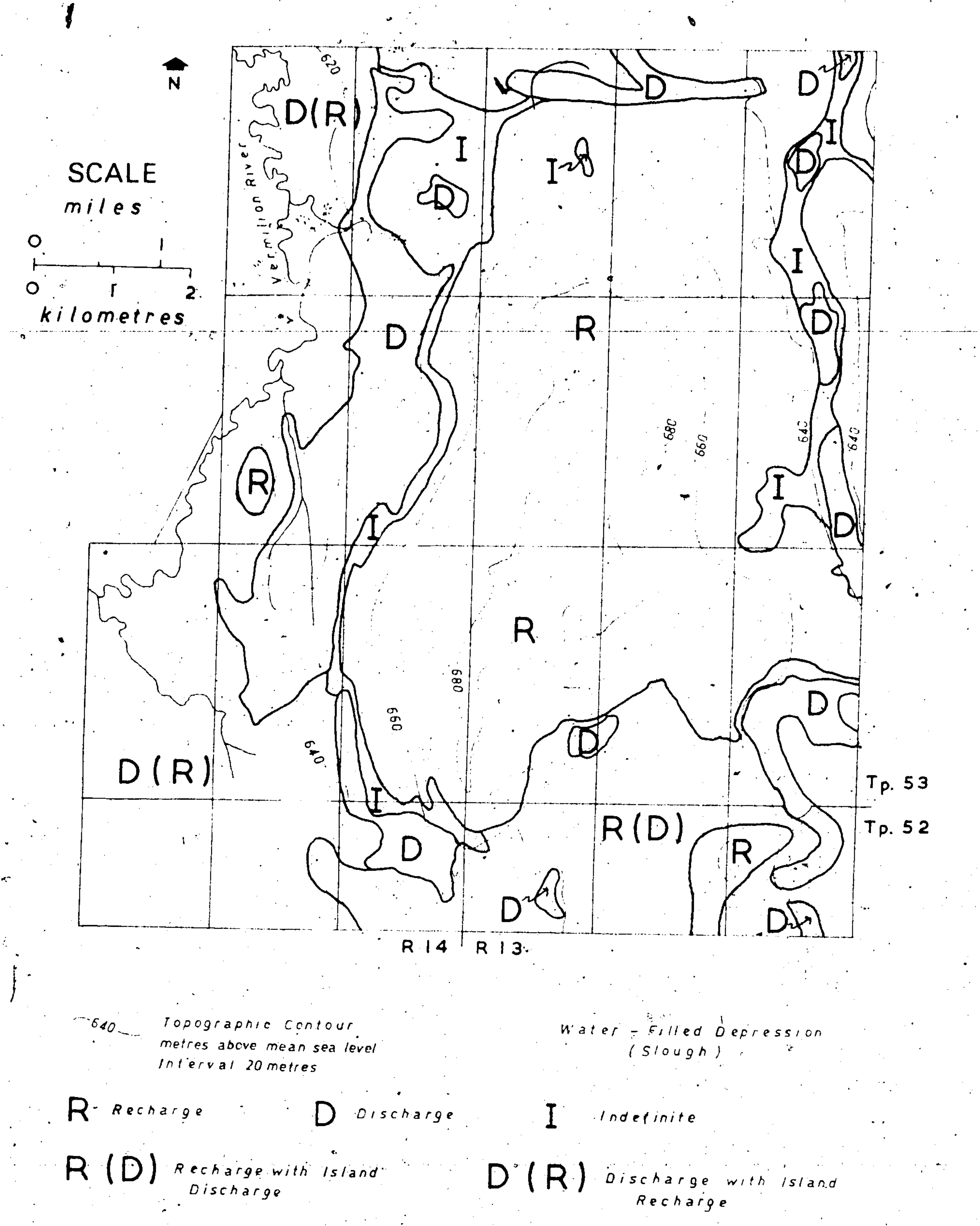


Figure 2. Groundwater in the Vegreville study area, as mapped by Leskiw (1971) from surface features.

because of differences in ionic potential (ionic radius ÷ charge), favour retention of calcium and magnesium and release of sodium, and as a result of solubility differences. Changes in anions occur because of solubility differences in combination with the dominant cations, and through reduction of sulphates. Geological formations in the Vegreville area are bentonitic, high in sodium, and contain carboniferous layers, and there should therefore be ample opportunity for all the above processes to occur.

Climatic zonation is caused mainly by differences in rainfall. Low rainfall causes the water reaching the water table to be higher in dissolved ions than is the case in areas of higher rainfall. Temperature also influences the amount of water that reaches the water table, but it also has a more direct effect on ionic content through influence on solubilities and rates of reaction.

Vertical zonation occurs first, because the length of flow path increases with depth. Water of shallow local flow systems may therefore have a completely different chemical composition from that of intermediate and regional flow systems (Tóth 1966). Secondly, permeabilities tend to decrease with depth, so increasing time of contact; and thirdly, in the absence of other governing factors, more saline waters, because of their higher specific gravity, tend to remain below water of lesser salt content (Back 1966).

II - MOISTURE MOVEMENT IN THE UNSATURATED ZONE

Liquid Flow

Darcy's law, developed for saturated moisture flow, can also be used to describe unsaturated flow (Van Bavel 1969), but the hydraulic conductivity is no longer constant, but dependant on moisture content (Richards 1931, Childs and Collis-George 1950). Richards equation (Richards 1931) which is derived from Darcy's law therefore applies, but in the non-steady state form:

$$-\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[Kx\,\frac{\partial\phi}{\partial x}\right] + \frac{\partial}{\partial y}\left[Ky\,\frac{\partial\phi}{\partial y}\right] + \frac{\partial}{\partial z}\left[Kz\,\frac{\partial\phi}{\partial z}\right]$$

Kx, Ky, Kz are hydraulic conductivities in the x, y and z directions respectively, ϕ is fluid potential, θ is volumetric moisture content, t is time.

For flow in one direction, the equation reduces to:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[Kz\,\frac{\partial\phi}{\partial z}\right] \qquad \text{(Klute 1952)}$$

The term diffusivity, analogous to heat flow diffusivity, has been used in connection with unsaturated flow. It is defined as:

$$D = K\left[\frac{d\phi m}{d\theta}\right]$$

where ϕm is the matric component of potential. In terms of diffusivity, the flow equation, ignoring gravity, becomes:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[D\frac{\partial\theta}{\partial z}\right] \qquad \text{(Klute 1952)}$$

Where gravity potential is significant, the equation for vertical flow is:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[D\frac{\partial\theta}{\partial z}\right] - \frac{\partial Kz}{\partial z} \qquad \text{(Philip 1957)}$$

These equations have been developed for liquid flow resulting from matric and gravity potentials. Osmotic potentials are usually ignored as a mechanism for moisture movement in the liquid phase, in spite of evidence that soils high in clay may act partially as semi-permeable membranes (Kemper and Maasland 1964, Cary and Taylor 1967). Other forces, also usually ignored, are London forces, adsorption, H-bond, and double layer effects. All these may however be significant at high moisture tensions, though they are difficult to account for quantitatively (Cary and Taylor 1967).

Vapour Flow

Water movement in the vapour phase can result both from convective (bulk) flow of soil air, and from diffusion of water molecules. Usually only diffusion is considered, since convective flow is probably significant only near the soil surface. In free air, diffusion is described by Fick's law:

$$\frac{dq}{dt} = -K\frac{dc}{dx}$$

dq/dt is mass transferred per unit time perpendicular to the x-axis, D is the diffusion coefficient, and dc/dx is the concentration gradient in the x-direction (Evans 1965).

The equations may also be expressed in terms of conductivities, but only where osmotic and thermal contributions to vapour flow are negligible (Cary and Taylor 1967). The first equation then becomes:

$$\frac{dq}{dt} = -K \frac{d\phi}{dx}$$

In soils, the flow rate is usually many times that in free air, and considerably greater than predicted by simple theory (Philip and De Vries 1967). The discrepancy arises because of heterogeneity of thermal conductivity of the soil's constituents, and also from an accompanying thermally driven liquid phase movement (Philip and De Vries 1957, Woodside and Kuzmak 1958). A tortuosity factor, J, which must be found experimentally for each specific soil and moisture content, has therefore been inserted in the vapour flow equations (Cary 1965).

Rose (1965) measured both liquid and vapour conductivities in six porous materials. In a clay loam soil, he showed vapour phase transport accounted for only 5% of total moisture movement, where the pore space was more than 15% filled. The pore space had to be less than 5% filled before vapour phase movement reached 50% of the total. He (1968) concluded that only at tensions greater than 15 bars was vapour flow of any importance. In field situations moisture movement must therefore be largely in the liquid phase, except close to the soil surface. An exception may be movement in frozen soils.

Flow in Frozen Soil

Moisture movement in frozen soil may be of particular significance in Alberta, where below freezing conditions are encountered at some soil depth during seven months of the year. Flow in the vapour phase resulting from a temperature gradient, in the absence of osmotic and moisture gradients can be described by the equation:

$$\frac{dq}{dt} \doteq -\beta D \frac{dp_0}{dT} \frac{dT}{dz} \quad \text{(Philip and de Vries 1957)}$$

β is the tortuosity factor described in the previous section, D is the diffusion coefficient in air, dp_0/dT is the relationship between saturated vapour density of water and temperature at the temperature concerned, which is obtainable from Dorsey (1940), and dT/dz is the temperature gradient.

Taylor and Cary (1960) showed that a thermal gradient may cause large quantities of water to move in liquid phase. In a loam soil, Cary (1965), showed that with a tension of 0.066 bars, a thermal gradient of 0.5°C per cm caused as much water flow as a hydraulic gradient of 2 cm of water per cm, and 80% of the flow was in the liquid phase. At a tension of 2.2 bars, the same thermal gradient moved as much water as a hydraulic gradient of 250 cm water per cm.

Temperature induced liquid flow is complex, and occurs from several causes. First, flow from warm to cool zones occurs because the surface tension of water against air increases as the temperature falls. Second, moisture tension also increases with temperature fall, so contributing to this flow. Third, even under saturated conditions, some thermally induced movement occurs, and it has been suggested that this results from kinetic energy changes associated with hydrogen bond distribution (Cary 1965). Fourth, flow may be caused by thermally induced osmotic gradients produced by salt migration, or the soret effect (Peyton and Turner 1962). Because of the complexity of thermally induced flow, Cary (1965) resorted to the phenomenological equation:

$$\frac{dq}{dt} = - K \frac{Q}{gT} . \frac{dT}{dz}$$

K is unsaturated hydraulic conductivity, Q is liquid phase heat of transport, g is acceleration due to gravity, T is absolute temperature, and dT/dz is the temperature gradient.

Significant moisture movements in frozen soil have been reported in many locations (Lebedeff 1927, Meyer 1960, Jumikis 1962). Upward movements resulting in a fall in the water table and increasing the soil moisture content to saturation have been reported by Schneider (1961), Ferguson (1964), Willis et al. (1964) and Benz et al. (1968). Evidence for this phenomenon on the Canadian Plains has been contributed by Meyboom (1967b), Pelton et al. (1968), and van Schaik and Rapp (1970). Moisture vapour movement occurs along a vapour pressure gradient, as in unfrozen soil, but it is the vapour pressure of ice that must here be taken into account (Hoekstra 1966). Most moisture movement is however probably in the form of unfrozen liquid films in equilibrium with ice (Jumikis 1962, Hoekstra 1966). When moisture tension increases, freezing point is lowered, so with decreasing temperature, moisture films become thinner and are held with increasing tension. Liquid flow rates, unlike vapour movements, are therefore highly temperature dependant in frozen soil. Another important feature of moisture movement in frozen soil is that the driving force, which results from differences in the chemical potential of water, is almost independent of soil water content (Hoekstra 1966). It is independant because, as soil water content increases under isothermal conditions, the ice phase increases without necessarily affecting liquid film thicknesses (Hoekstra, 1966). A frozen soil therefore tends to act as a sink. Flow rates along a temperature gradient were reported by Hoekstra to be around 0.25 mm to 5.0 mm per day per °C per cm, or of a similar order to those in unfrozen soil (Cary 1966). Hoekstra used the following equation to describe liquid flow:

$$\frac{dq}{dt} = L \frac{dF}{dT} \frac{dT}{dz}.$$

L is an experimentally found coefficient, dF/dT is the slope of the curve relating chemical potential of ice and water to temperature and dT/dz is the temperature gradient.

Application of Unsaturated Flow Equations

The complexity of field conditions, with differing soil horizons, soil cracks, and root distribution and hysteresis effects, and with both liquid and vapour flow occurring simultaneously in response to matric, thermal and osmotic gradients, has meant that the flow equations have so far been of limited predictive value. All the equations employ coefficients which generally need to be found experimentally for each specific situation. Millington and

Quirk (1961) however produced a formula for estimating unsaturated liquid hydraulic conductivity from a soil's constituents which has proved useful provided a matching factor was added (Jackson et al. 1965). Attempts at combining the various flow processes into one equation have been made (Taylor and Cary 1960, Freeze 1967), but it has so far been possible to apply such equations only to simplified model situations (Freeze 1967). It is however likely that with the increasing size and speed of computers, useful equations will eventually be developed for more complex and realistic situations.

III - SOLONETZIC SOIL FORMATION

Early work on genesis of solonetzic soils, mainly in Russia, was summarized by Joffe (1936) and de Sigmond (19~~4~~8). In arid or semi-arid climates, alkali or solonchak (saline) soils were thought to have formed from materials high in sodium, particularly where removal of salts was impeded by impermeable layers. Gedroiz (1925) stated that presence of an appreciable proportion of exchangeable sodium ions resulted in dispersed soils. De Sigmond (1938) considered that if sodium occupied more than 10 to 15% of the exchange complex, then significant dispersion of the clay occurred when the total water soluble salt content of the soil was reduced to less than 0.15% by leaching. On drying, the dispersed colloids formed the dense compact illuvial horizon typical of solonetz soils. Joffe (1936) described a typical soil sequence as progressing from zonal soils on upper slopes through solonetz and solodized solonetz to solods on the lower slopes where greater leaching was thought to be the cause of solodization. Bentley and Rost (1946) showed that although the same sequence occurred in Saskatchewan, another common sequence was from zonal soils on high ground through solod, solodized solonetz to solonetz or solonchak (saline soil) at the lowest position. A high water table was thought to have inhibited leaching on these lower slopes, so accounting for lack of solodization. Salinity on the Canadian Plains also appeared to correlate with brackish bedrock formations (Allan 1943, Mitchell <u>et al.</u> 1944, Odynsky 1945) and with proximity to the bedrock (Wyatt <u>et al.</u> 1944).

Controversy existed over whether many soils in Alberta and Saskatchewan which had the structural features of a solonetz, could be classified as such, because they lacked the 12% exchangeable sodium percentage considered by de Sigmond (1938) as diagnostic. Magnesium was usually the dominant cation in these soils (Rost and Maehl 1943, MacGregor and Wyatt 1945, Bentley and Rost 1946) but magnesium did not possess the dispersive quality of sodium. It seemed unlikely that mechanical dispersion, suggested by Bray (1935) could account for the formation of the compact B-horizon, since it could not explain why some soils formed solonetzic B-horizons while others in close proximity did not. The consensus of opinion was that since the solonetz soils contained more exchangeable sodium than solodized and zonal soils (MacGregor and Wyatt 1945), sodium undoubtedly played a role in their formation while both bedrock and drainage had an important influence on the amounts of sodium present.

Groundwater was emphasized as a factor in accumulation of salts in soils by United States laboratory staff (1954). A saline soil, that is a soil with a saturated electrical conductivity over 4 mmhos/cm, was considered to be caused by capillary rise of groundwaters high in salts. Such a soil was normally neutral to slightly acid in reaction, but leaching, with consequent depletion of the salts, could result in hydrolysis of some of the exchangeable sodium, and the formation of a non-saline alkali soil with a pH between 8.5 and 10.0. Clay dispersion, as envisaged by de Sigmond, produced the dense illuvial B-horizon, but with further leaching, calcium and magnesium ions returned by vegetation, and produced by solution of carbonates and gypsum (Kelley 1951) replaced sodium on the exchange complex and initiated solodization. It is now recognized, as suggested by Nikiforoff (1937) that a soil need not pass through all these stages. An alkali soil can be formed directly by alkaline groundwaters, or by biological reduction of sulphates (Whittig and Janitzky 1963, Timar 1965), without being initially a saline soil, while many salt-affected soils are probably in 'dynamic equilibrium', or perhaps more correctly, in a 'steady state' with their surroundings (Simonsen 1959, Lavkulich 1969).

Muratova (1958) summarized earlier work in Russia suggesting that groundwater played an important role in salt accumulation in soils. On the Mil'sk plain, a water table less than 1.8 metres below the surface was thought to result in soil salinity. In the Belka Valley of Western Australia, salinity was shown by Bettenay et al. (1964) to be associated with discharge of saline waters from an aquifer close to the ground surface. In Hungary, all salt-affected soils are considered to have been associated with mineralized groundwaters (Szabolcs 1965, Varallyay 1968). Evidence is the close inverse correlation between salinity and depth to the water table in the Danube and Tisza valleys, and the occurrence of salts of decreasing solubility with increased depth in the soil profile. In the Danube valley, net groundwater discharge and salt-influenced soils normally only occur where the depth to water table is less than two metres (Varallyay 1968). In Central Alberta, solonetz soils developed in Glacial Lake Edmonton sediments, were found in relatively flat groundwater discharge areas where capillary rise from the water table was probably a

[redacted]

factor in their formation (Arshad and Pawluk 1966). Meyboom (1967) showed that in Saskatchewan, herb and shrub phreatophytes could facilitate significant groundwater discharge with a water table up to 2 metres from the surface, which agrees with the findings of Muratova (1958) and Varallyay (1968). Although discharge is possible with a water table at greater depths (Nazir and Ahmad 1965, Meyboom 1967), amounts of discharge in such cases are likely to be so slight as to be counteracted by the influence of rainfall infiltration, at least in the climate of the Canadian Plains.

In the Vegreville study area of Alberta, Leskiw (1971) showed that soils were related to the groundwater flow patterns depicted by surficial features. In areas of groundwater discharge, the most common sequence of soils was from Carbonated Saline Gleysol at the foot of the slope through Thin Black Solonetz to Black Solonetz with rising ground. In areas of recharge, the usual sequence up a similar slope ~~was~~: Orthic Humic Gleysol, Humic Eluviated Gleysol, Gleyed Eluviated Black Chernozem, Eluviated Black Chernozem.

Summarizing, it can be said that although climate, parent material and drainage are undoubtedly important in formation of solonetzic soils, groundwater discharge is increasingly considered to play an important role.

IV - SOIL TEMPERATURES

Soil temperatures influence rates of physical, biological and chemical processes in soil. In cold climates, soil temperatures also have important effects on moisture movement during winter and meltwater infiltration in spring (Pelton et al. 1967, Freeze and Banner 1970). Soil temperatures are usually measured either with thermistors or thermocouples. Both have the advantage of small size, almost instantaneous response, low heat capacity and adaptability to automatic recording. Both are sensitive to a fraction of 1 °C (Taylor and Jackson 1965). In order to allow comparison between experiments, temperatures should normally be measured at standard depths of 10 cm, 20 cm, 50 cm, 100 cm, 150 cm and 300 cm (Richards et al. 1952). Lead wires should always be buried for several feet, to reduce effects of thermal conduction along them (Taylor and Jackson 1965).

One dimensional flow of heat is described by the equation:

$$\frac{dT}{dt} = \frac{K}{C} \cdot \frac{d^2T}{dx^2} \qquad \text{(Patten 1909)}$$

T is temperature, t is time, K is thermal conductivity, C is volumetric heat capacity which is equal to the product of specific heat and density, x is distance.

The term Diffusivity, equal to K/C, is often substituted in the above equation.

Heat flow in soil is seen to depend on both the thermal conductivity and heat capacity of the soil's individual components. Both of these variables must therefore be taken into account when comparing soils differing in moisture content, organic matter or some other component. For example, with increase in soil moisture content, K/C increases to a maximum and then decreases (Baver 1956). Differences in soil temperatures within a similar climate may also arise because of variations in albedo, while moisture evaporation from the surface can be important in keeping wet soils cold in spring. Effects of vegetative cover have been most thoroughly investigated in Russia (Vznuzdayev 1967, Kuzmenko 1968). Both there, and elsewhere, it has been shown that while vegetative cover increases winter temperatures and decreases summer temperatures, it does not necessarily do both to an equal extent. Investigations in Montana (Mueller 1970) and California (Quashu and Zinke 1964) show lowered mean annual temperatures under mature trees, but the opposite is suggested by data for young spruce and poplar trees at the University of Alberta (Toogood, Priv. Comm.). In any case, soil temperatures may be affected at a considerable distance from tree cover (Kaiser 1960). Carson (1961), and Quashu and Zinke (1964) consider that the main effect of vegetative cover is to move the radiation surface away from the soil surface, so increasing the effective distance 'x' in the heat flow equation. However, its influence is complicated by such factors as air circulation, foliage albedo characteristics, soil moisture regime and winter snow retention, the last of which may be particularly important on the Canadian Plains (Anstensen and Anderson 1969).

Snow cover, like vegetation, moves the effective radiation surface away from the soil. In addition, warm air, which is high in water vapour from a thawed snow surface, affects the soil more rapidly through a layer of snow than cold air (Longley

1967). Because of this, and also because snow cover is largely confined to the coldest season, its presence tends to raise mean annual soil temperatures considerably.

V - SUMMARY

Groundwater discharge has increasingly been implicated in the transport of salts into saline and solonetzic soils. Evapo-transpiration causes concentration of these salts at a depth which is greatly influenced by water table position; the depth to water table in turn being dependent on a balance between rates of groundwater discharge, and evapo-transpiration and infiltration. Examination of the effects of groundwater on a soil requires a knowledge of both saturated and unsaturated moisture flows at various seasons of the year, in the vicinity of the soil in question. Although saturated flow is dependant on well-defined physical laws, the complexity of field conditions makes mathematical prediction of the flow pattern difficult and field measurements of water potential remain the only method of obtaining precise quantitative information at individual sites. Piezometers arranged in a nest provide information primarily on the vertical hydraulic gradient but they may also be used to give estimates of hydraulic conductivity. In addition, sites can be chosen in a way that allows construction of two-dimensional flow diagrams, such as valley cross-sections. Surface features such as vegetation or salt-precipitates can provide reliable groundwater information of a qualitative nature, while supplementary information can be obtained by applying the principles of hydrogeochemistry to analyses of water samples, obtained both from surface sources and wells.

Moisture movement in the unsaturated zone is much more complex than saturated flow, because hydraulic conductivities are dependent on moisture content. In addition, flow is affected by soil horizon differences, soil cracks, root distribution, hysteresis, and movements in the vapour phase. Osmotic gradients have a small effect on flow, while the effect of temperature gradients may be considerable, even in a frozen soil. Equations describing unsaturated flow generally employ phenomenological coefficients which need to be experimentally found for each soil situation. Such equations are therefore of even less value for prediction purposes than those used for saturated flow, and detailed field measurements at individual sites are necessary, preferably with replication.

Studies of moisture flow can never be complete without information on soil temperatures, for these not only affect physical, biological and chemical processes in soil, but in the Canadian Plains climate, their role in causing moisture movements in winter and their effects on meltwater infiltration in spring, requires further exploration. It is known that soil temperatures can vary markedly even wit[illegible] a similar climate, as a result of differences in soil moisture, organic matter content, vegetative cover and snow cover.

PHYSIOGRAPHY

OF THE

VEGREVILLE AREA

PHYSIOGRAPHY OF THE VEGREVILLE AREA

Climate

According to Koppen's system (Trewartha 1954), the climate is cold humid continental. The mean annual temperature is 1°C (34°F). Winters are cold, all months from November to March averaging below freezing, and the coldest month, January, averaging -17°C (1°F). Summers are however relatively warm, July having a mean of 17°C (62°F) and an average daily maximum of 24°C (76°F). Frost-free days average 115. Mean annual precipitation varies according to recording station between 410 mm (16.2 in) and 450 mm (17.7 in). Most precipitation occurs during the growing season, with the maximum amount, 81 mm (3.2 in), falling in July. High sunshine amounts during the growing season (Table 1) together with persistent winds however combine to maintain potential evapo-transpiration rates well above the precipitation values for each month. Adequate soil moisture levels are therefore dependent on storage of spring meltwater in addition to summer precipitation. Although actual evapo-transpiration is limited by moisture available, groundwater recharge still occurs. Estimates of groundwater recharge vary between 0.73 and 3.8 cm per year (Meyboom 1967); the groundwater supply presumably being maintained by infiltration during and following the thaw (late March to mid April) but also by moist depressions which capture surface runoff from summer storms as well as spring meltwater.

Table 1. Climatic means (1941-1970, except wind 1947-1965) for May to September in the Vegreville area.

	May	June	July	Aug	Sept
Temp. Daily Max °C	17	21	24	22	16
Daily Min °C	3	7	10	9	4
Precipitation mm	36	66	81	72	45
Sunshine Daily hrs.	8.5	8.6	9.7	8.4	6.1
Wind Speed* Km/hr	16	15	13	13	15
Evapo-trans. Potential mm.	76	104	122	104	61
Actual mm	76	91	89	76	43

*Temperature (Environment Canada 1973a), Precipitation (Environment Canada 1973b) and Sunshine (York and Kendall 1972) were recorded at Ranfurly while wind speeds (Canada Dept. Transport 1968) are means of values recorded at Edmonton and Vermilion. Potential and actual Evapotranspiration were calculated for Ranfurly by MacIver (1970).

Topography

Topography of the study area is mostly gently sloping or gently rolling, and much of the area is characterized by a deranged drainage pattern typical of many recently glaciated regions, with abundant depressions in the landscape holding water either temporarily or permanently. The Vermilion River and its tributaries flow northwards eventually joining the N. Saskatchewan River. Altitudes range mainly between 610 m and 670 m (2000-2200 ft) above sea level.

Vegetation

The natural vegetation is Parkland Prairie, and prior to cultivation two poplar consociations covered much of the area (Moss 1955). Aspen poplar (*Populus tremuloides* Michx.) favoured dry sites, while Balsam poplar (*Populus balsamifera* L.) was more abundant in moist lowlands. The dominant native grass species was Rough fescue (*Festuca scabrella* Torr.). Poplar is now largely confined to isolated stands around farm buildings and along fence-lines. Willow (*Salix* spp.) normally surrounds non-saline moist or water-filled depressions. Common wild rose (*Rosa woodsii* Lindl.), Dogwood (*Cornus stolonifera* Mich.) and Saskatoon (*Amelanchier alnifolia* Nutt.) are common near the edge of poplar stands. Western snowberry (*Symphoricarpus occidentalis* Hook.) and Silver-berry (*Eleagnus commutata* Bernh.) often occur on uncultivated Chernozemic soils within areas of Solonetzic soils. Nuttal's salt meadow grass (*Puccinella nuttaliana* (Schultes) Hitche), Foxtail (*Hordeum jubatum* L.) and Red Samphire (*Salicornia rubra* L.) dominate moist saline situations (see Plate 1). Introduced species common in pastures, are Brome grass (*Bromus inermis* Leyss.) and Alfalfa (*Medicago sativa* L.), while much of the arable area is used to grow Wheat (*Triticum* spp.) and smaller acreages of Rape (*Brassica napus* L.), Oats (*Avena sativa*) and Barley (*Hordeum vulgare*).

Bedrock Geology

The bedrock geology of the region was described by Hume and Hage (1941), reviewed and reclassified by Shaw and Harding (1949) and more recently summarized by Le Breton (1963). The Belly River Formation underlies all the area around Vegreville and consists of Upper Cretaceous shale and sandstone beds of marine and marine-deltaic origin. The exact dip of the beds has been difficult to determine because of variable horizon thickness, but it approximates 3.8 metres per kilometre (20 ft/mile) to the south-west (Hume and Hage 1941). Formation members of importance in the Vegreville area are, in ascending order, Ribstone Creek, Grizzly Bear, Birch Lake, and Oldman. The Ribstone Creek member is described as massive grey soft sandstone of continental and marine deltaic origin, containing coal seams and ranging in thickness from almost nothing to 36 metres. The Grizzly Bear member consists of dark blue-grey shale of marine neritic origin containing ironstone and sandstone nodules and ranging in thickness to 42 metres. The Birch Lake has been separated into lower and upper members both of which consist of soft cross-bedded buff coloured sandstone of marine deltaic origin. They are separated by the Mulga member which is soft grey shale of marine neritic origin containing some silt and carbonaceous layers. The three Birch Lake members are of variable thickness, and together do not exceed 30 metres. The Oldman which is the upper member of the Belly River Formation consists of light grey bentonitic sandstone and dark carbonaceous shales of continental and marine deltaic origin. It ranges in thickness up to 300 metres, but only the lower horizons occur in the study area.

Typically all these members of the Belly River Formation are brackish; sandstone as well as shales are often bentonitic, and thin seams of coal or carbonaceous material are usually present. They are generally soft, though some hard horizons exist.

Surficial Geology

Glacial and Fluvio-glacial drift from the Laurentide ice sheet covers the bedrock almost completely and ranges up to 30 metres thick. The drift tends to accentuate the bedrock topography, areas near the valleys being typically covered by only a few metres of Ground Moraine Till whereas upper elevations are covered by 6 to 30 ~~metres of~~ Hummocky Disintegration (stagnant ice) moraine consisting of till mixed with stratified drift (Ellwood 1961). The till is normally clay loam textured and contains 1-3% carbonate. Stream trench materials of sand and gravel occur in places, and may be of importance in shallow groundwater movement (Gravenor and

Bayrock 1956). A narrow band of alluvium occurs along the Vermilion River.

Soils

Black Chernozemic soils are dominant in the area, but Solonetzic soils are frequently encountered at lower elevations. Smaller areas of Gleysolic and Regosolic soils have been mapped in and around moist depressions and seepages (Wyatt et al. 1944, Bowser et al. 1962, Leskiw 1971). Soils are described in greater detail in subsequent sections.

SITES AND

INSTRUMENTATION

SITES AND INSTRUMENTATION

In selecting sites within the Vegreville study area, it was desirable to include examples of the more important groundwater features mapped by Leskiw (1971) together with associated soils. It was also desirable that sites follow a line approximately at right angles to major drainageways to allow construction of flow diagrams. It was necessary where possible to avoid the influence of man-made devices such as dams, dugouts, ditches and wooded fencelines. The sites also had to be selected, in co-operation with farmers, where they would not interfere with crops. The limitations left little final choice of location and at two of the sites, wooded fencelines could not be avoided. Sites 1, 2 and 3 (Figures 3,4) were located on high ground (Sect. 6 Tp. 53 R. 13-W4) in a line running uphill from a slough which was typical of the slow recharge type (Lissey 1968). The soil sequence was: Orthic Humic Gleysol at Site 1; Eluviated Humic Gleysol at Site 2; and Orthic Black Chernozem at Site 3. Site 3 unfortunately received shading and an exceptionally deep snowcover because of its situation on the north side of a wooded fenceline (see Plate 2). The remaining six sites (Figures 3,4) were situated on lower ground (Sect. 11 Tp. 53 R. 14-W4) where both theory and surficial features suggested groundwater discharge predominated. They formed an approximate line running from Site 4, just below the theoretical midline down the slope to Site 9 which was next to a slough of the slow saline discharge type (Lissey 1968). Site 4 was unfortunately located on the west side of a wooded fenceline,

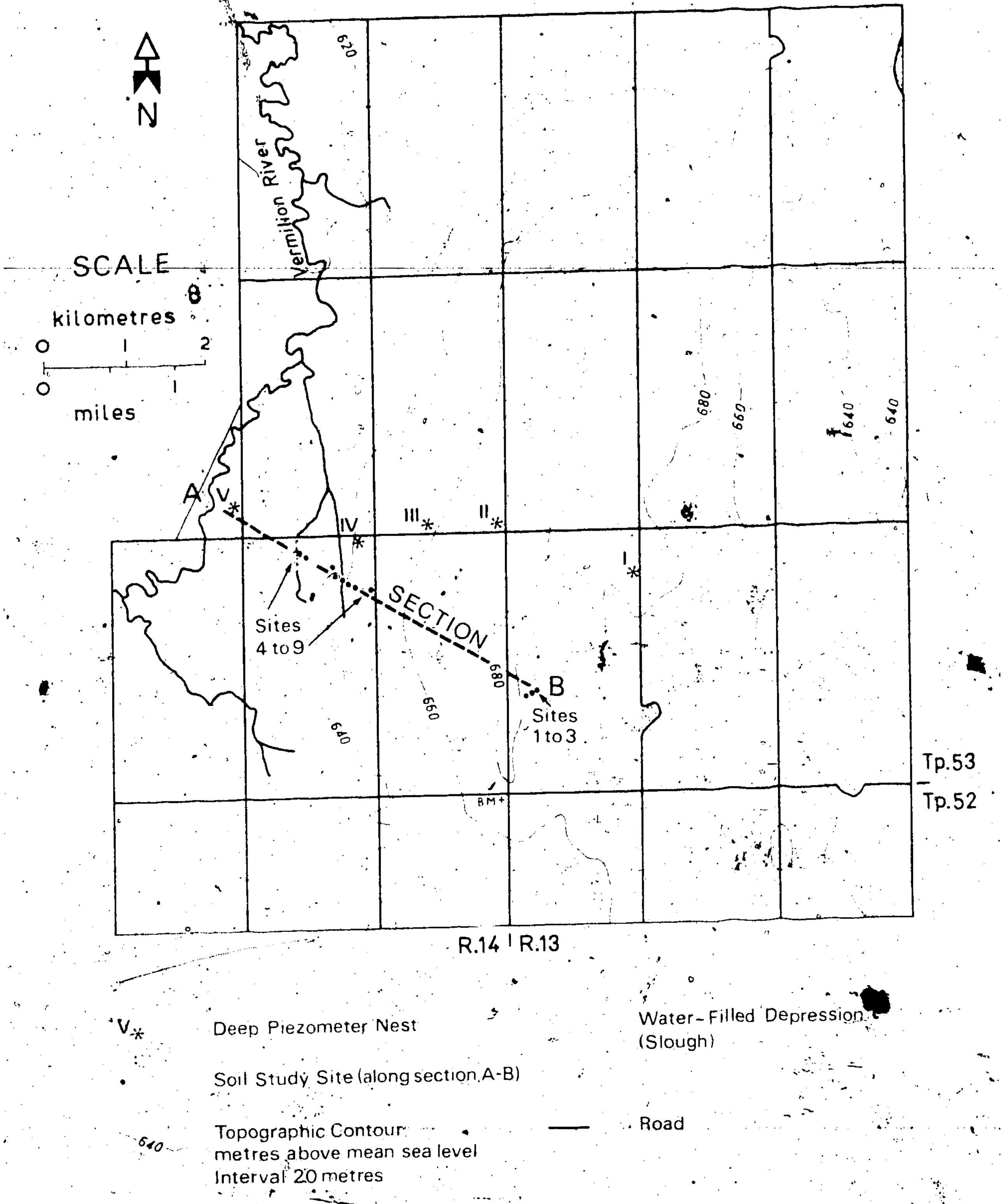


Figure 3. Area studied by Leskiw (1971) showing position of piezometer nests installed as part of his study, and the soil study sites used in the present study.

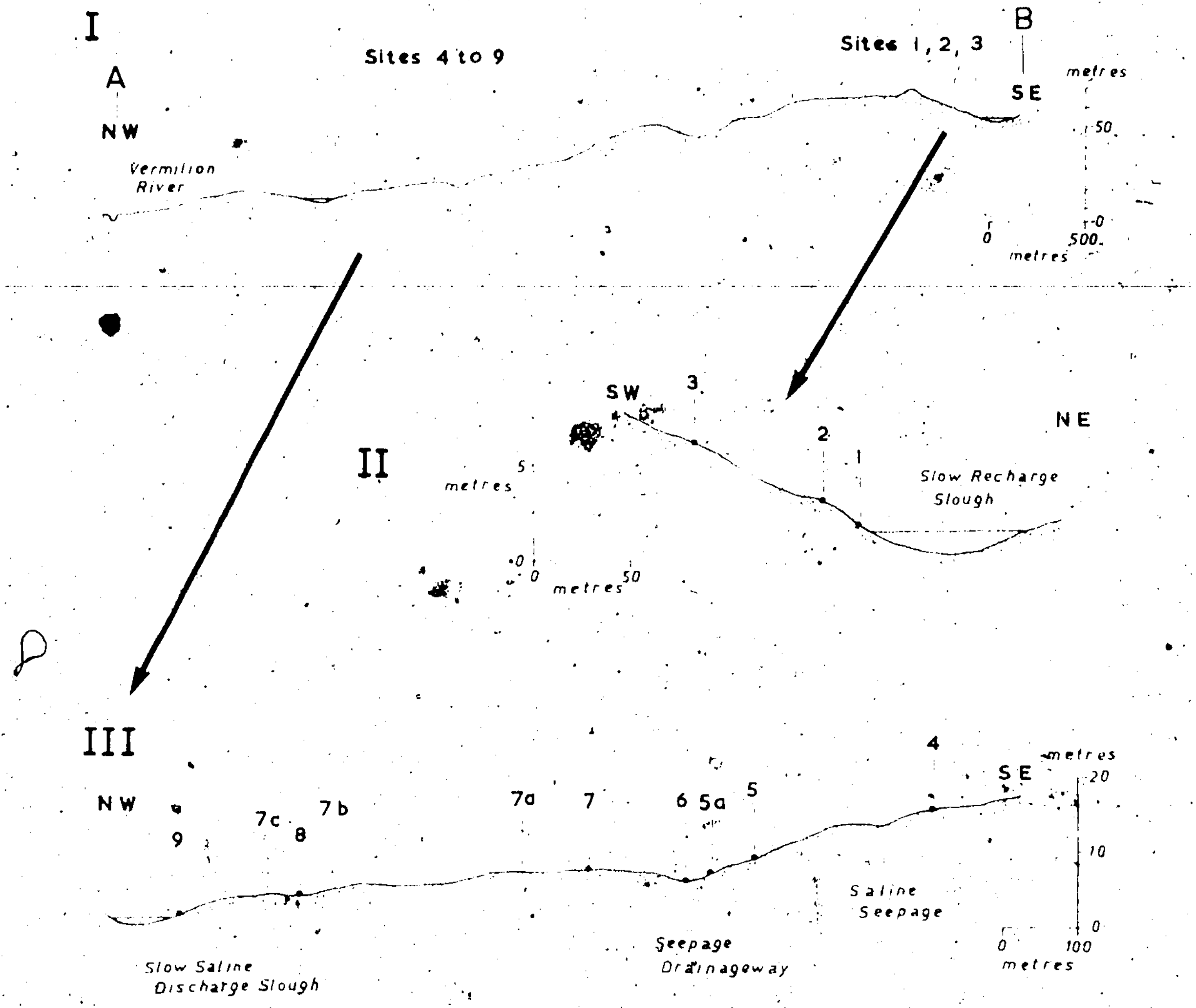


Figure 4. Vertical cross-sections, I along section A - B of Figure 3, II and III at an enlarged scale to include study sites 1 to 3, and 4 to 9 respectively. Dashed lines indicate sites offset from the line of section.

and, like Site 3, received an abnormally deep snow cover. Site 6 was in a natural seepage-drainage way, while Site 7 was near the summit of a slight rise, close to small temporary willow-ringed sloughs which suggested recharge within the area of overall discharge. Sites 5 and 8 were at intermediate points. Soils ranged from Orthic Black Chernozem at Site 4 through Black Solonetz at Sites 5, 7 and 8, to Alkaline Solonetz at Site 6 and Saline Black Solonetz at Site 9 next to the slough.

Four additional sites were located to provide supplementary shallow groundwater information. Site 5a was situated between Sites 5 and 6. Sites 7a and 7b were situated near Site 7 in small willow-ringed sloughs of the temporary fast recharge type, and Site 7c was located at a spring, close to Site 7b, but on lower ground.

Installation of piezometers was started early in June 1971. Thick-walled black iron pipe of 9.5 mm internal diameter was initially used. A headed rivet was attached to one end of the pipe and temporarily held in place with sticky tape. A narrow hole was made in the ground with a truck-mounted coring device and the rivetted end of the pipe lowered into it. A heavy hammering device was inserted over the top of the pipe, which was then pounded into the ground to the desired depth. An iron rod inserted inside the pipe was then hammered down five centimetres to remove the rivet and create a cavity 5 cm long and 1.6 cm diameter at the lower end of the pipe. It was intended that the piezometers should measure potentials at 3.05 metres (10 ft) and 6.1 metres (20 ft) below the apparent water table. Hard layers or rocks however limited the depth to which pipes could be hammered.

so that the final depth often differed from that intended. At Site 9 hard bedrock prevented further penetration than 2.4 metres while the greatest functioning depth reached was 7.3 metres below the surface, in stratified drift at Site 2.

For information at greater depths, it was necessary to resort to mechanical augering. A 20.3 cm (8 in) diameter hole was dry augered by a commercial firm and a 1.9 cm I.D. pipe, hacksaw slitted at the lower end, was lowered into the hole. Sufficient coarse 10/20 graded sand was poured into the hole to cover the lower 30 cm of pipe. A small quantity of the augered material was then added, followed by sufficient wet-mixed 40:50 parts by weight cement and bentonite to fill a 1.5 m depth of hole. The remainder of the hole was then refilled with augered material. Piezometers were installed by this method to a maximum of 24.4 metres (80 ft) below the apparent water table. The final situation was that at each of the main sites, piezometers terminated at approximately 3.05, 6.1 and 12.2 metres below the water table, and at Sites 4, 6, 7, and 9, an additional piezometer terminated at 24.4 metres below the water table. Only two piezometers were installed at each of Sites 5a, 7a, 7b and 7c, all terminating at less than 5 metres below ground level. In every case, stems 90 cm long were left above ground, to allow for measurement under snow cover, and for the possibility of above ground water levels. At the request of one of the farmers, these above ground portions of the pipe were in places made to be removable.

Access tubes for measurement of soil moisture with the neutron probe were made in July 1971 by hand pushing 3.81 cm I.D.

aluminum pipe into approximately 3 metres deep holes which were of similar diameter to the outer diameter of the pipe. The depth was in places limited to less than 3 metres by the capabilities of the truck-mounted coring device in stony material. The lower 5 cm of each pipe was hacksaw slitted and the lower ends were left open so that the tubes could also be used to measure depth to the water table. A removable 60 cm length of pipe was left above ground to allow access in winter and this was covered with insulating material to reduce heat transfer. Although the tubes worked well for neutron probe measurement above the water table, they failed at most of the sites to measure the water table accurately. At three sites, the water table fell in late summer below the bottom of the pipes and at two other sites, response was so slow the fluctuations could not be recorded and errors seemed to be caused by entry of surface water. Additional water table access tubes were installed at these sites in the summer of 1972, using 1.3 cm diameter perforated plastic pipe in 2.5 cm diameter holes which extended to the expected lower limit of the water table. This allowed the water table to be measured reasonably accurately at most of the sites, though slowness of response caused by low permeabilities was still a problem.

Thermocouples and psychrometers were installed in September 1971 at depths of 20 cm, 50 cm and 150 cm at Sites 1, 2, 3, 7, 8 and 9, by inserting them with narrow wooden rods into 2.5 cm diameter holes made with the truck-mounted coring device. The holes were back-filled with the original material. The wires were extended for a distance of at least 1 metre from the hole.

along a 15 cm deep trench to terminate at a wooden post, so minimizing heat conduction down the wires and effects of trampling the snow cover in winter. In May 1972, additional thermocouples were installed so that they were then present at all nine sites at depths of 20 cm, 50 cm, 150 cm and 300 cm. At the same time, psychrometers were installed at 20 cm and 50 cm at Sites 4 and 5 and at 20 cm at Site 6.

In May 1972, tensiometers were installed in 7.5 cm diameter holes made either with a hand auger or with the truck-mounted coring device. A slurry of soil was used to backfill the holes to ensure good contact, and the tops of the holes were sealed with dry bentonite. The upright, stoppered top of each tensiometer protruded from the soil for access, while the tube leading to the mercury manometer was buried under at least 10 cm of soil. Manometer tubes from the 4 to 8 tensiometers at each site were mounted together on a single post of aluminum I-beam material. Where the water table was likely to exceed a depth of 250 cm, as was the case at Sites 3, 4 and 8, tensiometers were installed at depths of 20 cm, 50 cm, 150 cm and 250 cm, with two tensiometers, separated one to two metres apart, at each depth. At Sites 2, 5 and 7, where the water table was expected to remain above 150 cm, the 250 cm installation was omitted. However, at Site 7, the 150 cm tensiometers later indicated a deeper water table, so tensiometers were then installed at 250 cm at this site. At the wet sites, 1, 6 and 9, installation was made only at depths of 20 cm and 50 cm.

SAMPLING, MAPPING AND RECORDS

SAMPLING, MAPPING AND RECORDS

Pits, approximately 1 metre deep, were dug at each site and the soil profile described and photographed. Samples of each horizon were then taken from the walls of each pit, so as to be representative of a metre square area horizontally. Thick horizons were split for sampling into two or three equal depth intervals. Samples were transported in bags, air-dried the following day, and crushed and sieved (2 mm) prior to analysis. The truck-mounted coring device was used to obtain 4.7 cm diameter cores, to a maximum depth of 3 metres, but to a lesser depth at wet sites. These were obtained where possible at depths of 120 cm, 150 cm, 200 cm and 300 cm. Additional cores at depths of less than 100 cm, were obtained with a small hand-coring device. Most of these cores were packed moist in containers and then placed in cold storage pending analysis. However, some of the cores from depths greater than 100 cm were air-dried and sieved to supplement analytical information from the pit samples.

Water samples were obtained from observation wells and all piezometers, in October 1971. Deep piezometers installed prior to this study were sampled by lowering a bucket-device. The other piezometers and observation wells were sampled as close to the bottom as possible, using a plastic tube. Samples were stored in polypropylene bottles in a refrigerator until analyses could be made.

Soil mapping at a scale of 1 : 5280 was carried out along a narrow strip 50 m wide enclosing the 9 selected sites. Elevations were mapped in detail with a survey level, using as a reference, a benchmark situated slightly over 1 Km south of Sites 1 to 3.

Visits to take readings at the Vegreville sites were made initially every few days following installation of piezometers in June and August, 1971. After September 1971, visits were made at two weekly intervals. The deep piezometers installed prior to this study were at first read every two weeks, but because of increased recording work, readings were subsequently taken only at every second visit. The shallow piezometers, because of their greater fluctuations, were read on every visit. Thermocouples, following their installation in October 1971, were read every two weeks. Psychrometers installed at the same time were read every two weeks, but only during the period mid-April to mid-November. Neutron probe readings beginning October 1971 were made at every second visit during the winter months and at every visit from 1st April to 1st October. Tensiometers were read every two weeks from May to October 1972. In addition, slough levels were recorded at each visit during summer and occasionally in winter. Snow depths were recorded at each site during winter, and cores were taken for measurement of snow density in March, just prior to runoff, in order to calculate the quantity of water present.

ANALYTICAL METHODS

ANALYTICAL METHODS

I - PHYSICAL ANALYSES

Hydraulic potential from Piezometers

The static water level in a piezometer, installed so that it is only open at the bottom, is a measure of the hydraulic head at the base of the piezometer. The hydraulic potential is the hydraulic head multiplied by acceleration due to gravity, but because gravity is constant, it can be expressed numerically as hydraulic head above a chosen reference point. Because groundwater potentials are always changing, the water [illegible] measured in a piezometer may differ significantly from the static water level or the true hydraulic potential, particularly where the piezometer terminates in a poorly permeable material. In such cases, it may be possible to install a narrower pipe ~~or~~ 'reducer' inside the existing pipe stem which will cause more rapid response to changes in groundwater potential (Lissey, 1968). The narrow pipe diameters used in this study and expense, precluded use of this method. The alternative method outlined by Hvorslev (1951), adjusting piezometer readings to take account of lag time, was therefore used. The recovery rate of each piezometer after removal of water, was measured. The ratio Ht/Ho (difference between the final level and the level at time t divided by difference between the final level and the level immediately following water removal) was then plotted on a log scale against time on a linear scale. The 'basic time lag' which is the theoretical time required for equalization if the initial rate of rise (following bailing) was maintained corresponds to Ht/Ho = 0.37 on the graph. This value was found for each piezometer. Where basic time lag exceeded two weeks, its value was used to correct piezometer readings. Where the value was less than two weeks as in over half the functioning piezometers, its effect on readings was too small for adjustment to be significant on a seasonal scale, and readings were left unadjusted. Hvorslev's method of adjustment is based on the equation $E = \beta T$ where E is the error in rate of rise or recession, β is actual rate of rise or recession, and T is the basic time lag. Since most piezometer readings varied annually in a sinusoidal manner, adjustment of amplitude and phase shift according to Hvorslev's method was relatively simple. Where the changes were more complex, annual curves were split into segments approximating a half wave length for adjustment.

Hydraulic conductivities from piezometers, cores, and disturbed soil samples

Hydraulic conductivities can be derived from drawdown recovery tests on piezometers (Luthin and Kirkham 1949). Interpretation is based on the equation:

$$K = \frac{\pi r^2 \, \mathrm{Ln} \, Z_1/Z_2}{S(t_1 - t_2)}$$

r is the radius of pipe and Z_1 and Z_2 are the depths to water at times t_1 and t_2 measured from the original level prior to drawdown. S is a piezometer shape factor.

If the basic time lag (T), defined in the previous section is substituted in the equation (Hvorslev 1951), it becomes:

$$K = \frac{\pi r^2}{(S)\ T}$$

The value of the shape factor S, varies not only with the dimensions of the cavity at the piezometer base, but also with the assumed degree of anisotropy of the material in which the cavity is situated. Since three different types of piezometer were used and the lithology varied, several different situations occurred as follows:

1. Piezometers in augered and drilled holes

The formula given by Hvorslev (1951) is:

$$S = \frac{2\pi L}{\operatorname{Ln}\left[\frac{mL}{D} + \sqrt{\left(\frac{mL}{D}\right)^2 + 1}\right]}$$

$m = \sqrt{Kh/Kv}$ where Kh/Kv is the assumed degree of anisotropy. L is cavity length, 30 cm for augered holes, and 90 cm for drilled holes. D is cavity diameter, 20 cm for augered holes, and 10 cm for drilled holes.

Where $\frac{mL}{D}$ exceeded 2, as was usually the case, hydraulic conductivity estimates were increased over the calculated values by a small factor shown experimentally by Al-Dhahir and Morgenstern (1968) to be necessary.

2. Piezometer pipes hammered into the ground, rivet on the end knocked down 5 cm.

(a) Loose sands.

If the sand is assumed to re-fill the cavity above the rivet, but not to enter the pipe appreciably, and if the degree of anisotropy of the sand is assumed to be 1, then S = 2.75D where D is the pipe internal diameter, here 0.95 cm (Hvorslev

1951; Luthin and Kirkham 1949).

(b) Firm materials, Till or Bedrock.

Here, the materials are sufficiently resilient to deformation that the cavity is assumed to remain of 5 cm length and 1.6 cm diameter. Al-Dhahir and Morgenstern (1968) consider that the S value of a cavity such as this, closed at both ends, differs little from one closed only at one end, and the method used for augered and drilled holes therefore applies.

Hydraulic conductivities calculated from piezometers depend on estimated degree of anisotropy. Freeze (1969) quotes anisotropy values of 10 to 100 for bedrock, 1 to 20 for till, and 1 to 100 for stratified drifts. Degrees of anisotropy, much above unity, together with piezometer cavity shapes having heights exceeding their diameters, combine to produce values for hydraulic conductivity which are valid for horizontal rather than vertical flow. The calculated vertical hydraulic conductivities are subject to large errors, and therefore where these are of importance, supplementary evidence obtained by means other than piezometers is almost essential. Hydraulic conductivities have been related to particle size analysis with varying degrees of success, but such relationships can hold only where pores rather than fissures are the main conductors of water. Using particle size analyses, hydraulic conductivities of materials low in clay were estimated from Hazen's line, as quoted by Freeze (1969), while for materials containing more than 20% clay, type of clay and sodium content were taken into account in selecting values quoted by Lambe and Whitman

(1969).

Further information still regarding vertical hydraulic conductivity was provided by laboratory determinations on 4 cm diameter cores obtained with the mechanical coring device. Sampling was limited to a depth of 3 metr[illegible] hence only a few cores were from bedrock. The cores, sealed [illegible] into plastic tubes with paraffin wax, were confined top and bottom with perforated plastic caps and hydraulic conductivity was then determined by the falling head method, similar to that described by Klute (1965). The water used had approximately the same salt content as the groundwater from where the core was obtained. Hydraulic conductivities were adjusted for effects of temperature differences between laboratory and groundwater on water viscosity. Adjustments for water density differences were considered to be too small for inclusion.

Saturated hydraulic conductivity was also determined on disturbed 2 mm sieved samples of Ah horizons by the constant head method. The samples, in plastic percolation tubes, were saturated from below prior to measurement, and an inverted flask was used to provide the head (Fireman 1944).

Neutron Probe Moisture Readings

An aluminum access tube with an internal diameter of 3.8 cm was pushed into a hole made at each site with a truck-mounted coring device. The diameter of the hole was only fractionally larger than the outside diameter of the tube. The tubes were made to protrude 61 cm above ground to facilitate usage under snow cover. They were not sealed at the bottom as often recommended, but rather, the lower 15 cm was perforated to provide information on the position of the water table. Insulating material was wrapped around above ground portions of the pipe to reduce heat transfer, even though it has been shown that effects of conduction along the pipe on moisture transfer in the soil are small (Dickey et al. 1964). A Nuclear-Chicago model P19 neutron probe with scaler, was used to take two minute counts, with the source at depths of 10 cm, 20 cm, 30 cm, 50 cm and beyond that at 50 cm intervals to the tube limit, or to the water table where this was above the tube limit. Readings were obtained every four weeks while the ground surface was frozen (mid-October to early April) and at other times every two weeks. Initially, standard counts were taken only two to three times during a day of readings. However, it became apparent that during colder weather, counts varied much more than the normal 2-3%, at times reaching 7-8%. A change in procedure was therefore adopted in early March 1972, standard counts being taken at the start and finish of readings at each individual site. The standard count assigned to each individual reading was then estimated by interpolation over the period of readings at the site in question. The ratio of reading to its standard count was then obtained. Since counts are partly dependent on temperature, a large variation during cold weather can be expected, because of the wide temperature differential between access tubes and the outside air. Below 10 °F (-12 °C), rapid fall-off in count values occurs, which increases the error. Consistent readings were almost impossible to obtain at 0°F (-18°C) and at -10°F (-23°C), almost no counts were recorded. Thus, whenever possible, readings were taken when the temperature exceeded 10°F (-12°C).

Calibration of the count ratios with soil moisture was accomplished by gravimetric sampling. For depths to 100 cm. samples were obtained within a 2 metre radius of the access tube, using a small hand auger. Each gravimetric determination was performed on a composite sample which consisted of 3 subsamples taken on different sides of the access tube. Samples were taken once in October 1971, and again in May, June and October 1972. At depths below 100 cm, the truck-mounted coring device was used, but sampling dates were limited to once in early May and once in late October 1972.

Volumetric moisture content, calculated from gravimetric samples and bulk densities, was plotted against Neutron Probe count ratios for each depth sample. A considerable scatter obtained could be largely explained by the normal variation involved in gravimetric sampling. A gravimetric determination must be based on about 7 field samples for the error to be the same as for one neutron probe count (Stone, Shaw and Kirkham 1960), but soil disturbance and the work involved made this number of samples impracticable. Comparison of the probe ratio-moisture content relationships showed that samples from 10 cm depth differed significantly from other samples. Their abnormality could be expected to result from influence of the soil surface-air interface (Lawless *et al.* 1963; Visvalingham and Tandy 1972). Moisture contents for this depth derived from regression lines, could therefore only be considered valid provided snow or water cover was absent, and even then could not provide as accurate an estimation of moisture content as results from deeper levels.

A measure of the sample volume involved by neutron probes determinations is the Sphere of Influence. This is defined as the sphere around the source that contains 95% of all thermal neutrons (Nuclear-Chicago Corp. 1972). Its radius is given by the equation:

$$r\ cm = 15\sqrt[3]{\frac{100}{\%H_2O\ volume}}$$

Another measure that has been suggested is the Sphere of Importance (Mortier et al. 1960). This is defined as the sphere around the source which, if all the soil and water outside the sphere were removed, would yield a neutron flux at the source that is 95% of the flux obtained in an infinite medium. Its radius is given by the equation:

$$r\ cm = \frac{100}{(0.1 \times \%H_2O\ volume) + 1.4}$$

At a moisture content of 35% by volume, both the Sphere of Influence and Sphere of Importance are close to 20 cm. When, however, the moisture content is only 10%, the Sphere of Influence is 33 cm and the Sphere of Importance is 42 cm. This means that when moisture contents were low, readings taken at 20 cm and 30 cm resulted in Spheres of Influence and Importance intersecting the ground surface and it would be reasonable to expect that snow cover should influence readings at these depths. However, experiments by Vredenburg and Willis (1970) showed negligible effects of snow upon readings at 20 cm, but significant effects at 5 cm, 10 cm, and 15 cm. It is probably safe to conclude that effects of snow cover on probe readings are insignificantly small at depths greater than 20 cm, over the normal range of moisture contents prevailing in winter.

Samples showed no significant difference between sites in moisture content-count ratios relationships. Pooling of regression data therefore seemed likely to give the most accurate equation for prediction, and a correlation coefficient r of 0.892 was obtained for the relationship between count ratio and moisture where all 113 values obtained from depths greater than 10 cm were included. Since a small increase in count occurred with increase in depth at all sites, inclusion of depth in a multiple regression equation was considered an improvement over simple regression. The inclusion of Log_{10} depth in the equation gave little improvement in fit over just depth; however, this form was considered superior since it was reasoned that the effect of depth should decline as depth increased. The final equation (Figure 5) gave a multiple correlation coefficient of 0.896.

The increase in probe reading with depth was not unexpected since counts are known to be influenced positively by bulk density as well as by neutron absorbing elements such as magnesium and potassium (Visvalingham and Tandy 1972), and both of these increase with depth in most soils. However, organic matter which also increases the count, decreases with depth, and should therefore have some counteracting effect. At shallow depths, an increase in count with depth can also be expected from decreasing

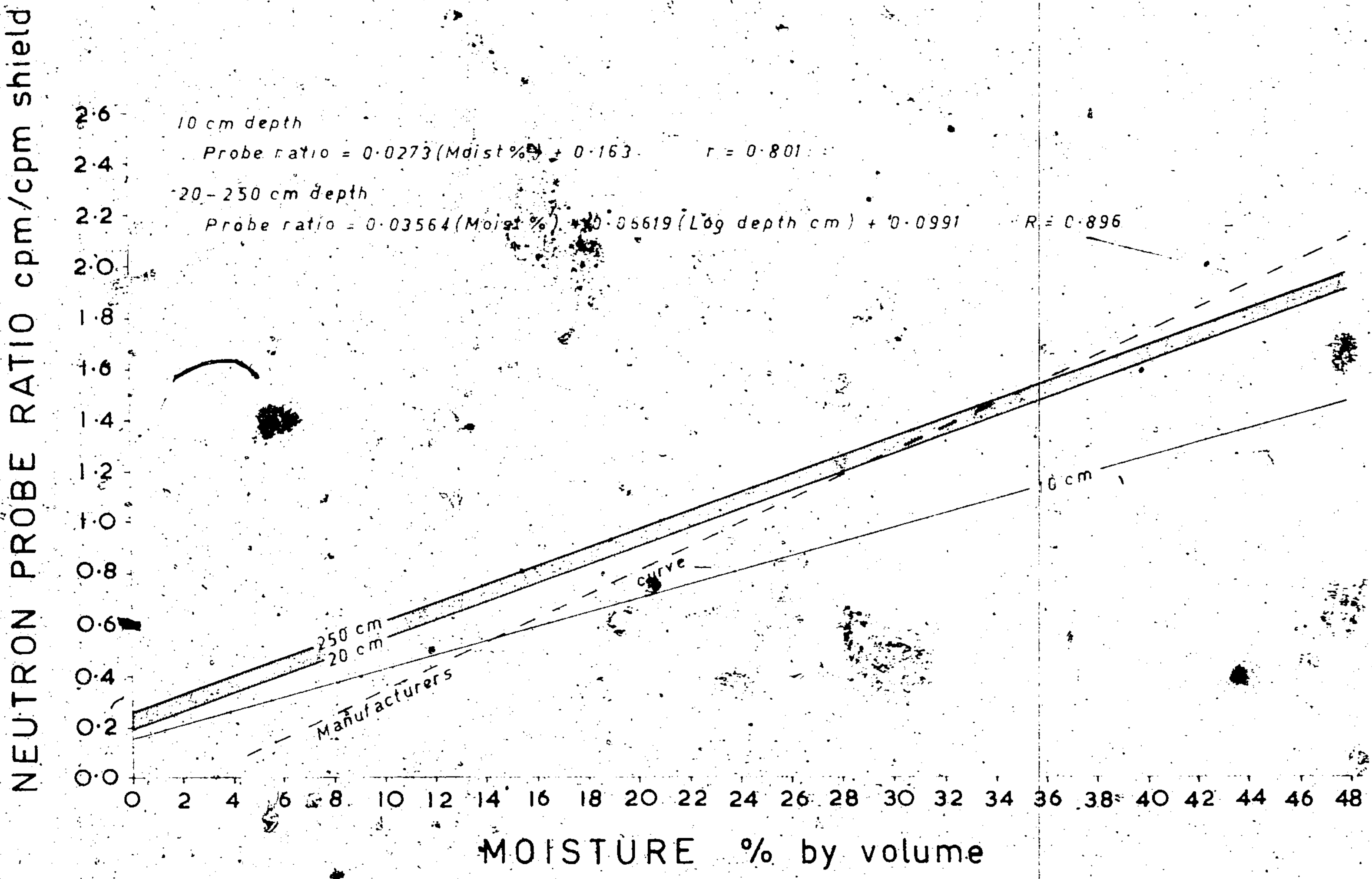


Figure 8. Relationship between soil moisture content and neutron probe count ratio for the 10 cm sample depth and for 20 cm to 250 cm sample depths.

effects of the soil surface-air interface. Bulk density did not account for as much variation as depth when substituted in the regression equation, and inclusion of electrical conductivity as a third independent variable did not significantly improve fit. The most satisfactory equation therefore involved only moisture and depth in the prediction of neutron probe reading and this equation was therefore used to calculate moisture contents at depths of 20 cm and more at all sites. A separate simple regression relationship (Figure 5) was used for 10 cm depth readings.

The percentage error associated with probe readings becomes smaller, the larger the count (Nuclear-Chicago Corp. 1962), but as an absolute quantity the error is smallest at low moisture contents or low counts (Merriam and Knoerr 1961). Based on the slope of the moisture-count ratio relationship found here, and a 95% probability level, the confidence interval at 35% moisture (by volume) should be ± 1% Moisture, At 10% moisture it should be ± 0.55% Moisture, and at 5% moisture, ± 0.39% Moisture. It is possible that statistical accuracy may have been improved slightly over these figures by adoption of individual standard counts, but for calculations involving moisture changes, it would seem reasonable to apply values of at least this order since errors arising from inaccuracy of slope of the regression lines is also involved. A still larger error is involved in the prediction of actual soil moisture rather than simply moisture changes, for here the full errors associated with prediction from gravimetric samples and bulk density measurements are included.

Moisture tensions from tensiometers and psychrometers

Tensiometers are the only well-established direct method of measuring matric soil moisture tensions in the field, though they suffer from certain drawbacks. First, they will not measure moisture tensions in excess of 0.8 bars, and second, they require constant maintenance. One advantage is their ability to measure small positive pressures below a water table. Tensiometers available commercially are expensive, so to minimize costs, they were hand-assembled from relatively simple materials, essentially as described by Webster (1966). Each consisted of a 7.9 mm I.D. nylon tube with a ceramic cup glued to the base, and a nylon T-piece glued to the top to form a side branch. Joints were covered with rubber sleeving to improve seal. A fine 0.86 mm I.D. nylon tube was inserted with one end inside the porous cup, and was threaded out through the side arm of the T-piece by way of a rubber stopper to terminate at the other end in a vessel of mercury, where it was looped to form a manometer. The other (upright) branch of the T-piece was closed with a removable rubber stopper and used for topping up with water. De-airing of the fine nylon tube was performed by attaching one end of a rubber hose to the T-piece and blowing at the other end. Once in operation, a continuous column of water extended from the soil at the porous cup to the mercury in the manometer tube. The fineness of the manometer tube served two purposes. First, volume of water movement was reduced to a minimum, this being essential in keeping response times within reason in poorly permeable materials.

Second, the amount of mercury involved, an expensive item, was minimized.

All items except ceramic cups were available locally. The cups were made and baked in the laboratory using clay and casting material from a local ceramic supplies.

The tension at the porous cup was calculated from the equation $T = 12.6\,M - H$, where M was the height of mercury in the manometer above that in the vessel, and H was the depth of the top of the porous pot below the vessel mercury level (Webster 1966).

Under conditions of growing plants, soil water is not at equilibrium, this being particularly the case in poorly permeable materials well above the water table. The effect is that lateral variation in moisture tensions is considerable, making replication almost essential. Webster (1966) considers that the geometric mean of a minimum of three tensiometers should be used. In this study, tensiometers were only in duplicate, but since they were mainly used to provide information on hydraulic potential close to the water table, where changes in tensions are slow, it was thought that valuable information could still be obtained.

Psychrometers were originally introduced for the measurement of soil and leaf moisture tensions under laboratory conditions (Monteith and Owen 1958; Korven and Taylor 1959). Only in the last few years have refinements been such as to encourage their tentative use in the field (Rawlins and Dalton 1967; Rawlins 1971). The soil psychrometer is in effect a wet-dry bulb thermometer sensitive to changes in relative humidity in the range 95-100%. A very fine copper-chromel thermocouple junction is wetted by passing an electric current through it to cool it by the 'Peltier effect' (Spanner 1951) and the temperature of the wetted junction is compared to the temperature of the same junction when dry, electrically. Interpretation is based on the formula:

$$e = ew - Ap\,(Ta - Tw)$$

e is vapour pressure of air; ew is saturated vapour pressure with respect to ice or water whichever is applicable; Ap is atmospheric pressure; Ta and Tw are the temperatures of the wet and dry bulbs respectively.

The soil moisture tension in bars, ΔP, is related to vapour pressures by the formula:

$$\Delta P = \frac{-RT}{\bar{V}} \ln \frac{e}{ew}$$

R is the gas constant, T is the absolute temperature, and $\bar{V}$ is the partial molar volume of water.

At low temperatures, a lowering of the saturated vapour pressure of water results in loss of precision. Once freezing occurs, the saturated vapour pressure of ice is involved, which being highly temperature dependent, makes results difficult to interpret. Psychrometers then, like tensiometers, provide information on tension gradients in the soil mainly during the growing season. Information obtained from psychrometers however differs from that of tensiometers in two important respects. First, a psychrometer reading includes both osmotic and matric components of moisture tension. Where significant amounts of salts are present, osmotic tension must therefore be calculated separately and subtracted to obtain matric suction. Second, psychrometers cover a much wider range of tensions than tensiometers. The Wescor Inc. model PT 51 psychrometers used in this study have a range of 0 to 50 bars, but it was found impracticable under field conditions to make replicate measurements, and individual values were repeatable only to about the nearest bar. It was essential therefore, that tensiometers be used in conjunction with psychrometers to adequately cover the range 0-1 bar. Psychrometers were used mainly at shallow soil depths where high tensions could be expected, but because of expense, only one psychrometer was installed at each depth location. Measurements were taken with a Wescor Inc. model MJ 55 microvoltmeter, and psychrometers were individually calibrated in salt solutions prior to installation. Where osmotic potentials appeared significant, they were estimated from knowledge of the chemical content of saturation extracts, the moisture content of the soil paste prior to extraction and field soil moisture contents obtained from neutron probe readings. They were therefore based on the somewhat dubious assumption that their relationship with moisture content was a simple dilution effect, and the salt content of the soil was constant. These osmotic potentials were then subtracted from psychrometer values to provide rough estimates of matric potentials.

Soil temperatures from thermocouples

Insulated copper-constantan thermocouple wire was used to measure soil temperatures with the Wescor Inc. model MJ 55 microvoltmeter mentioned above. Thermocouples were checked in the laboratory and individual calibration was found to be unnecessary.

During winter, abnormal variation occurred presumably as a result of improper functioning of the built-in reference junction in cold air temperatures, and readings during this period were therefore corrected by reference to a thermocouple immersed in ice-water mixture and carried in the field. Temperatures appeared to be reproducible to within about 0.2°C.

Bulk Density

Bulk densities were calculated from the mean of three 5 cm diameter cores obtained at each site using a truck-mounted coring device. When applied to calculation of porosity and volumetric moisture contents, it became obvious that the core method considerably over-estimated bulk densities of near surface samples, presumably because of compaction. Determinations we[illegible] therefore repeated using a Nuclear-Chicago model 5901 surface moisture density gauge, which derives moist density from degree of gamma radiation scattering in a sample approximately 15 cm deep in situ, below the gauge. A gravimetric moisture determination was made on a large soil sample which incorporated the 15 cm of soil immediately below the gauge and this was then used to correct the moist density values derived from the manufacturer's calibration curve to bulk density using the equation: bulk density = moist density / (1 + (% moisture/100)). Bulk density determinations representing sample depths f[illegible] to 50 cm were obtained by successive soil excavations to 4[illegible] with the probe lowered into the shallow pit so formed.

The gamma radiation method has the advantage of measuring soil in its natural state, and as expected, values obtained were lower than for the core method particularly at the wetter sites where core sampling presumably caused the most compaction. With increasing depth, however, bulk densities obtained by the core method approached those from the radiation method, and it is thought that at 100 cm and deeper, the cores gave a reasonably true value. Between 10 cm and 50 cm depth, only the results of the density gauge method were used. Values were corrected to the nearest 0.05 gm/cc, since it is doubtful if a closer approximation can be obtained by either method, because of sample variation.

Particle Density

This was determined by the pycnometer method using 50 ml specific gravity bottles (Blake 1965), and a 10 gm quantity of soil with water as the displacement fluid. The method is reproducible to the third place of decimals, but values contain errors from two known sources: The first of these, over-estimation arising from activity of the clay fraction, is normally considered to be less than 1% (Gradwell 1955). The second source of error is from solution of salts. The extent of this error can be seen by taking as an example, a sample high in salts. The Ah horizon of the saline solonetz soil at Site 9, with an electrical conductivity of 28 m mhos/cm, contained approximately 1.6% Na_2SO_4. 0.4% $MgSO_4$ and 1% $CaSO_4 . 2H_2O$ (Gypsum) was also present. The concentration of dissolved Na_2SO_4 in the pycnometer bottle solution should have been

0.3% and at this low concentration, it will have dissolved with a volume increase approximately equal to the solute itself (Hodgman et al. 1961) therefore producing no error. The $MgSO_4$ concentration of 0.06% in solution will have dissolved with a volume increase of about 50% of the solute volume (Hodgman et al. 1961), giving rise to a 0.15% error in particle density. However, the total 1% of gypsum in the sample should also have dissolved giving rise to a 0.2% concentration in solution. With a volume change of about 50% of the solute volume, the particle density was over-estimated by about 0.5%. Since soluble salt concentrations of other samples are all lower than the example given, errors in particle density from this source are generally well below 0.1%. However, gypsum, where amounts are large, as occurs in several horizons, can dissolve to the extent of 1.3% of the soil (Jackson 1958) giving rise to a 0.7% error in particle density. It should be realized that this error exists in such cases but since values were used mainly in conjunction with bulk densities where errors are much larger, for calculation of porosity, correction of values was not considered justified.

Particle size analysis

The pipette method (Kilmer and Alexander 1949) with some modifications made by Toogood and Peters (1953) was used. Sand was separated into five fractions by sieving on a shaker for 10 minutes.

Moisture retention

Soil and till cores obtained with the truck-mounted coring device were enclosed in rubber rings and cut to 3 cm lengths before being placed, still in field-moist condition, on a Soil Moisture Equipment Co. 15 bar ceramic plate extractor. Following saturation, soil cores were subjected to pressures of 0.1, 0.33, 1.0 and 15 atmospheres, using nitrogen gas. Till cores were subjected to pressures of 0.05, 0.1, 0.33 and 1.0 atmospheres. After about five days allowed for equilibriation, this being the time normally necessary for cessation of outflow, the cores were carefully removed, weighed and replaced before being re-saturated and subjected to further pressure treatments. Loss of material from the cores between treatments which could result in considerable error, was kept to a minimum. The alternative but more accurate method, employing different cores for each pressure treatment would have involved a prohibitively large number of cores.

II - CHEMICAL ANALYSES

Cation Exchange Capacity

The method of Bower et al. (1952) was used. This involved treatment of soil in a centrifuge tube with sodium acetate, and displacement of sodium with ammonium acetate. Sodium in the displacement solution was determined using a Perkin Elmer 303 atomic absorption spectrometer.

Exchangeable Cations

Using the method of Bower et al. (1952), 1N ammonium acetate was employed to displace the cations, which were then determined using the atomic absorption spectrometer. Only samples low in soluble salts were employed.

Soluble Salts

Saturation extracts were obtained by the method of Scofield (1932) from soil and shallow till samples. In addition, 1 : 5 soil-water extracts, or where large amounts of gypsum were known to be present, 1 : 25 or 1 : 50 extracts, were prepared by shaking with water overnight followed by centrifuging. Only 1 : 5 soil-water extracts were obtained from deep till and bedrock samples.

Soil, till and bedrock extracts, as well as water samples from piezometers were analyzed for Ca^{++}, Mg^{++}, Na^{+} and K^{+} using the turbimetric method involving precipitation of barium sulphate (Chesnin and Yien 1951) with modifications used by Massoumi and Cornfield (1963). Carbonate and bicarbonate were determined by titration using the method of Magistad *et al.* (1945). Chloride was determined by titration with standard silver nitrate in the presence of potassium chromate (Magistad *et al.* 1945).

Soil Reaction

The soil paste method outlined by Doughty (1941) was used, with a Beckman model H2 glass electrode pH meter.

Electrical Conductivity

This was measured on the saturation extracts using a Yellow Springs Instrument Company model 31 conductivity bridge with 3403 cell.

Carbonates

Calcium carbonate equivalent was determined using a Smolik calcimeter (Bascomb 1961). In addition, soil and till samples which had already been extracted with sufficient water to remove salts and gypsum, were then extracted overnight with 2N HCl, and calcium and magnesium were determined in these extracts using the atomic absorption spectrometer. The calcium and magnesium removed should have come from carbonate and from the exchange complex. Since calcium and magnesium are approximately equally strongly held by the exchange complex, the ratio of calcium to magnesium there should be similar to that in soil solution, but may differ from that in carbonate form because of solubility differences. However, where amounts of carbonates are large, and the proportion in the exchangeable form is small compared to the total, the Ca : Mg ratio in the extracts will approach the ratio in carbonate form. The ratio in the extracts was therefore applied to the carbonate equivalent values to obtain approximate separate values for calcium and magnesium carbonates.

Gypsum

Deb's method, as reported by Hesse (1971), was used to estimate gypsum content by comparing the amount of sulphate in water extracts which were sufficiently dilute to dissolve all the gypsum with the amount of sulphate and calcium in saturation extracts. The extracts were those used to obtain soluble salts.

Organic Carbon

The wet combustion method of Walkley and Black (1934) was used.

RESULTS AND DISCUSSI

RESULTS AND DISCUSSION

I. - GROUND TEMPERATURES

The 0 °C isotherm penetrated less deeply during winter 1972/3 than during winter 1971/2 at the six sites for which full information is available (Figure 6), presumably because of differences in air temperature. The mean air temperature at Vegreville for the five month period, November to March, was -14.6 °C in 1971/2 and -11.2 °C in 1972/3. It seems likely that soil temperature differences between the two years would h[illegible]en greater but for a shallower snow cover during the colde[illegible] December, January and February 1972/3 (mean 16 cm) than [illegible] previous year (mean 27 cm). Differences in summer heat penetration between the two years appear small.

There were considerable differences among sites over the period in spite of the sites all being under fairly similar grass vegetation cover. Winter penetration of the 0 °C isotherm was only 150 cm at Site 4 compared with over 300 cm at Site 7. Site 7 was only 3 metres from the west side of a poplar wood and this could largely account for its exceptionally warm winter temperatures. Snow drifted to a depth of 0.6 to 0.9 metres at this site but since snow drifted to a similar depth at Site 3 where the 0 °C isotherm penetrated much deeper, the protective effect of the wood, and possibly the effects of aspect may be more important factors than snow depth in influencing the winter soil temperatures. At Site 4, and also Site 3 which was partially

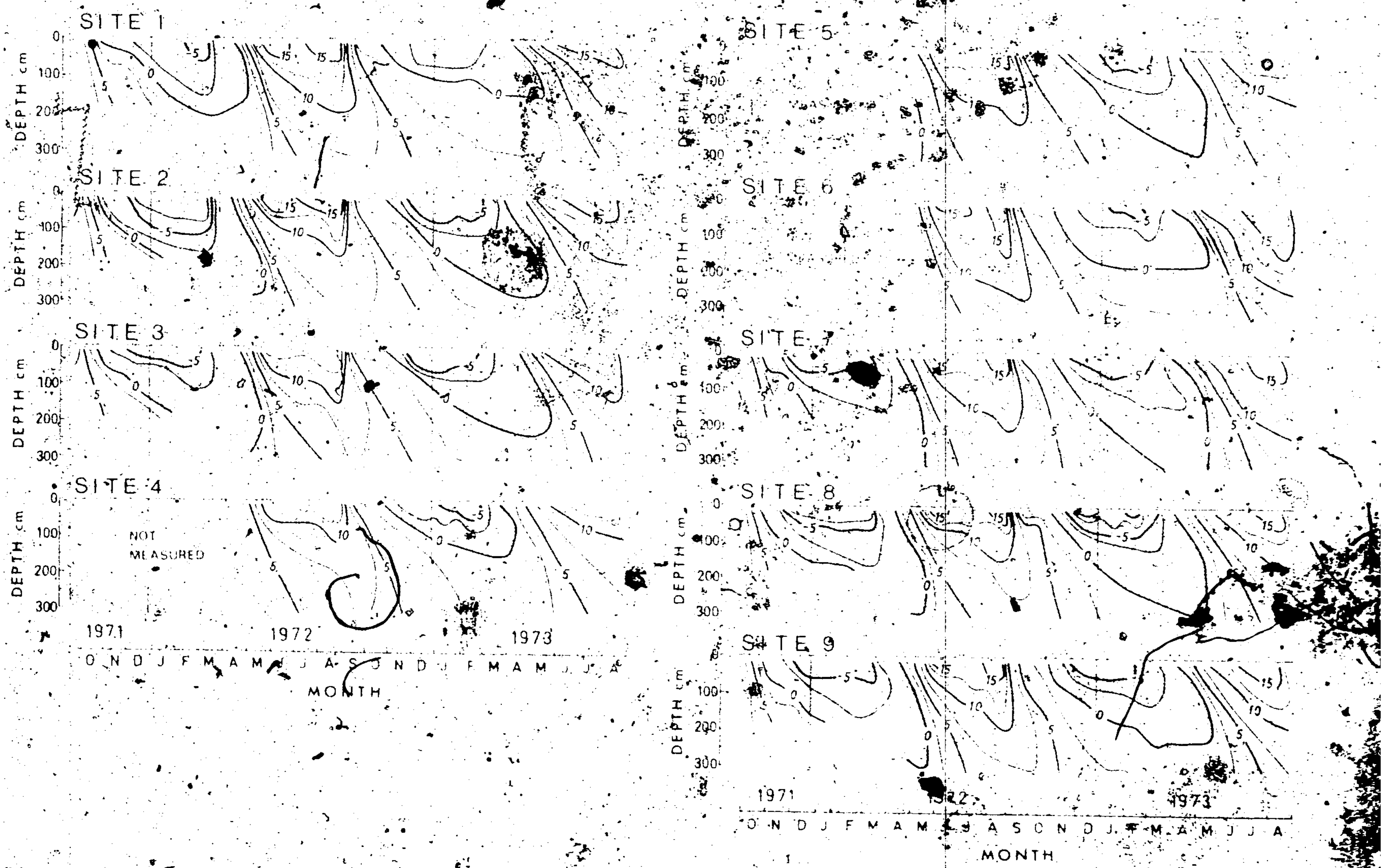


Figure 6. Isotherms in relation to time and depth at the soil study sites. Temperatures below 0°C are shaded.

shaded by a thinly wooded fenceline, summer temperatures were cooler than at other sites. Sites 1, 6 and 9, where the water table was usually within 1 metre of the surface (Table 2), exhibited a lesser penetration of the 0 °C isotherm in winter than all other sites except Site 4, but summer heat penetrated deeper at these wet sites than at other sites, the effects being most pronounced at Site 6, where the water table was closest to the surface. This suggests that the wetter sites should have warmer mean annual temperatures than neighbouring drier sites, which was confirmed (Table 3). Since temperatures were always recorded during daytime, the means for 20 cm are probably slightly in error, because detectable diurnal fluctuations can penetrate to this depth, but temperatures at other depths should be reasonably reliable and are 2-3 °C warmer than the mean air temperatures for the same period: -0.4 °C in 1971/2 and +1.4 °C in 1972/3, recorded at Ranfurly. The deeper penetration of the 0 °C isotherm at Site [illegible] than at other sites is not easily explained. Winter snow depths averaged about 2 cm less at Site 7 than at Site 8, and very slightly less than at Site 5: it is also likely that a greater bulk density of both soil (Table 2) and till at this site, and consequently lesser porosity, would, through its effect on thermal conductivity, be a contributing factor.

Strong soil temperature gradients in September and October and again in spring, provide an opportunity for thermal diffusivities to be estimated. Such estimates made *in situ* are not very precise due to temperature fluctuations at the soil surface, and soil air and water movements, but they are useful

Table 2. Some site characteristics influencing soil temperatures.

Site	Altitude metres a.m.s.l.	Aspect	Open (O) or Sheltered(S)	Depth to water table Average(approx) cm 1971/2	1972/3	Snow depth Max. cm 1971/2	1972/3	Bulk Dens. 50cm depth
1	675	Nil	O	80	70	56	43	1.6
2	676	NE	O	220	190	38	28	1.5
3	679	NE	S	320	310	[illegible]	46	1.4
4	647	W	S	260	240	68	61	1.3
5	640	W	O	110	100	35	19	1.7
6	638	Nil	O	60	50	45	20	1.6
7	639	Nil	O	180	180	36	18	1.8
8	636	W?	O	290	280	43	[illegible]	1.6
9	633	Nil	O	70	90	38	[illegible]	1.7

Table 3. Mean soil temperatures for the periods October 1, 1971 to October 1, 1972 and October 1, 1972 to October 1, 1973 at the nine study sites, in °C.

Depth cm	Site 1	2	3	4	5	6	7	8	9
				October 1971 - October 1972					
20	5.1	3.7	3.5	-	-	-	3.7	2.7	3.5
50	4.5	3.1	3.2	-	-	-	3.6	2.9	3.3
150	4.9	3.7	3.4	-	-	-	3.8	3.1	3.6
300	-	-	-	-	-	-	-	-	-
				October 1972 - October 1973					
20	4.1	3.5	2.3	3.0	2.5	4.0	2.0	[illegible]	2.8
50	3.5	3.4	2.7	3.7	3.1	4.2	3.2	3.7	3.0
150	4.2	4.1	3.5	4.1	3.5	4.2	3.6	[illegible]	3.3
300	4.3	4.2	3.7	4.1	3.8	4.4	3.5	3.4	3.4

for comparative purposes. At 50 cm depth, the rate of temperature change, dT/dt, is generally greater at the wetter sites (1, 6 and 9) than at neighbouring drier sites (5, 7, 8) and since diffusivities at this depth are not consistently different (Table 4), the cause is unlikely to be differences in thermal properties at 50 cm depth (diffusivity being a measure of the rate of temperature change that occurs under a given situation of heat supply and temperature gradient), but possibly differences in thermal diffusivities nearer to the soil surface. Other causative factors could however be greater albedo of darker wetter soil surfaces and a thinner vegetative cover, at the wet sites. In winter, in [illegible] of initially more rapid cooling at the wet sites, penetration of the 0°C isotherm is presumably limited to a greater extent than [illegible] sites by the moisture reserve which under conditions inv[illegible] heat of freezing, acts as a heat source.

Diffusivities are of fairly similar magnitudes to those quoted by Van Wijk (1963) and Longley (1967). However, sites at higher elevations (1 to 3) show greater values for September than June, whereas the other sites show the reverse trend. The differences reflect similar differences in the magnitudes of d^2T/dz^2 (rate of change with depth of the temperature gradient) which could result from several causes, the most important of which are probably differences in aspect, water infiltration and air movement.

Table 4. Rate of temperature change (dT/dt), rate of change with depth of the temperature gradient (d^2T/dZ^2) and diffusivity (D) in late Sep [illegible] 1972 and late June 1973 at 50 cm depth at the nine study sites.

Site	dT/dt °C/day		d^2T/dZ^2 x 10^{-3} °C/cm²		D x 10^{-3} cm²/sec	
	Sept	June	Sept	June	Sept	June
1	-0.22	0.16	-0.5	1.8	4.9	1.4
2	-0.17	0.14	-0.7	1.3	2.7	1.2
3	-0.15	0.12	-0.8	1.0	2.1	1.4
4	-0.20	0.11	-2.0	0.2	1.1	6.0
5	-0.21	0.10	-1.7	0.1	1.5	8.3
6	-0.24	0.14	-1.4	0.3	2.0	5.1
7	-0.21	0.11	-1.1	0.3	2.2	4.7
8	-0.20	0.12	-1.1	0.4	2.0	3.1
9	-0.20	0.16	-0.6	0.[illegible]	3.6	4.5

T = temperature; t = time; Z = Vertical distance; D [illegible]ty

IX - HYDRAULIC CONDUCTIVITIES

Hydraulic conductivities of Fluvio-glacial and Bedrock materials

Materials of the Hummocky Disintegration Moraine showed extreme variability of texture (Figure 7), and therefore the very sandy loose materials (sands, loamy sands and sandy loams) underlying Sites 1 and 2, because of their distinct properties, were considered separately from other stratified drifts and till in calculating hydraulic conductivities. However all these materials are in places intermixed. In contrast, samples of Ground Moraine Till from the lower study sites, even though greater in number than those from Hummocky Moraine, showed a relative uniformity of texture and no separation was necessary. Coring did however show that some thin bands of high permeability existed in this otherwise poorly permeable till. Such layers occurred at depths of about 3 metres at Site 4, and 2 metres at Site 5. A few samples from bedrock showed enormous variability of texture. However no basis for separation could be found from descriptions made during drilling, since most materials consisted of closely alternating layers of sandstone and shale, both of which, being high in montmorillonite, could be expected to be equally low in permeability.

1. Loose sandy materials of Hummocky Disintegration Moraine origin

Because of the looseness of these materials, degree of anisotropy (Kh/Kv) is difficult to estimate, and for the purpose

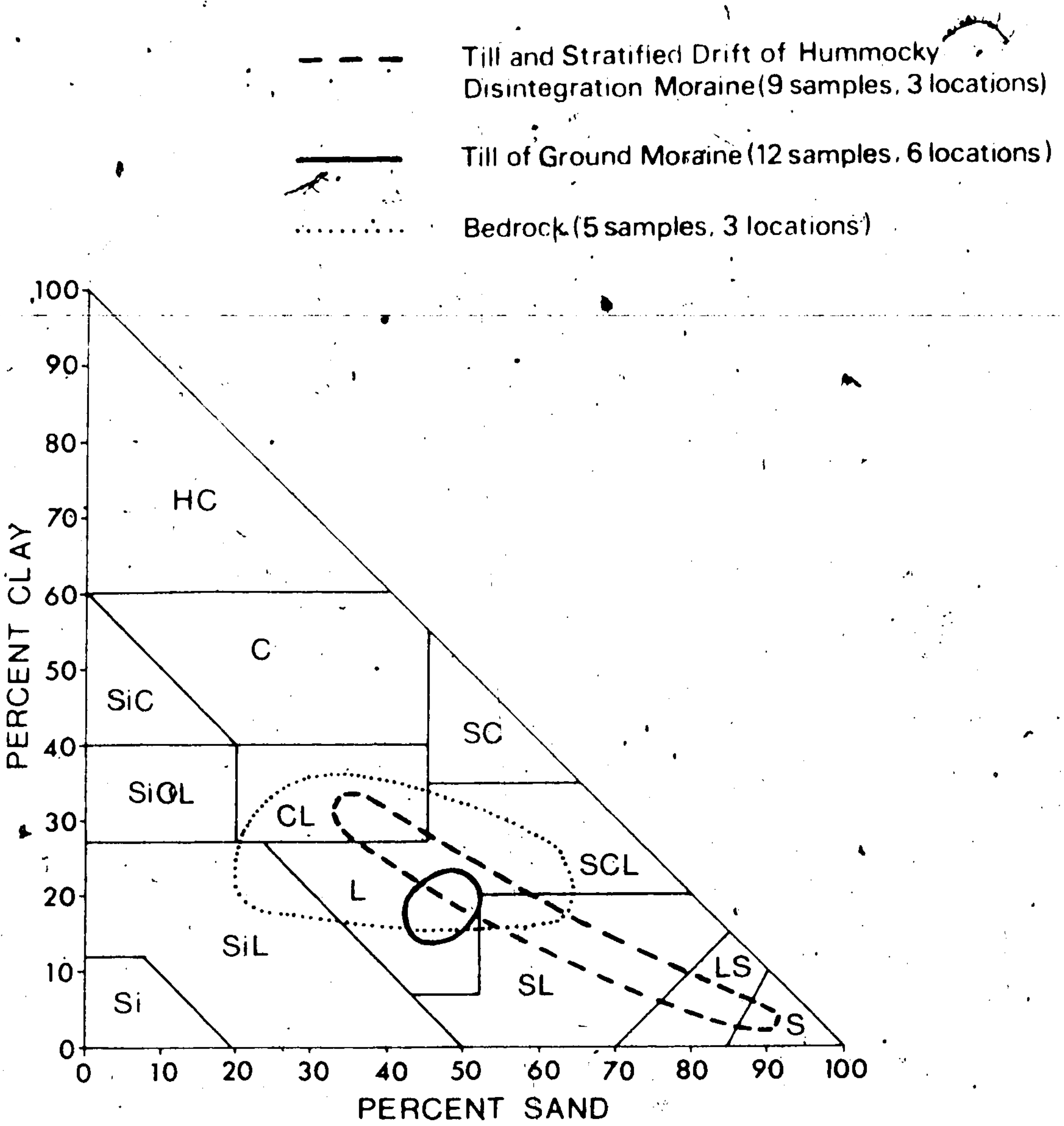


Figure 7. Range of particle size analyses for samples from fluvioglacial drift and bedrock at the soil study sites, using the Canadian textural classification diagram (Toogood 1958).

of calculating hydraulic conductivity from piezometers, it was assumed to be equal to one. Agreement is fairly good between hydraulic conductivities calculated from piezometers, a laboratory determination, and a prediction made from particle size analysis using Hazen's line (Table 5). The approximate value of 4 cm/hr is much higher than for the other surficial materials or bedrock.

2. Other Stratified drifts and Till of Hummocky Disintegration Moraine origin.

Hydraulic conductivity values obtained from these materials were extremely variable (Table 6). Calculation of horizontal conductivities from piezometers was based on a degree of anisotropy (Kh/Kv) of 10 used by others for similar materials (Freeze 1969). Hydraulic conductivities obtained from cores were much larger than those predicted from particle size analyses using information from Lambe and Whitman (1969). Some cracking or shattering of the cores may be the reason for this discrepancy. It would be difficult to provide an overall estimate of hydraulic conductivities applicable to either the stratified drifts or the till, since both are intermixed, and at Sites 1 and 2 they also appear to be partially intermixed with the loose sands. At Site 3 where the till is predominant, values for horizontal conductivity (Kh) of 0.002 cm/hr and vertical conductivity (Kv) of 0.0002 cm/hr are tentatively suggested.

Table 5. Hydraulic conductivity of loose sandy materials from piezometers, laboratory cores, and predicted from particle-size analysis.

Site	Depth cm	Hydraulic conductivity cm/hr Piezometer	Laboratory	Predicted
1	300	3.2	-	-
	600	9.7	-	-
2	300	-	4.0	2.5
	430	1.6	-	-
Means		4.8	4.0	2.5

Table 6. Hydraulic conductivity of stratified drifts of Hummocky Disintegration Moraine from piezometers, laboratory cores and predicted from particle size analysis.

Site	Depth cm	Hydraulic conductivity cm/hr Piezometer Horizontal(Kh)	Laboratory Vertical(Kv)	Predicted Mean(Km)
		STRATIFIED DRIFT		
1	150	-	0.012	0.001
1	200	-	0.049	0.00007
2	150	-	0.52	0.01
2	730	0.00008	-	-
3	320	-	0.12	0.01
3	520	0.15	-	-
Means		0.08	0.17	0.005
		TILL		
3	150	-	0.00003	0.00007
3	200	-	0.0007	0.00007
3	230	-	0.0011	0.00007
3	250	-	0.0007	0.00007
3	300	-	0.0013	0.00007
3	820	0.0002	-	-
Means		0.0002	0.0008	0.00007

3. Ground Moraine Till

Results for the three methods of estimation are not dissimilar (Table 7) if allowance for anisotropy is made. It is likely that degree of anisotropy (Kh/Kv) is closer to 5 than 10, since there is a relative lack of stratified materials in these deposits, and a value of 5 gives a better agreement between piezometer and laboratory determinations. Average values are assumed to be 0.001 cm/hr for horizontal conductivity (Kh) and 0.0002 cm/hr for vertical conductivity (Kv).

4. Bedrock

With equipment available, core samples could only be obtained where the bedrock was close to the ground surface. Consequently only three laboratory determinations were made. The mean of two determinations on sandstone was 5.6×10^{-5} cm/hr, while a value of 7×10^{-5} cm/hr was predicted from particle size analysis. The remaining core, described as shale but more properly siltstone (Folk 1954), gave a value of 2.1×10^{-4} cm/hr in the laboratory, rather smaller than the value of 2.5×10^{-3} cm/hr predicted from particle size analysis. The very low values for sandstone are a consequence of a high montmorillonitic clay content and relatively small silt content.

A total of 43 piezometers which terminated in bedrock provide estimates of hydraulic conductivity where assumptions concerning anisotropy are made. The value chosen for degree of anisotropy is 50, based on research results on similar bedrock

Table 7. Hydraulic conductivity of tills of ground moraine from piezometers using two assumed values for degree of anisotropy, from laboratory cores, and predicted from particle size analysis.

Site	Depth cm	Hydraulic conductivity cm/hr			
		Piezometer		Laboratory	Predicted
		Horizontal(Kh)		Vertical(Kv)	Mean(Km)
		Kh/Kv=10	Kh/Kv=5		
4	200	-	-	0.0012	0.0003
4	300	-	-	0.0011	0.0015
4	670	0.0035	0.0031	-	-
5	150	-	-	0.00003	0.0003
5	200	-	-	0.00003	0.0003
5	300	-	-	0.0001	0.0010
5	460	0.0001	0.0001	-	-
5a	180	0.0002	0.0002	-	-
6	150	-	-	0.00006	0.00007
6	180	0.0002	0.0002	-	-
7	150	-	-	0.00002	0.00007
7	200	-	-	0.0001	0.005
7b	180	0.0028	0.0024	-	-
7c	180	0.0003	0.0003	-	-
8	150	-	-	0.0001	0.001
Means		0.0012	0.0010	0.0003	0.001

materials (Freeze 1969). Values obtained for horizontal hydraulic conductivity (Kh) show an enormous range (Table 8), but statistics for the soil study sites were remarkedly in agreement with those obtained from the deep piezometers installed as part of Leskiw's (1971) study. A most noticeable feature was the very skewed distribution of values (Figure 8). This presumably arises because occasional fissures or bands of very high permeability (aquifers) exist in a material, the bulk of which has a very low permeability. The skewed distribution has to be taken into account in estimating an 'average' value for the bedrock. The arithmetic mean is over-influenced by the few very high values, so the median, or mean of the logged values should be more representative. Should the very high values represent horizontal bands having much influence on horizontal flow but little effect on vertical flow, then it is possible that the mean may come closer than the median in estimating horizontal conductivity, while the median or mean log representing the bulk of material may be closer to the vertical hydraulic conductivity. Approximate values, which are in agreement with those found on similar materials elsewhere (Freeze 1969), are 0.004 cm/hr for horizontal conductivity and 8 x 10^{-5} cm/hr for vertical conductivity, but where applied to individual sites and depths, some account should be taken of the actual values at those locations.

Soil saturated hydraulic conductivities

These values (Table 9) are of interest in comparing the

Table 8. Hydraulic conductivities in bedrock, calculated from piezometers.

		Statistics	
	Soil Study Sites	Deep Piezometer Nests	All Piezometers
Sample Size	28	15	43
Maximum, cm/hr	0.42	0.39	0.42
at Site	4	III	4
at Depth, m	12.8	47	12.8
Minimum, cm/hr	5×10^{-6}	3×10^{-5}	5×10^{-6}
at Site	9	I and III	9
at Depth, m	24.4	124, 97	24.4
Mean, cm/hr	0.019	0.027	0.022
Median, cm/hr	0.00010	0.00017	0.00014
Mean log, cm/hr	0.00026	0.00032	0.00028

Table 9. Saturated hydraulic conductivities (K) in 2 mm sieved soil from Ah and Ap horizons.

	Site								
	1	2	3	4	5	6	7	8	9
Horizon	Ah	Ap	Ap	Ap	Ap	Ah	Ap	Ap	Ah
K cm/hr	2.2	2.8	2.0	2.3	1.5	0.4	1.8	1.7	1.6

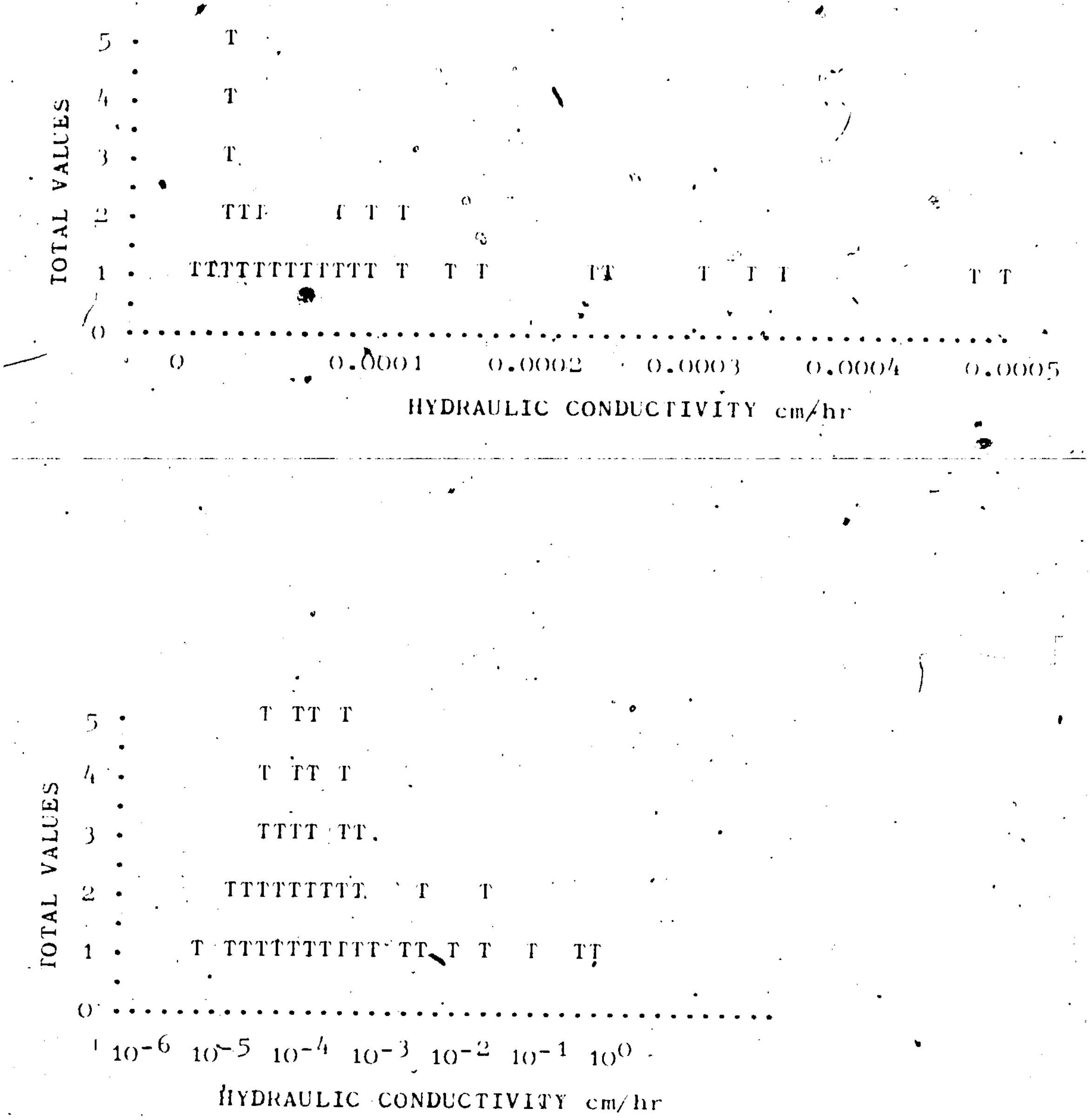


Figure 8. Frequency histograms showing distribution of Bedrock hydraulic conductivities on an arithmetic scale (above) and on a log scale (below).

extent to which Ah or Ap horizon permeabilities might limit rainfall or snowmelt infiltration in different soils. Unsaturated flow would however be a more usual condition than saturated flow in surface horizons. Solonetzic soils (Sites 5-9), as expected, had smaller hydraulic conductivities than soils at other sites, and the only alkaline Solonetz (Site 6) had the smallest value. Salts in solution, by maintaining flocculation, presumably contributed to the much larger value in the saline Solonetz at Site 9, than in the alkaline Solonetz. With the exception of the alkaline Solonetz, differences between soils were not large, and it appears that the Ah and Ap horizons are able to absorb and transmit water fairly freely, even in most Solonetzic soils.

III - GROUNDWATER CHEMISTRY

Analyses of water samples from piezometers installed as part of Leskiw's (1971) study, after its completion, are in general conformity with conclusions reached by Leskiw himself from well and spring water samples obtained from the same area. Results of these analyses presented as a computer print-out diagram (Figure 9) obtained using the contouring program Symap (Shepard 1970, Symap Manual 1971) are therefore only briefly discussed here. With decline in site elevation, there is an increase both in total dissolved solids and in the sum of sodium and potassium concentrations (mainly sodium since potassium amounts are small) as a proportion of total cations. This is to be expected from increase in length of groundwater flow paths and thus time of contact between water and lithology towards the valley floor (Chebotarev 1955, Schoeller 1959). The sum of sulphate and chloride concentrations as a proportion of total anions also increases with decline in site elevation, but only near the ground surface. Since little chloride is present in groundwaters of this area, the sum of sulphate and chloride closely reflects sulphate alone, and as suggested by Leskiw (1971), the small amounts in deep samples near the valley floor may result from sulphate reduction. The ratio of calcium to magnesium, which can be expected to decline with increase in flow path length (Tóth 1966), did not follow any consistent pattern here, presumably because of almost negligible amounts of magnesium in many samples.

Aspects of groundwater chemistry of interest here are

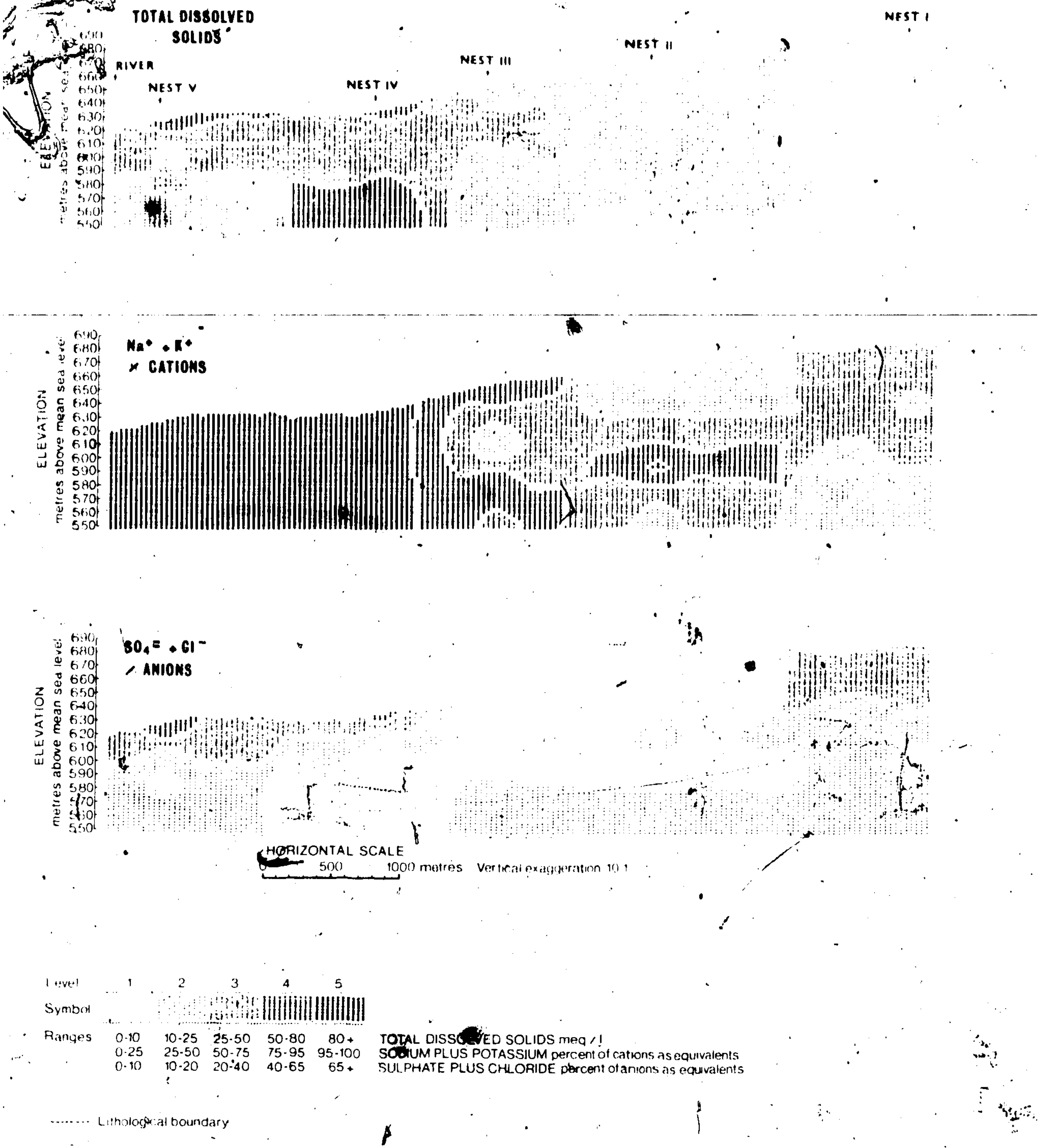


Figure 9. Distribution of total dissolved solids, sodium plus potassium as a percentage of cations, and sulphate plus chloride as a percentage of anions obtained from analysis of water in piezometers installed as part of Leskiw's (1971) study.

those most likely to have a bearing on soil genesis at the individual soil study sites. In this connection, total dissolved solids, sodium as a proportion of cations, and to a lesser extent, sulphate as a proportion of anions, were considered of most interest in waters from the upper and lower soil study areas. There is a lesser content of dissolved solids and proportion of sodium in the upper study area than in the lower study area (Figure 10), presumably for reasons discussed above. Within the upper study area, total dissolved solids are least at intermediate depths where a sand layer is located and most in the till, and in the absence of large amounts of sodium or potassium, presumably largely reflect calcium and magnesium content of the lithology. Sodium amounts as a proportion of total cations are larger in the sand layer, which is close to the surface at Sites 1 and 2, and reflect a low calcium and magnesium content rather than a greater absolute sodium content. In the lower study area, both total dissolved solids and sodium as a proportion of cations are greatest close to low lying areas around Sites 6 and 9 where groundwater discharge of deep origin might most reasonably be expected. Evapo-transpiration has presumably aided in concentrating total dissolved solids close to the ground surface. The extension of high total dissolved solids and high sodium content at Site 6, westward to beneath higher ground at Site 7 where local recharge would be expected to cause decline in salinity, may result from strong lateral flow towards the river within more permeable layers of the bedrock (see p.115).

Sulphate as a proportion of total anions does not follow

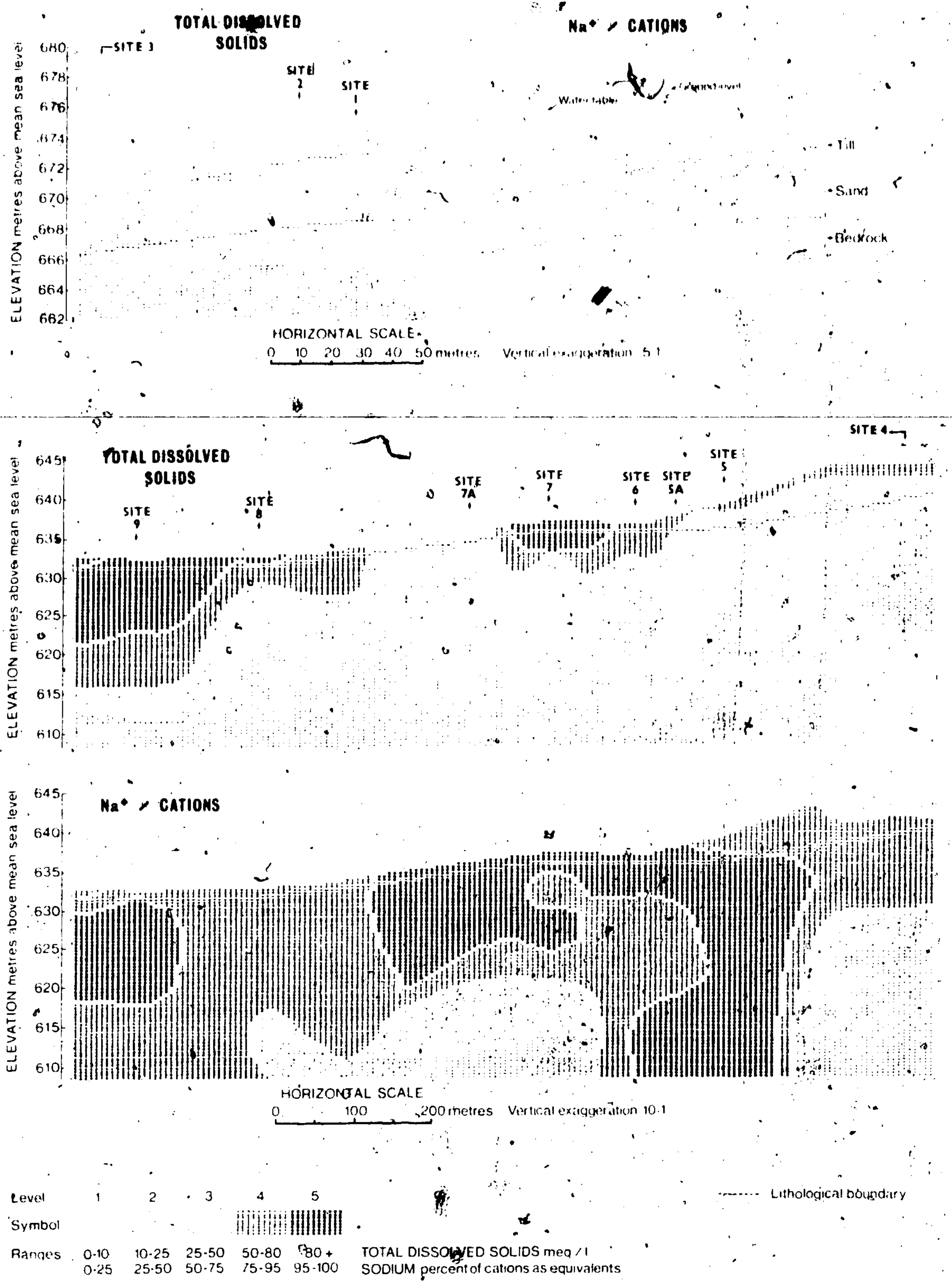


Figure 10. Distribution of total dissolved solids, and sodium as a percentage of cations in groundwater from Upper and Lower soil study areas.

as consistent a pattern as total dissolved solids or sodium and zones of high and low concentration occur in both upper and lower study areas (Figure 11). In the upper study area a high sulphate content appears to be associated with the till, which is thick at Site 3 and thins towards Site 2 while low concentrations exist in the sand layer which underlies the till and the bedrock. In the lower study area, sulphate near the ground surface shows some relationship with expected concentrations of groundwater discharge, but as discussed in connection with piezometers installed as part of Leskiw's (1971) study, sulphate concentrations deep within the bedrock are fairly low throughout the flow system.

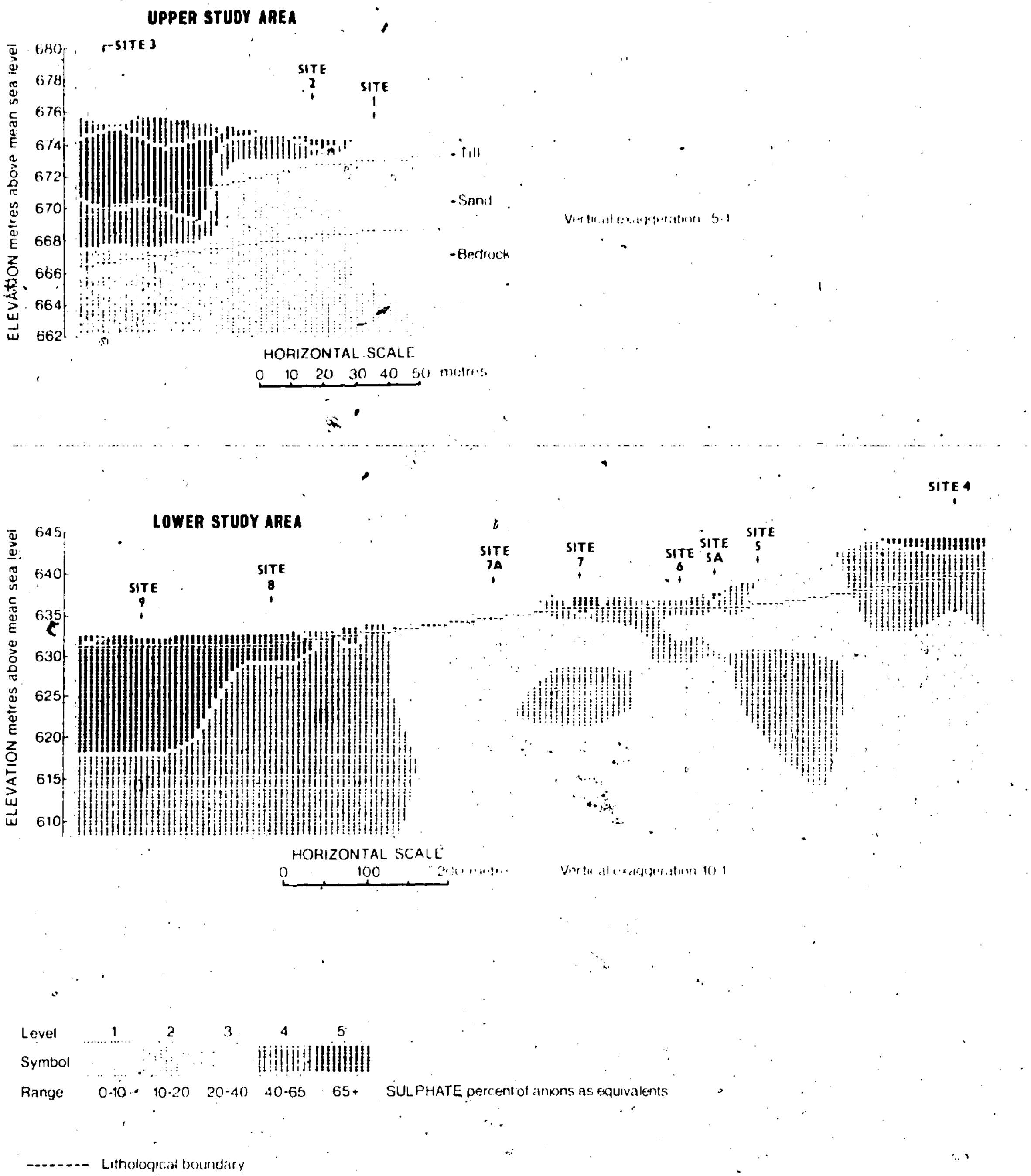


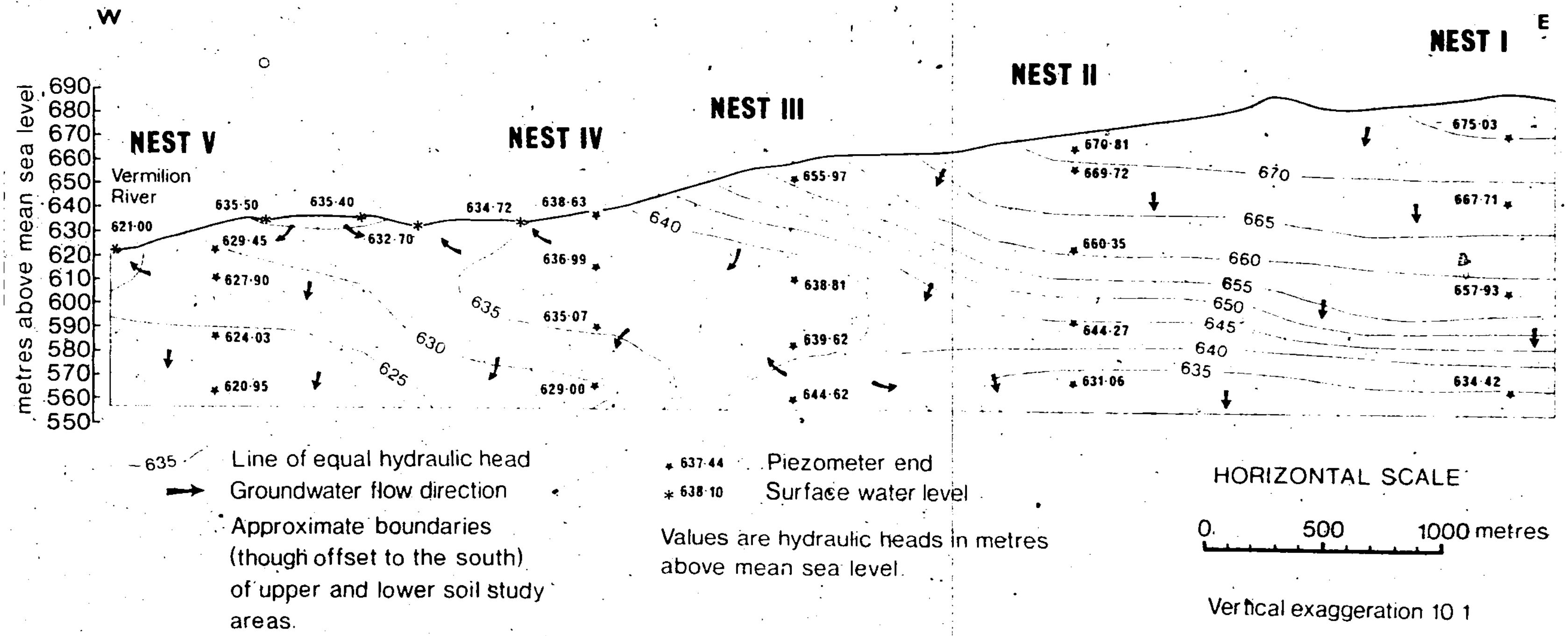
Figure 11. Distribution of sulphate as a percentage of anions in groundwater from Upper and Lower soil study areas.

IV - GROUNDWATER FLOW

Groundwater flow beneath the whole west slope

Piezometer nests installed by the Department of Environment have provided information on deep groundwater flow which should be applicable over much of the western sloping portion of Leskiw's (1971) study area, including the sites involved in this study, which approximately parallel the nests, 0.5 to 2 km to the South. Except for a few of the shallower piezometers, seasonal water level fluctuations were extremely small and since differences between annual means for the two years of study were almost negligible, the mean levels for the period October 1972 to October 1973, for which fullest information is available, were considered reasonably representative of the whole study period. Hydraulic potentials of surface water bodies were included along with these piezometer means to aid in calculating the correct position of equipotential lines using the computer contouring program Symap (Shepard 1970, Symap Manual 1971). This program used in conjunction with the subroutine CContr prepared by the Civil Engineering and Computer Services Departments at the University of Alberta enabled drawing of equipotential lines to be performed by a Calcomp 770/663 plotter. Flow directions were then calculated from these equipotential lines to take account of both a bedrock anisotropy of 50 : 1 and the vertical exaggeration (Figure 12).

Downward flow predominates throughout the area, the



igure 12. Groundwater flow beneath the western slope of the area studied by Leskiw (1971).

hydraulic gradient being greatest and most consistent between nests I and II beneath topographically high elevations. At nest III, near the theoretical midline (Tóth 1962), shallower flow remains downward but deeper flow is more confused becoming mainly lateral at around 600 m elevation between nests III and IV. At nests IV and V, deep flow is still downward, but at shallow depths small zones of upward flow are indicated both to the west of nest IV and at the Vermilion River, separated by a local downward flow beneath a small rise in ground level. Supporting evidence for discharge in the vicini [illegible] nest IV is provided by the shallowest piezometer at this nest, since it had a mean water level just above ground level, which is at least 1 metre above the estimated position of the water table, and in September 1971, the water level in this piezometer rose to a peak of 0.8 m above the ground.

A predominantly downward regional flow even beneath topographically low elevations is a departure from the ideal 'small drainage basin' of Tóth (1962), but not a unique situation on the Plains. Meyboom (1967b) describes such a situation in the Arm River valley of Saskatchewan where regional flow towards the river is superimposed on a deeper regional downward flow into the highly permeable Beechy Sandstone. Examination of stratigraphy of the Vegreville area (Shaw and Harding 1949) does not reveal the presence of such a well-defined aquifer below the Vermilion River, but beds of sandstone such as the Victoria member of the Belly River Formation should be present 100 m or so below the river and could cause downward flow in the less permeable beds above by conveying water northwards to discharge at lower elevations downstream.

Flow towards the 600 m elevation at nest III and away from it at nest IV suggests the presence of a horizontal aquifer at about this depth. The piezometer terminating at 610 m elevation at nest III showed that the material at its base has a horizontal hydraulic conductivity 3000 times the median for the bedrock, providing further evidence for the existence of such an aquifer, which if terminating near nest IV could contribute to the near surface discharge observed there. Such effects caused by lenses of high permeability are explained in more detail in ~~a subsequent section (see pp. 101, 103).~~

Groundwater flow at the soil study sites

1. Characteristics of Hydraulic Potentials at shallow depths

Hydraulic potentials at shallow depths exhibited marked fluctuations. In the upper study area (Sites 1-3) and at Site 4 in the lower study area sharp rises occurred in response to spring thawing and the very heavy rainfalls of summer 1973 with declines in levels during winter (Figure 13). In contrast, potentials at sites further downslope were generally little affected by short term weather changes, and in the extreme cases of Sites 8 and 9, followed almost perfect annual sinusoidal curves (Figure 14). At Sites 7, 8 and 9, fluctuations in potential at different depths were generally not in phase as was normally the case at the higher sites. The shallowest piezometers showed maximum hydraulic potentials in August at Site 7 and in September at Sites 8 and 9

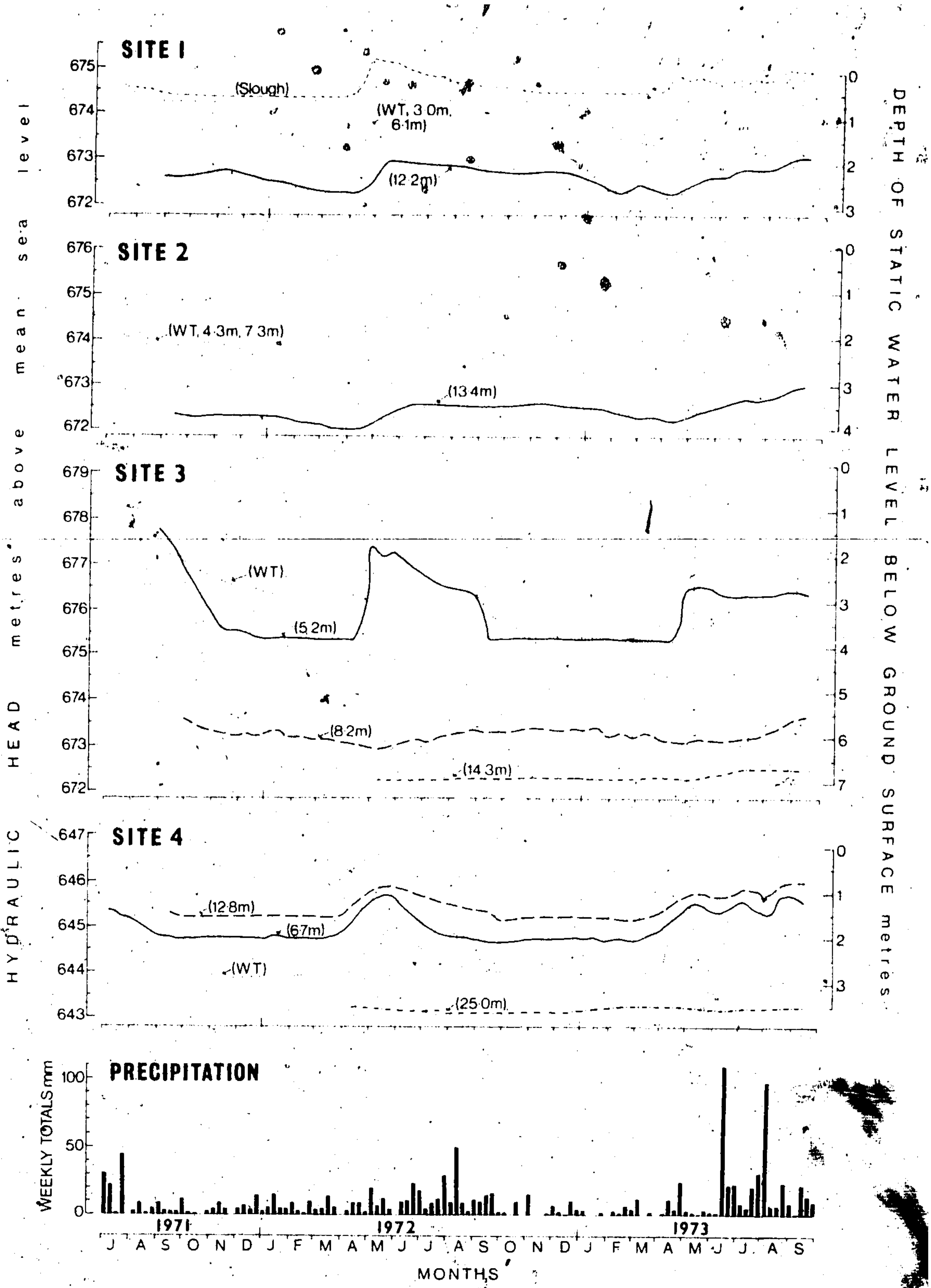


Figure 13. Sites 1 to 4 water table (WT), slough, and piezometer levels adjusted for basic time lag (end depths bracketed), in relation to time and precipitation.

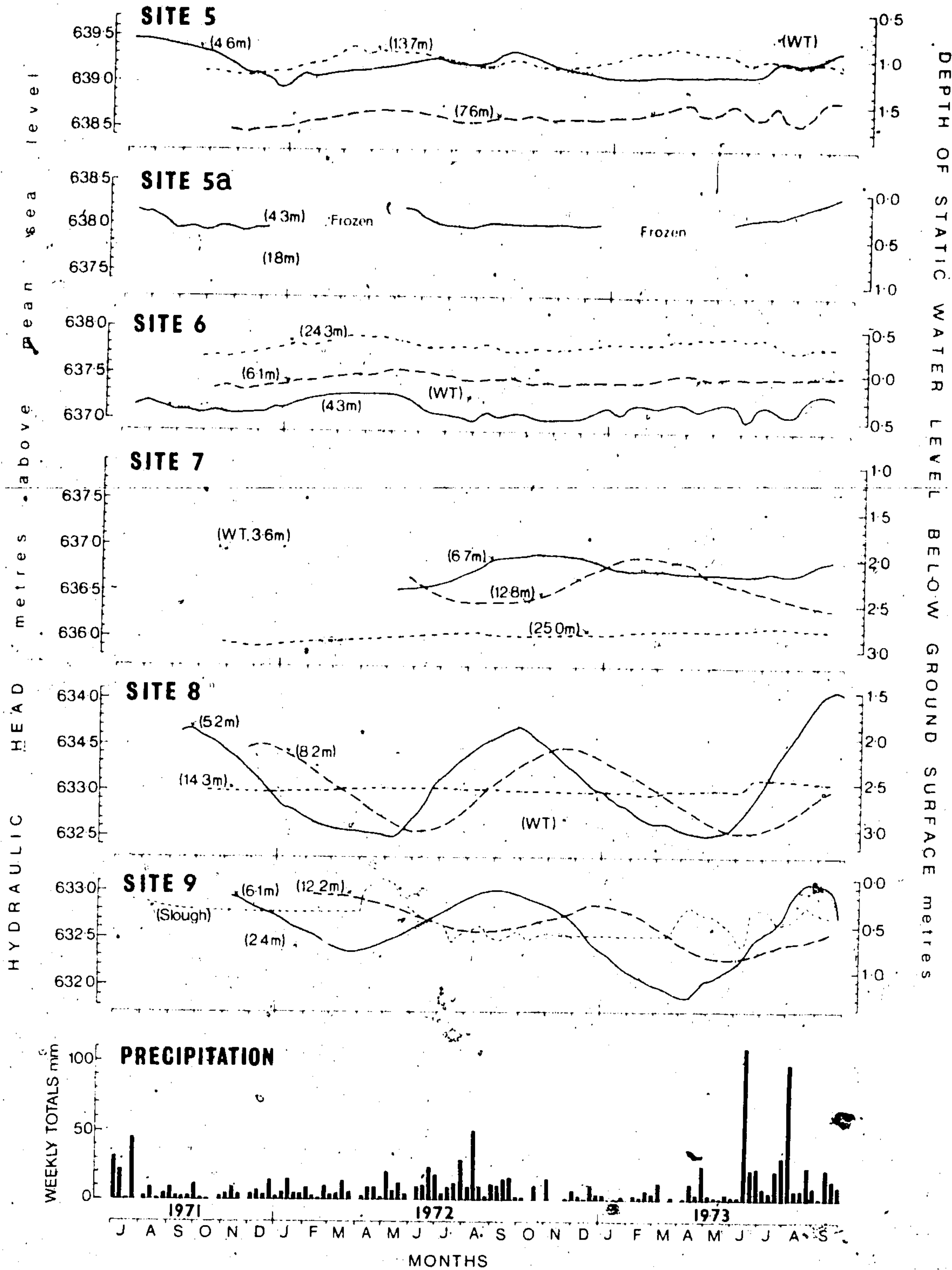


Figure 14. Sites 5 to 9 water table (WT), slough, and piezometer levels adjusted for basic time lag (end depths bracketed), in relation to time and precipitation.

while potentials at greater depths reached peaks progressively later suggesting a possible lag effect in addition to reduction in amplitude with depth, and also a possible lag effect with respect to position downslope. Some small delays in adjustment to seasonal infiltration might be expected because of small though significant compressibilities of both water and rock (Ferris et al. 1962) and these would of course be enhanced by the presence of any entrapped gases. Probably more important factors contributing to lag effects are permeability contrasts causing effective separation and connection between different flow zones, and the gradual lateral movement of water downslope through the more permeable near-surface layers both above and below the water table. Frost effects must be taken into account in the interpretation of some near-surface water level fluctuations. The decline of near-surface water tables in winter has been partly attributed to upward movement of water, into the frost layer, and the rapid rise in spring partly to subsequent thawing (Schneider 1961, Willis et al. 1964, Meyboom 1967b). Site 1, situated 3 to 4 metres from open water showed a decline in both water table and shallow piezometer potentials from levels only slightly below the adjacent open water (slough) in October to around 1.5 m below the slough by winter's end. Although limited neutron probe moisture readings available for winter 1971 showed a sufficient increase in moisture content of the unsaturated zone to account for the fall in water table level (Figure 15), most of this moisture increase occurred prior to December 31 while less than 50% of the water table fall had occurred by this date, and the deeper moisture

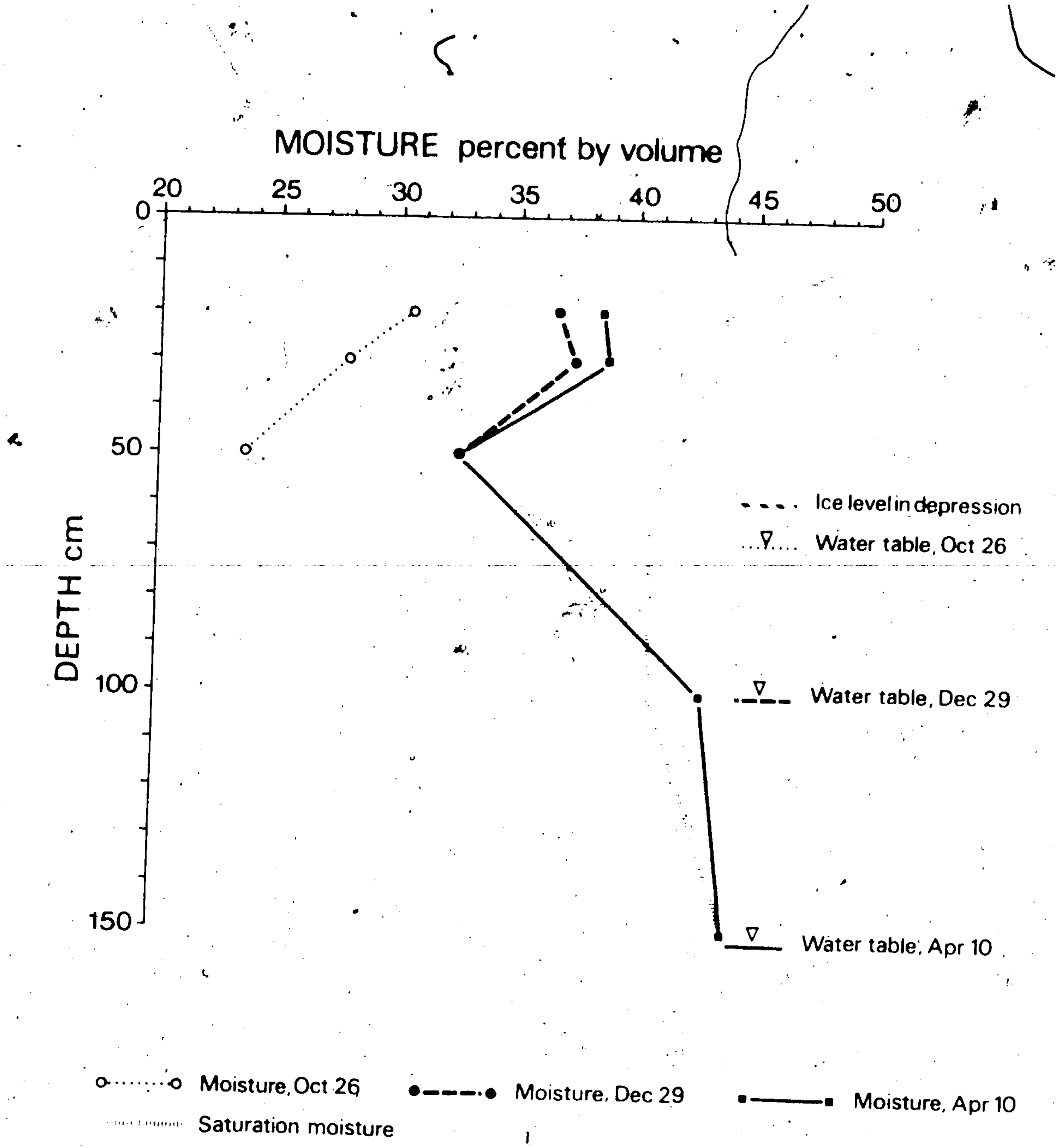


Figure 15. Changes in soil moisture, and water table level relative to ice level in the adjacent depression, at Site 1 over winter.

readings suggest that the soil was still saturated well above the apparent water table at winter's end. Although a more thorough evaluation of moisture changes would have been possible with inclusion of neutron probe readings below the water table requiring sealed access tubes rather than open ones used here, it nevertheless appears that the ~~water table and~~ shallow piezometer readings reflect only the level of unfrozen water, which by late winter may be overlain by soil saturated with ice. This is also supported by the close relationship between depth of the 0°C isotherm (Figure 6) and the apparent water table. This relationship might be expected under conditions of recharge, since downward water movement, by lowering the unfrozen water level below the frozen zone above, would allow air to enter laterally between water and ice surfaces so creating a new apparent water table at the base of the frozen layer. However a similar fall in hydraulic potential 2.4 m below the ground surface at Site 9, to a level well below the water in the adjacent depression, suggests that recharge is not essential for this phenomenon. As suggested by Hoekstra (1966), thermally driven moisture movement towards growing ice surfaces, which occurs because of differences in chemical potential in a soil below 0°C is capable of causing moisture contents above the water table to increase beyond calculated saturation levels. Consequent ice lens formation and frost heaving perhaps causes cracks through which air enters resulting in the apparent fall in water table.

Both reductions in amplitude of fluctuation and delayed effects with depth, whatever their cause, have an important bearing on conclusions that can be made regarding flow gradients.

For example, where mean annual hydraulic potentials vary little with depth, such as at Site 8, either the reduction in amplitude of fluctuation, or the lag effect with depth, suggests changes from recharge at one season to discharge at another which may be more apparent than real. Conclusions regarding groundwater flow based on a period of less than one full wavelength of fluctuation must therefore be rather speculative, particularly near the discharge end of the flow system and where a wide depth range is involved. During winter, flow directions cannot be based on differences in levels between open ice surfaces and piezometer levels, since movement between the two is restricted, and not at equilibrium in the usual sense, and in spring, some of the apparent water rise must be attributed to melting within the ground rather than to infiltration of rain or snow meltwater.

2. Groundwater flow from piezometers in the Upper study area

Although the high elevation above the river of Sites 1 to 3 suggests that groundwater recharge should be dominant, some local discharge would not be unexpected because of the position of the sites near the foot of a 16 m high slope. Piezometers show a downward flow gradient into the bedrock throughout the year (Figure 16) with a flow rate estimated to be around 0.2 cm per year (Table 10), but in the highly permeable sand above the bedrock, gradients were small and rather inconsistent. At Site 1, the mean gradient, though small, was upward within and above the sand layer suggesting that at this site an upward groundwater flow overlies the downward flow into the bedrock. Since the

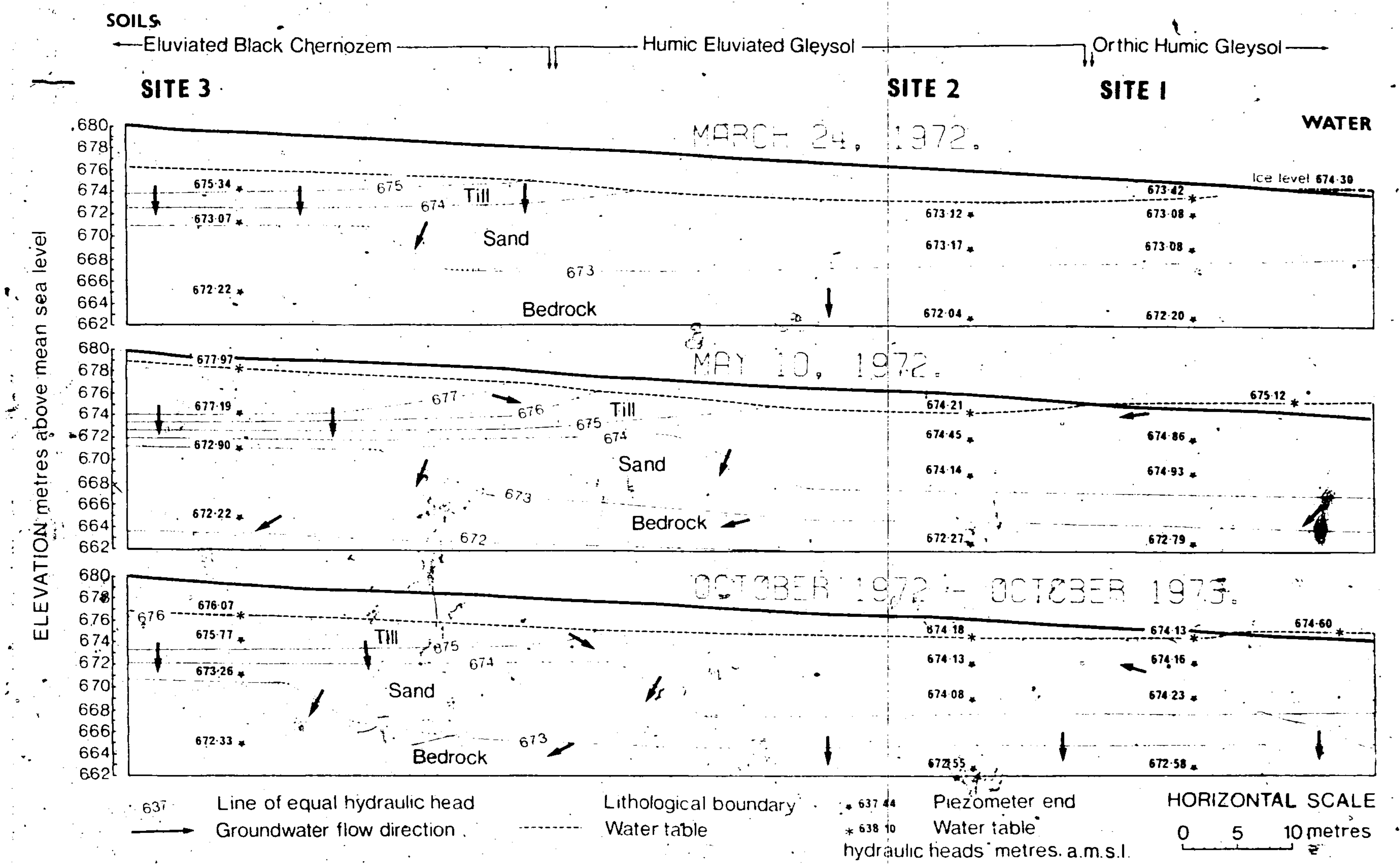


Figure 16. Groundwater flow in the Upper soil study area. based on hydraulic heads in March and May 1972, and means for October 1, 1972, to October 1, 1973, with soils included for reference.

Table 10. Rates of recharge and discharge estimated for different sites from hydraulic gradients and assumed hydraulic conductivities.

Site	Below surface depths,m, Source: Piezometer(P) or Tensiometer(T)	Material	Hydraulic Gradient Vert.m/m	Hydraulic Conductivity Assumed cm/hr	Recharge(R) or Discharge(D) Rate cm/year	Comments[1]
1-3	6.1(P) 12.2(P) at Site 1	Bedrock	0.27	8 x 10^{-5}	R 0.19	
	7.3(P) 13.4(P) at Site 2	Bedrock	0.25	8 x 10^{-5}	R 0.18	
4	3.0(P) 6.7(P)	Till	0.20	2 x 10^{-4}	D 0.36	
5	1.5(T) 2.1(P)	Till	0.30	2 x 10^{-4}	D 0.50	Summer only
	1.5(T) 4.6(P)	Till	0.11	2 x 10^{-4}	D 0.19	Summer only
5a	1.8(P) 4.3(P)	Till/Bdr	0.08	1 x 10^{-4}	D 0.08	
6	1.8(P) 6.1(P)	Bedrock	0.04	8 x 10^{-5}	D 0.03	
	1.8(P) 24.4(P)	Bedrock	0.03	8 x 10^{-5}	D 0.02	
7	Interpolated water table(P,T) and 3.7m(P)	Bedrock	0.16	8 x 10^{-5}	D 0.11	Summer only
	3.7(P) 6.7(P)	Bedrock	0.08	8 x 10^{-5}	R 0.06	
	3.7(P) 12.8(P)	Bedrock	0.05	8 x 10^{-5}	R 0.03	
8	Water table and 5.2(P)	Bedrock	0.11	8 x 10^{-5}	D 0.11	
9	Interpolated water table(P,T) and 2.4(P)	Bedrock	0.28	6 x 10^{-5}	D 0.28	Summer only
	2.4(P) 6.1(P)	Bedrock	0.04	6 x 10^{-5}	D 0.02	
	2.4(P) 24.4(P)	Bedrock	0.04	6 x 10^{-5}	D 0.03	

[1] Most values are based on 1 year means. Those based on shorter periods may include transient effects and are therefore less reliable.

potential in the water-filled depression (slough) was almost always higher than that of the water table at Sites 1 and 2, flow diagrams suggest that the source of discharge at Site 1 is from the slough itself which in turn must receive most of its water by overland flow possibly supplemented by discharge from the east.

3. Groundwater flow from piezometers in the Lower study area

The only unifying characteristic of groundwater flow in this area, is the overall westerly flow gradient in the direction of the Vermilion River (Figure 17). Vertical flow directions are extremely variable. Only at Site 7 is a downward direction indicated by all piezometers, and only at Site 9 is a consistently upward flow suggested. Elsewhere, reversals in vertical direction occur at varying depths presumably as a result of variations in lithology. Such reversals in direction are most probable where thin horizontal lenses high in permeability, or cracks and fissures, exist in a medium of overall low permeability (Figure 18). Such lenses are common in the till, while in the bedrock, seams of coal, or sandstone lacking the usual high bentonitic content (Shaw and Harding 1949) could serve a similar function. Such a lens or fracture in the bedrock must almost certainly be the cause of a flow reversal at Site 4 from an upward direction above 635 m elevation to a downward direction below this elevation. The hydraulic conductivity reading obtained from the piezometer terminating at 634 m provides evidence for this, as the value of 0.42 cm/hr for horizontal flow was 3000 times the median value

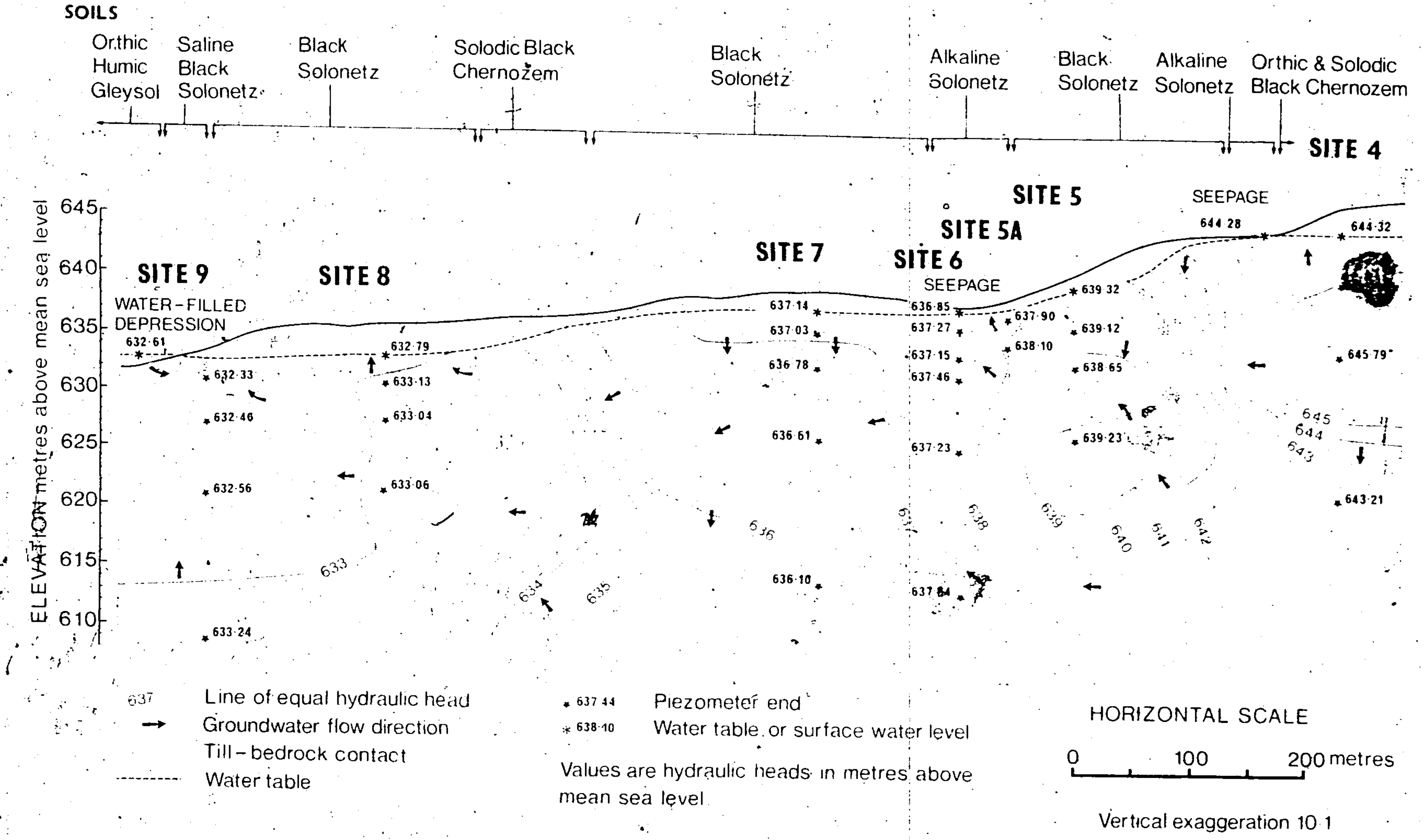
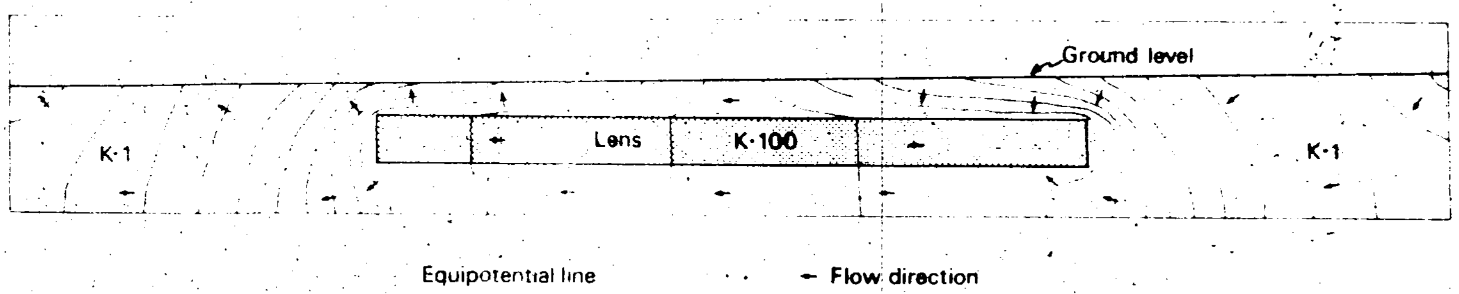


Figure 17. Groundwater flow in the Lower soil study area based on mean hydraulic potentials for the period October 1, 1972, to October 1, 1973. Soils are included for reference.



gure 18. Groundwater flow directions where a lens of high permeability exists (After Freeze and Witherspoon, 1966).

in the bedrock. Between Sites 5 and 6, vertical flow directions are variable, again presumably because of contrasting permeabilities, though no consistent pattern to permeabilities could be perceived either from hydraulic conductivity measurements or rock descriptions. However Sites 5a and 6 together suggest a dominantly upward flow in this area. Beneath the slight rise in ground at Site 7, the flow appears reversed, and definitely downward. This is an area of numerous small temporarily water-filled depressions, which where undisturbed, are normally willow-ringed (see Plate 6). On the edge of one such willow-ringed depression, at Site 7a, piezometers ending 2.1 m and 4.9 m below ground surface showed upward flow, though the shallower piezometer only functioned properly late in the study period, while at the centre of another similar depression (Site 7b), flow between similar depths was downward. Such variations appear normal in an area of willow-ringed sloughs (Meyboom 1966) and result from small local systems becoming established around each depression particularly during the summer months.

At Site 8, there is a fairly strong discharge gradient above the bedrock, which from piezometer records (Figure 14) appears to be fairly consistent throughout the year. This is superimposed on a mainly horizontal flow at greater depths. At Site 9 the vertical gradient, though apparently weak, is consistently upward from a considerable depth. However the piezometer terminating at 609 m elevation had not fully stabilized after two years, so the magnitude of the gradient between 609 m and 621 m elevation is rather speculative. The level of open water adjacent to Site 9 suggests outward movement from the slough similar to that occurring at Site 1, but unlike at Site 1, water is not lost to greater depths through recharge.

Because flow directions vary between different elevations at the same site, those calculated at great depth below the water table may not be the most applicable to genesis of the soil above. It is therefore important to obtain flow information as close to the water table as possible and although shallow piezometers can provide some of this information, valuable supplementary evidence can be obtained from tensiometers and interpretation of near-surface lithology. Unfortunately in the climate of the Canadian Plains much of this information is available only during the summer months, and because near-surface flow is most subject to short term fluctuation, it may not reflect the longer term situation. Near-surface flow information has therefore been used with some reservations in the site by site analysis below.

Groundwater flow close to the water table during summer

Particular care was taken in interpreting water levels in perforated pipes, since a highly permeable lens penetrated by such a pipe causes the water level to reflect the groundwater potential in the lens rather than the true position of the water table. Likewise where several such thin lenses are penetrated by a perforated pipe in a material of otherwise low permeability the water level in the pipe under conditions of either recharge or discharge varies with the depth of pipe. Under such conditions, nests of tensiometers, which act as piezometers when below the water table, were able to help in establishing the true position of the water table by interpolation. Flow diagrams based on combined information from piezometers, perforated pipes, tensiometers, and to a very limited extent psychrometers are presented for early June and mid September, because these times represent approximately the seasonal extremes within the limited frost free period for which full accurate information was available. Flow diagrams for 17 August 1973 are included because this date followed an exceptionally long spell of wet weather, and it was also the final date on which nearly full information was obtained. Some flow diagrams based on limited information available during winter at depths below the 0°C isotherm are included for comparison, and to assess the continuity of flow conditions through this period.

Sites 1 to 3

The diagrams (Figures 19,20) confirm that below the water table groundwater movement is predominantly downward. In a summer of fairly normal rainfall such as 1972, an excess of evapotranspiration over rainfall causes an upward potential gradient to become established above the water table which in combination with recharge results in a falling water table level over summer. The very wet summer of 1973 however provides an exception to this. Since the water table normally declines for a short distance away from the permanently water-filled depression near Site 1, outward movement of water from this slough acts as a supply not only for regional recharge but for a very local discharge close to its

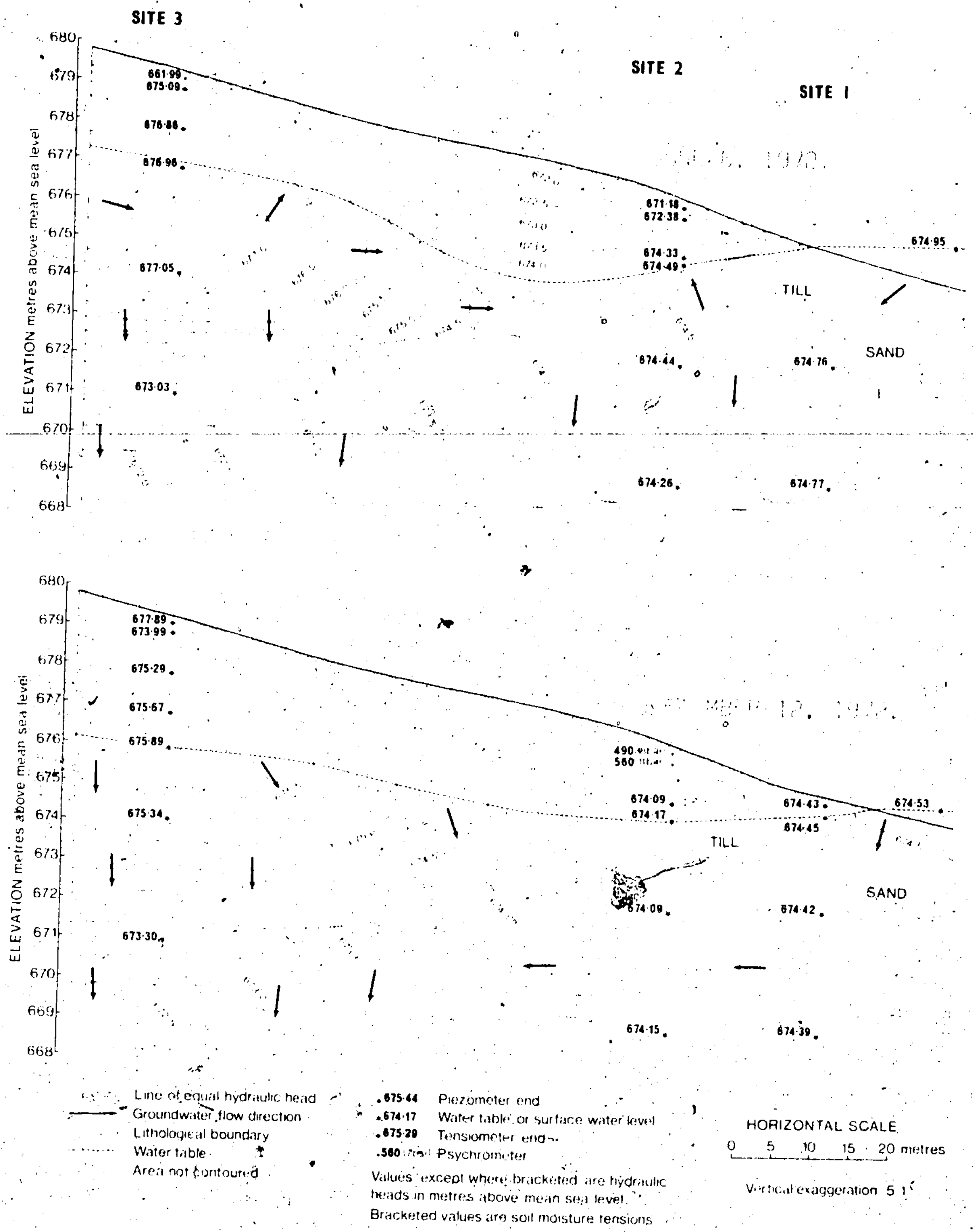


Figure 19. Groundwater flow at Sites 1 to 3, in 1972, with potentials in the unsaturated zone included.

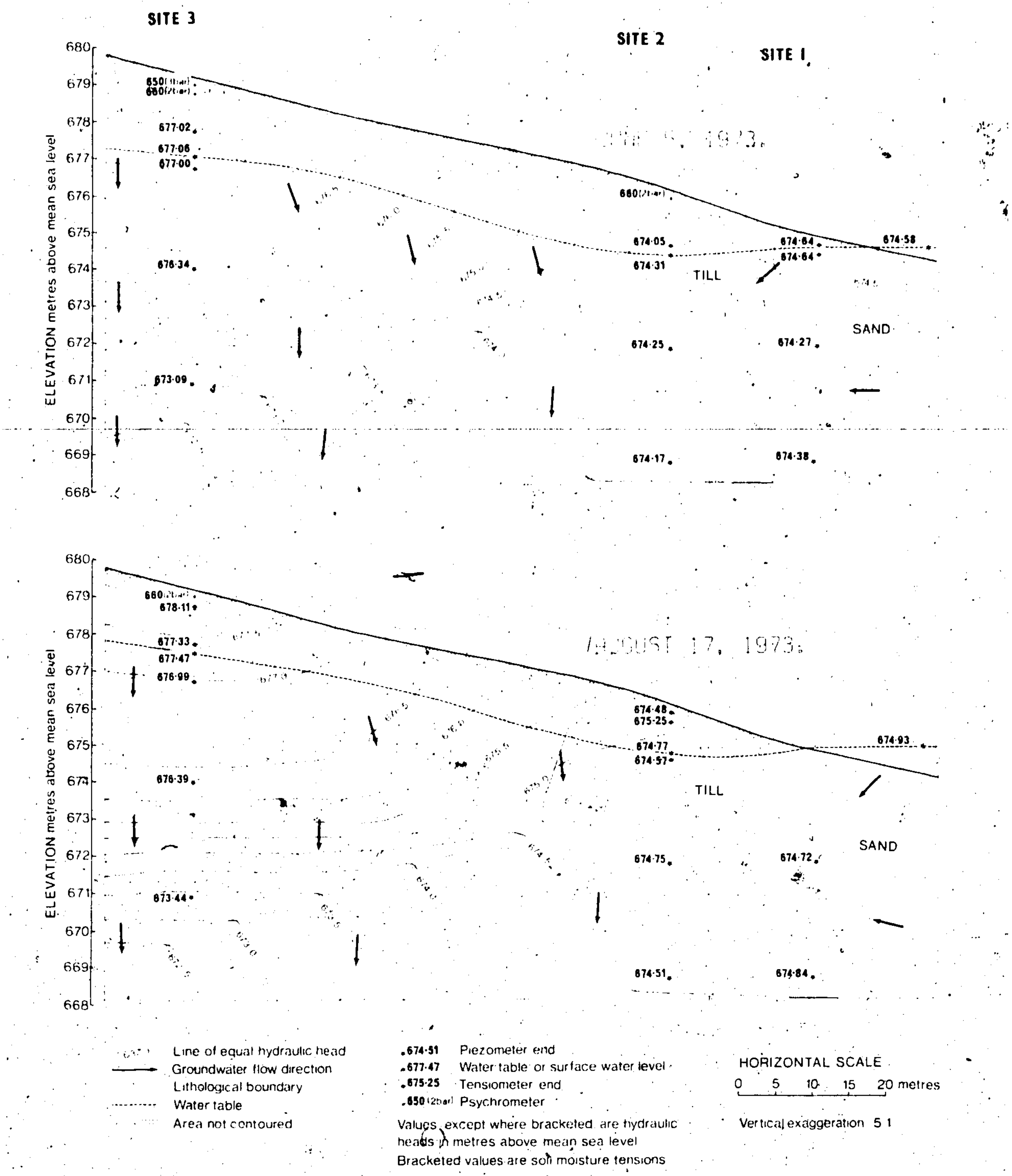


Figure 20. Groundwater flow at Sites 1 to 3, in 1973, with potentials in the unsaturated zone included.

fringes.

Sites 4 to 5

At Site 4, the water table access tube was considered to act as a piezometer terminating 3 m below the surface, because a sand layer penetrated the well at this depth and the material above appeared to be comparatively impermeable. Inclusion of tensiometer potentials confirms the existence of an upward flow direction towards the water table at this site and towards the seepage area downslope from the site (Figures 21,22). A lack of data values for potentials between Sites 4 and 5 means that flow directions between these sites is rather speculative.

Sites 5 to 7

Although flow directions based on piezometers alone suggest recharge at Site 5, inclusion of information from tensiometers and shallow access tubes shows that discharge almost certainly takes place near the water table. A properly functioning water table access hole was not obtained until late 1972, but even prior to that, coring operations and water levels in the neutron probe access tube suggested that water in a sand layer 2 m below the surface maintains a hydraulic potential throughout most of the year at about 1 m below ground level which is certainly above the level of the water table, suggesting discharge. The water, with an electrical conductivity of 2.8 mmhos/cm was more saline than water at greater depths, also suggesting upward flow. Tensiometers at 150 cm below the surface, which acted as piezo-

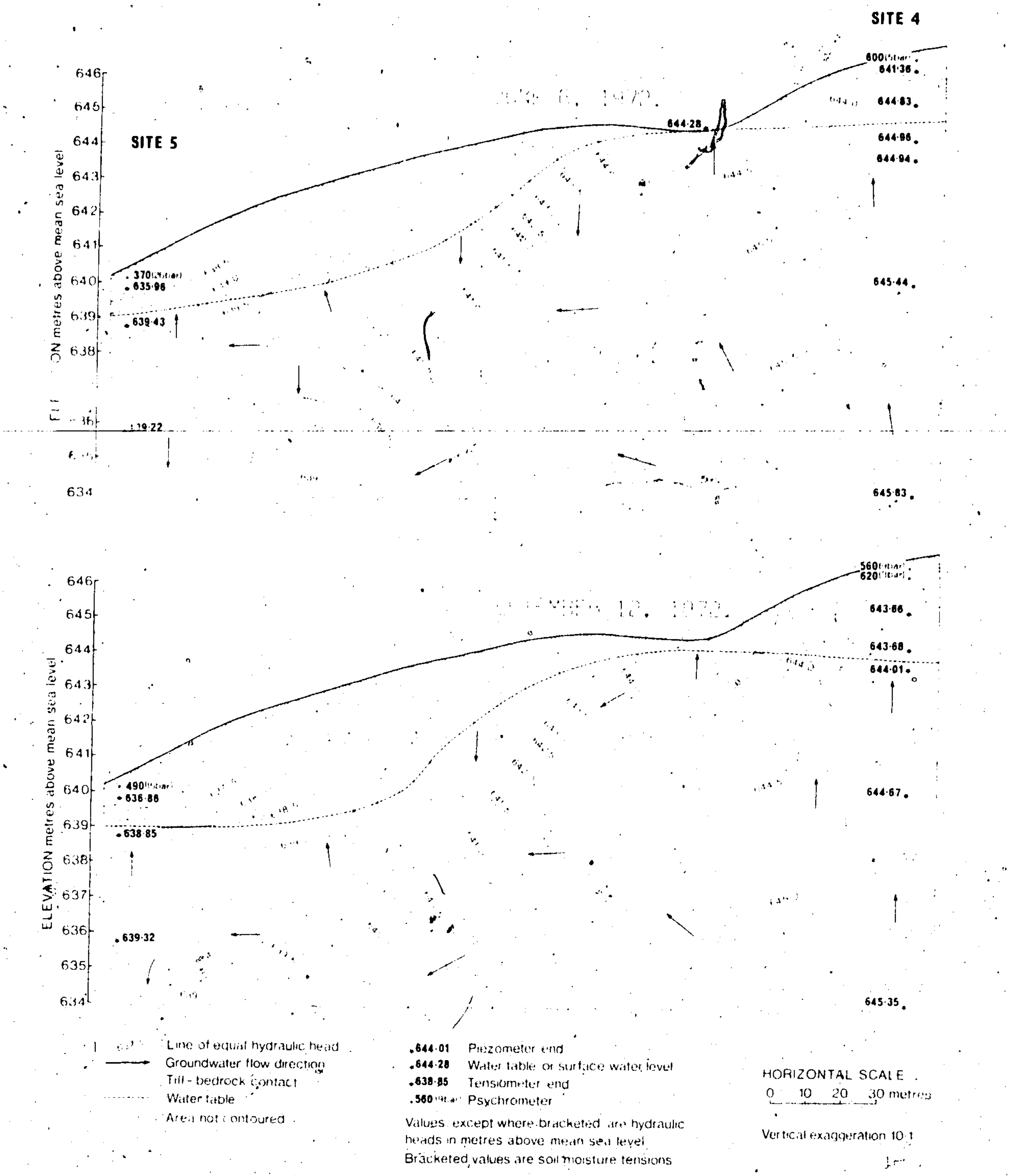


Figure 21. Groundwater flow at Sites 4 and 5 in 1972, with potentials in the unsaturated zone included.

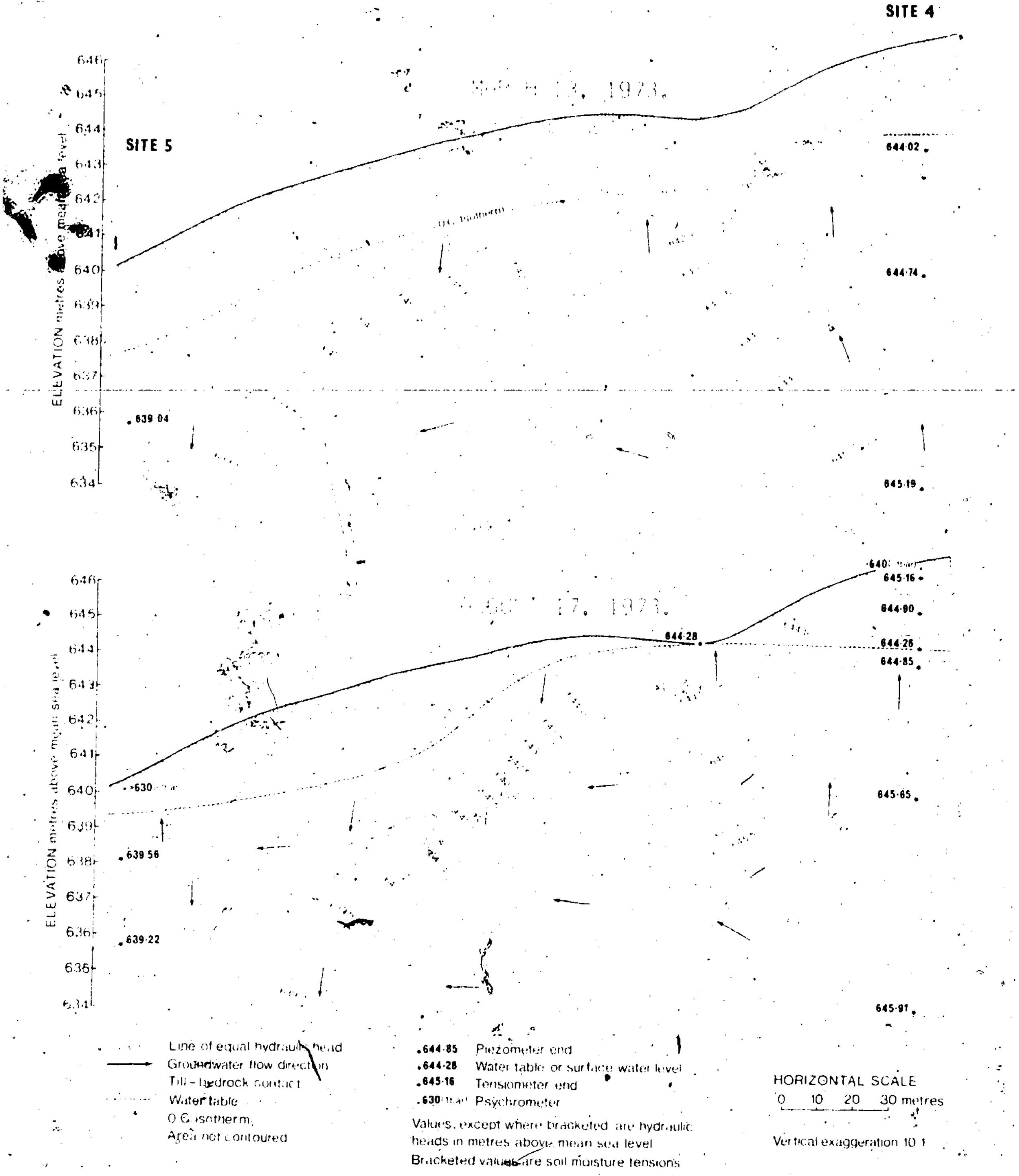


Figure 22. Groundwater flow at Sites 4 and 5, in 1973, with potentials in the unsaturated zone included.

meters since they were below the water table, also suggested discharge above this sand layer in summer (Figures 21,22). Unfortunately tensiometers were not available on August 17, 1973, because farm operations necessitated their removal.

The two piezometers at Site 5a suggest upward flow while at Site 6 an erratic though predominantly upward flow is suggested by piezometers. Tensiometers were not installed in sufficient number or at sufficient depth to fully confirm upward movement immediately below the water table, but flow diagrams (Figures 23,24) suggest that upward flow is dominant. Since the site is in a drainageway with buried gravel layers above the bedrock, some mixing of surface water probably occurs within these layers following rainfalls.

At Site 7, piezometers alone indicate an apparently simple condition of downward flow, but additional information suggests that the situation may be more complex. Attempts at installing a properly functioning water table access tube met with little success, as wells penetrating less than 3 m below the surface produced little water, and so poor response while a highly permeable layer was penetrated at 3 m below the surface which produced a water level the same as that in the piezometer ending 3.7 m below the surface. The level of this water fluctuated in a regular annual cycle with a peak in late summer and this, together with its salinity which was the highest analysed (Figure 14), suggests a non-surface origin. Also, even though an observation well penetrating 2.4 m below the surface gave a very poor response, differences between the water levels in it and in the piezometer

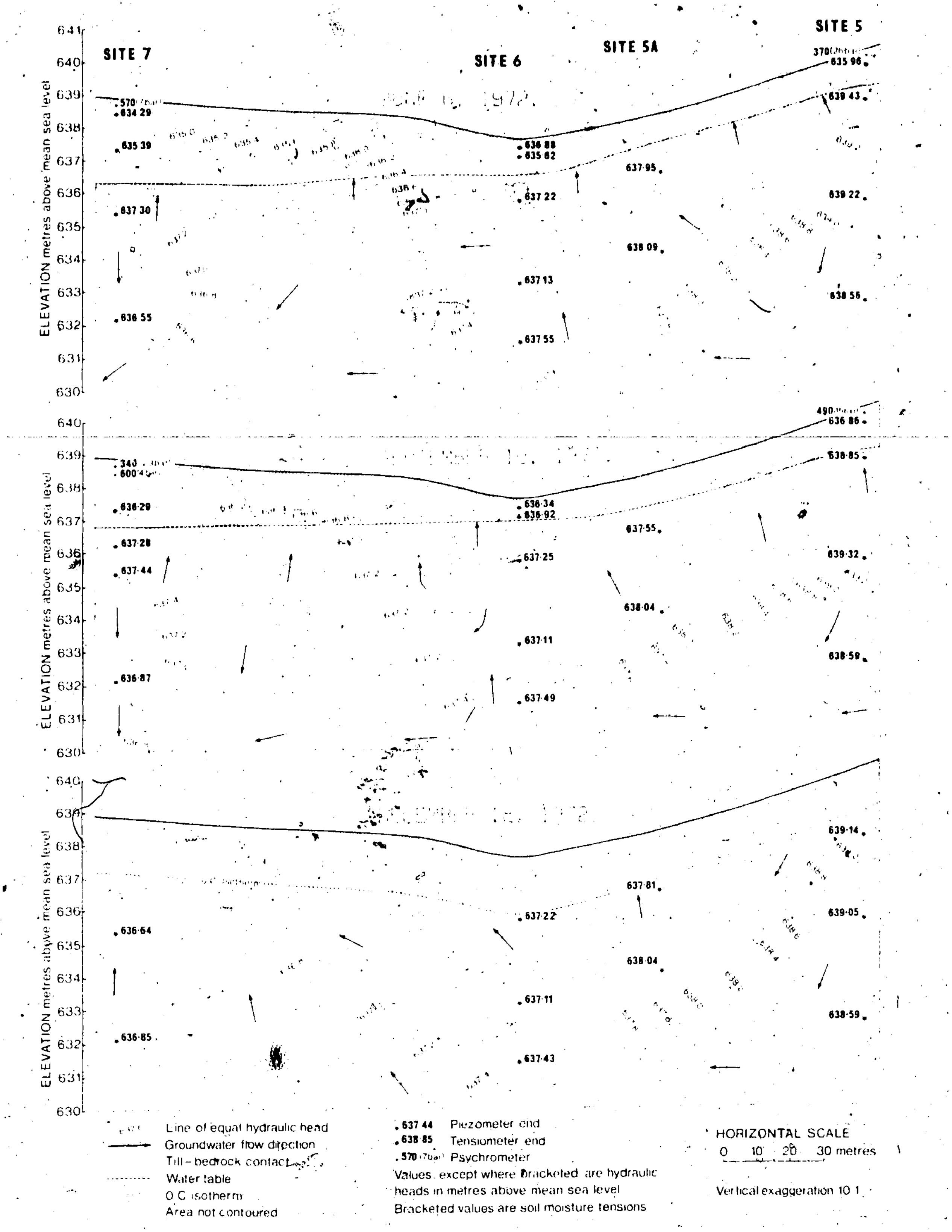


Figure 23. Groundwater flow at Sites 5 to 7, in 1972, with potentials in the unsaturated zone included.

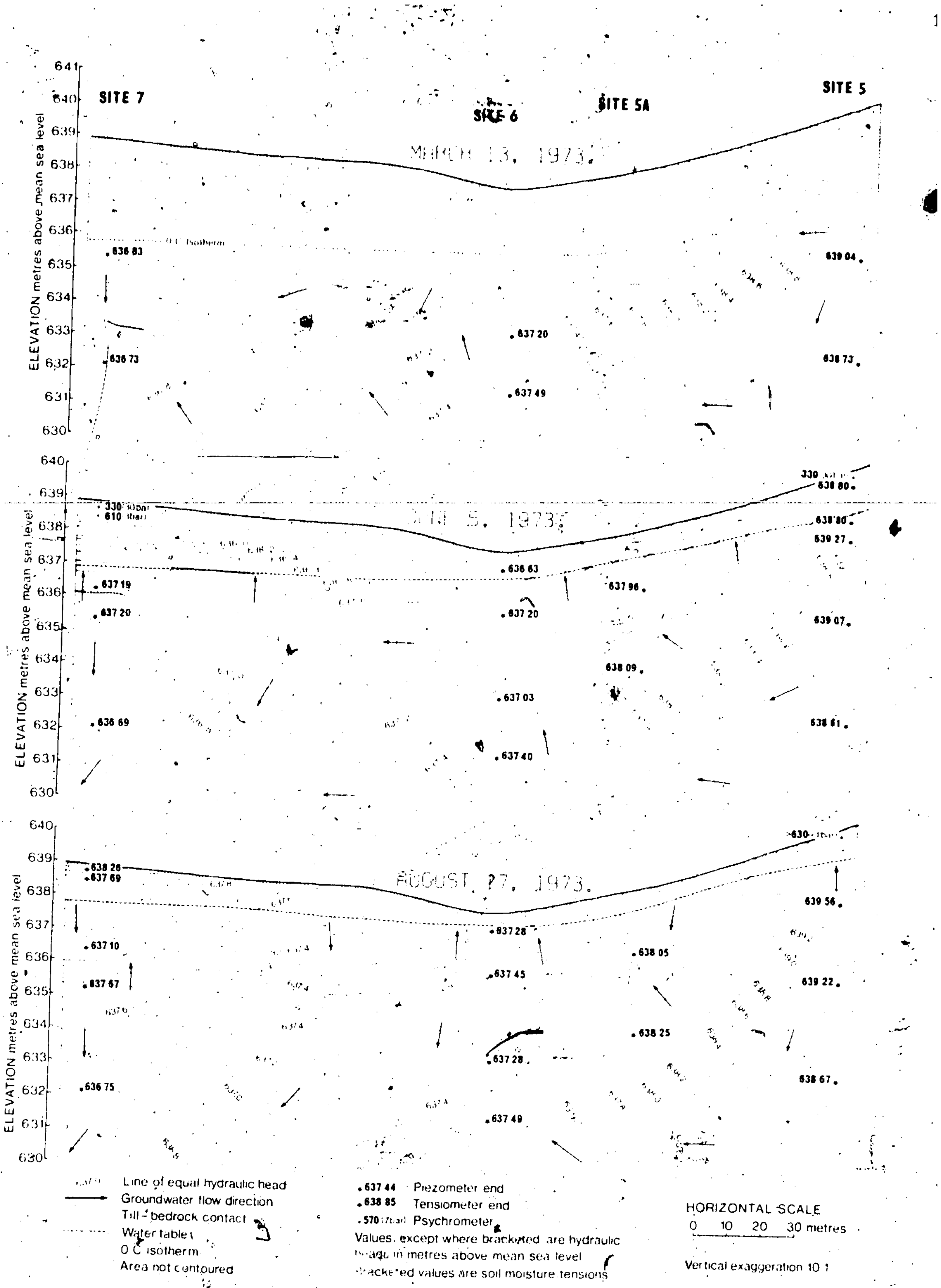


Figure 24. Groundwater flow at Sites 5 to 7, in 1973, with potentials in the unsaturated zone included.

terminating 3.7 m below ground level could at times only mean discharge. For example on 17 July 1973 the water well level was at 637.01 m elevation and falling while the level in the deeper piezometer was at 637.54 m elevation and rising. The flow diagrams (Figures 23,24) with tensiometer information included also suggest upward flow above about 635 m elevation with water possibly entering the more permeable layer at this elevation from east of Site 6. However, it seems possible that discharge occurring in summer, when the water table is lowered by evapo-transpiration, may be compensated, at least partially by recharge in winter and following the spring thaw or as suggested for August 17, 1973, recharge following heavy rains.

Sites 8 to 9

A perforated pipe penetrating 3.7 m below ground surface was thought to provide a reasonably accurate measure of the water table position at Site 8, since no highly permeable layers penetrated the well. Continuous upward groundwater flow is suggested between the shallowest piezometer terminating at 630.5 m elevation and the water table, and tensiometer readings conformed with this situation (Figures 25,26). The water level in the shallowest piezometer fluctuated in an annual rhythmic manner, peaking in September when surface water levels are normally low, and salinity was slightly less in water from this piezometer (700 ppm Na) than at the water table (1020 ppm Na). Both of these phenomena would not be normal except where discharge is occurring. It is possible that a small depression situated just

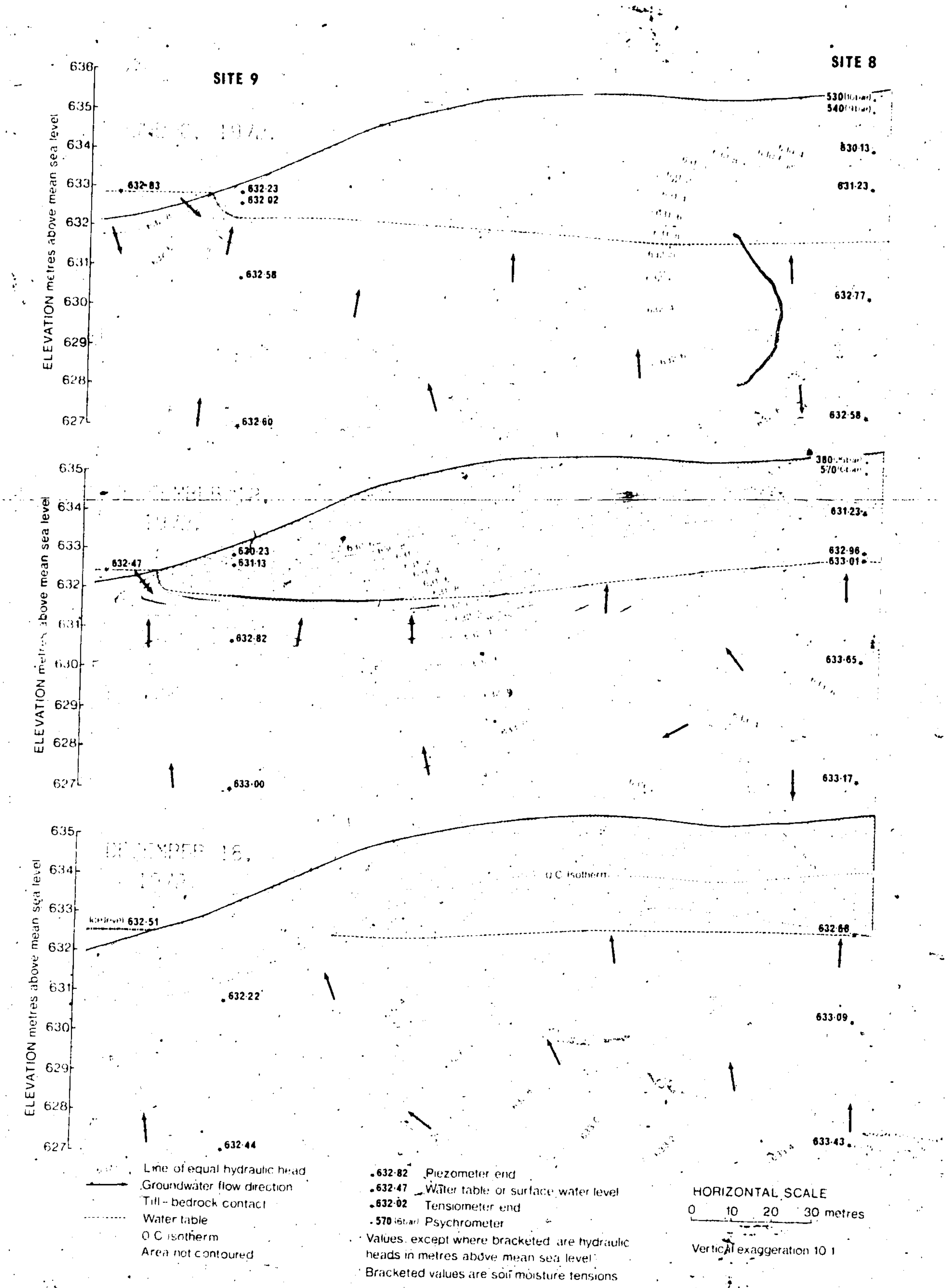


Figure 25. Groundwater flow at Sites 8 and 9, in 1972, with potentials in the unsaturated zone included.

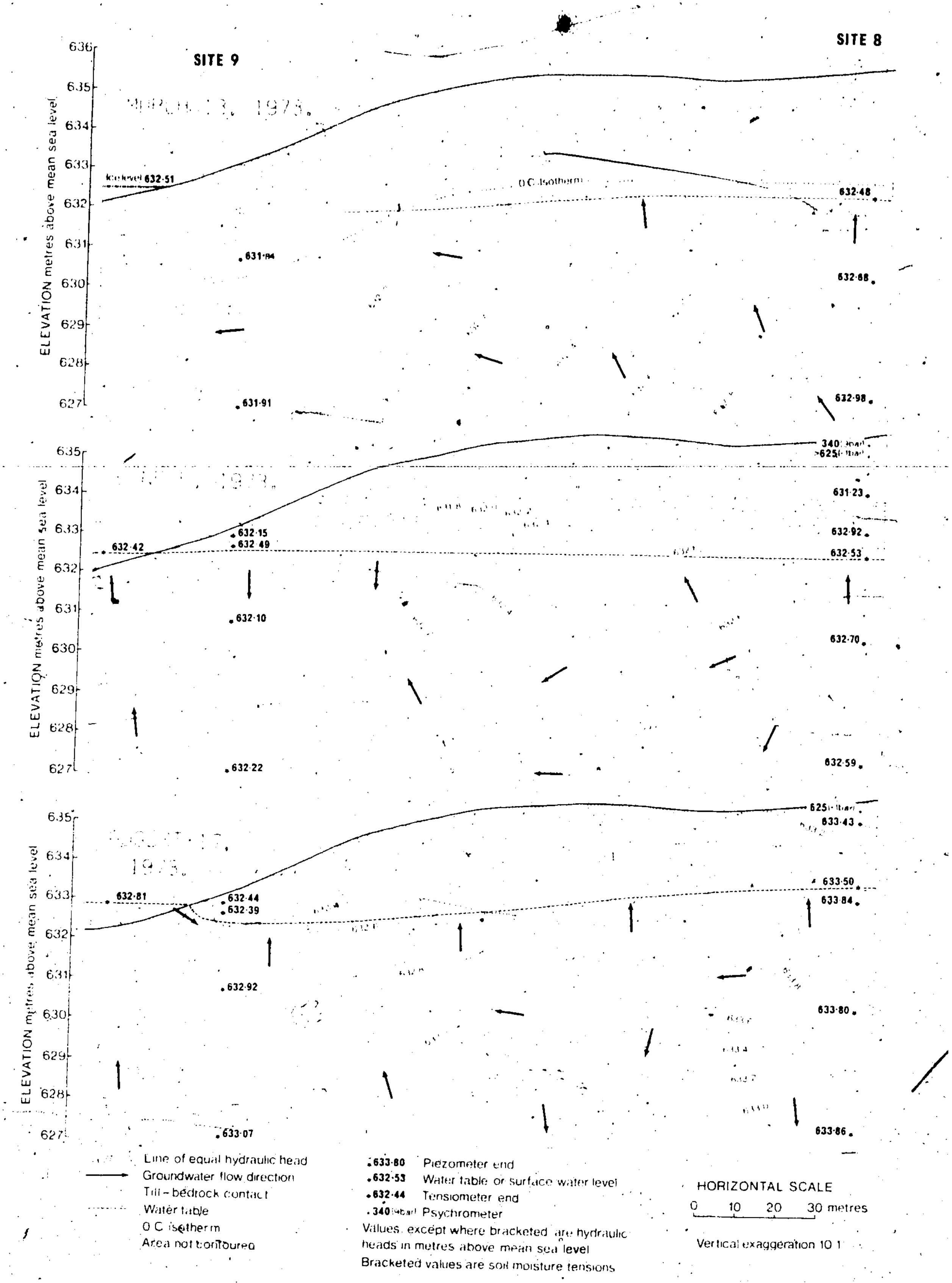


Figure 26. Groundwater flow at Sites 8 and 9, in 1973, with potentials in the unsaturated zone included.

to the north which is frequently filled with water to a level at least 1 m above the water table at Site 8, could be a source of some of this discharge.

At Site 9 where discharge extends from a greater depth than at Site 8, tensiometer readings generally conformed with a discharge situation except in early June 1973 (Figure 26) when suggested shallow recharge was probably very temporary. Since hydraulic potentials derived from piezometers at Site 9 were always less than that of water in the adjacent depression, the slough water must be largely derived from overland flow rather than discharge and it then acts as a supplementary source of discharge water around the fringes of the depression in a manner similar to that at Site 1, but with the important difference that no permanent loss of water occurs by deeper recharge, with the result that salts become concentrated (Figure 27).

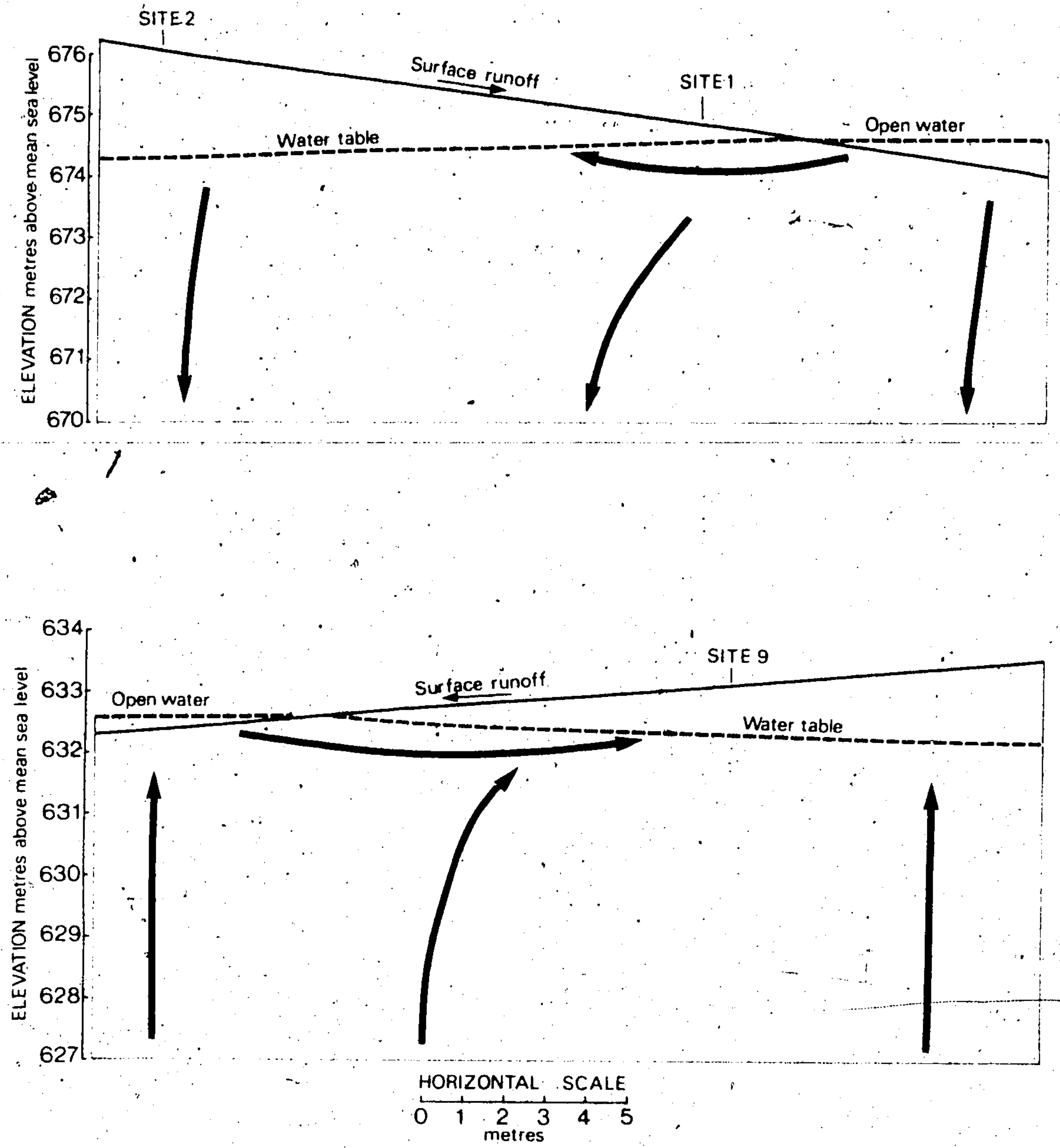


Figure 27. Essential differences in groundwater flow directions in the vicinities of water-filled depressions at Sites 1 and 2 (above) compared with Site 9 (below).

V - MOISTURE FLOW ABOVE THE WATER TABLE

Presence of frost limits direct information on water potentials above the water table to the period between early June and mid October, though considerable moisture movements obviously occur at other times, particularly during spring thaw which in some years may be the only period during which downward flow gradients extend throughout the unsaturated zone. During winter, high moisture suctions resulting from partial freezing of water near the ground surface, create upward flow gradients, though moisture movements may be small since permeabilities within unfrozen films at high suctions are inevitably low. During winter and spring, information on moisture flow must be obtained from soil moisture contents which in this study were obtained with a neutron probe.

Moisture flow during Summer

During summer 1972, rainfall was near normal, and at sites where the water table exceeded 1 metre depth, matric suction heads increased with distance above the water table (Figure 28). Except for short periods at Site 3 these increases were consistently greater than elevation head differences so that hydraulic gradients indicated continual upward flow in the 1 to 2 metre zone immediately above the water table from early June to late October. Suctions measured at 20 cm depth where salinity was low, using psychrometers (Figure 29) were mostly between 1 and 20 bars (3 and 4.3 on the log scale) except at Site 3. At Site 3 observation

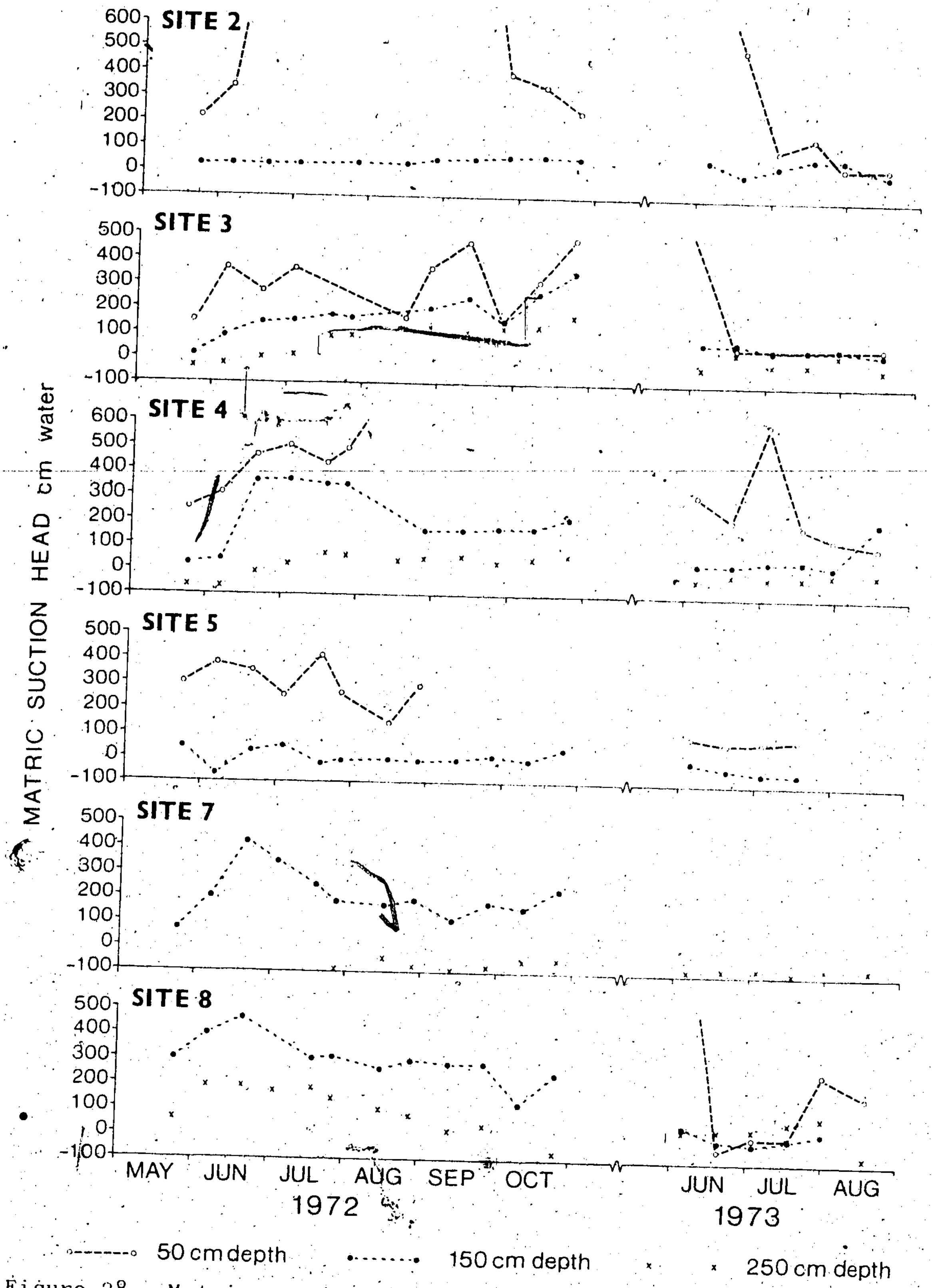


Figure 28. Matric suction heads obtained using tensiometers at various depths excluding the near-surface, at sites where depth to the water table exceeded 1 metre.

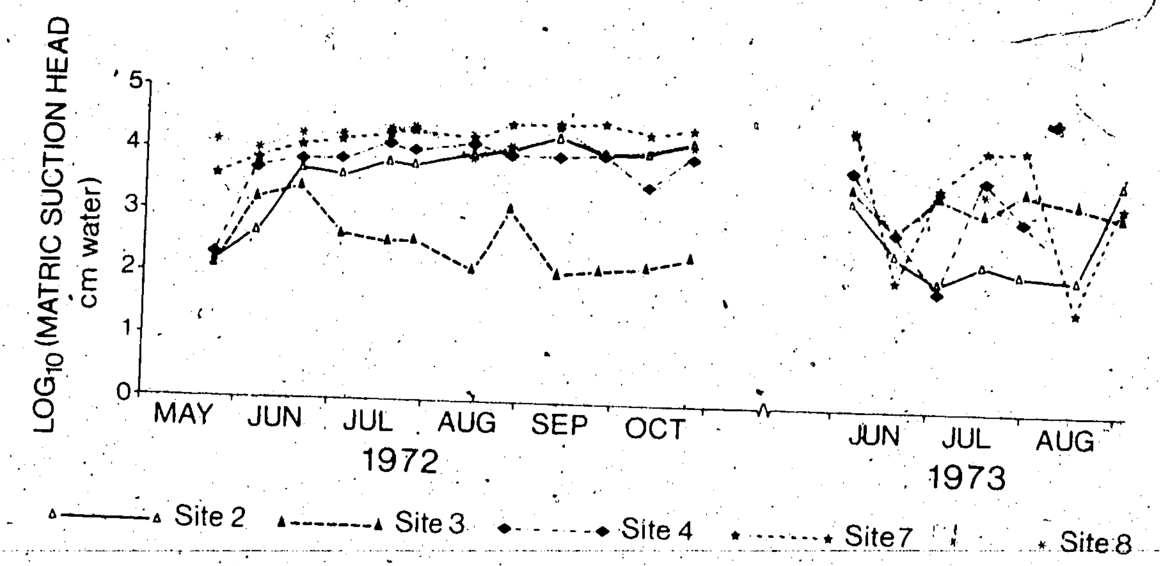


Figure 29. Log matric suction heads at 20 cm depth obtained using psychrometers where salinity was small at sites where depth to the water table exceeded 1 metre.

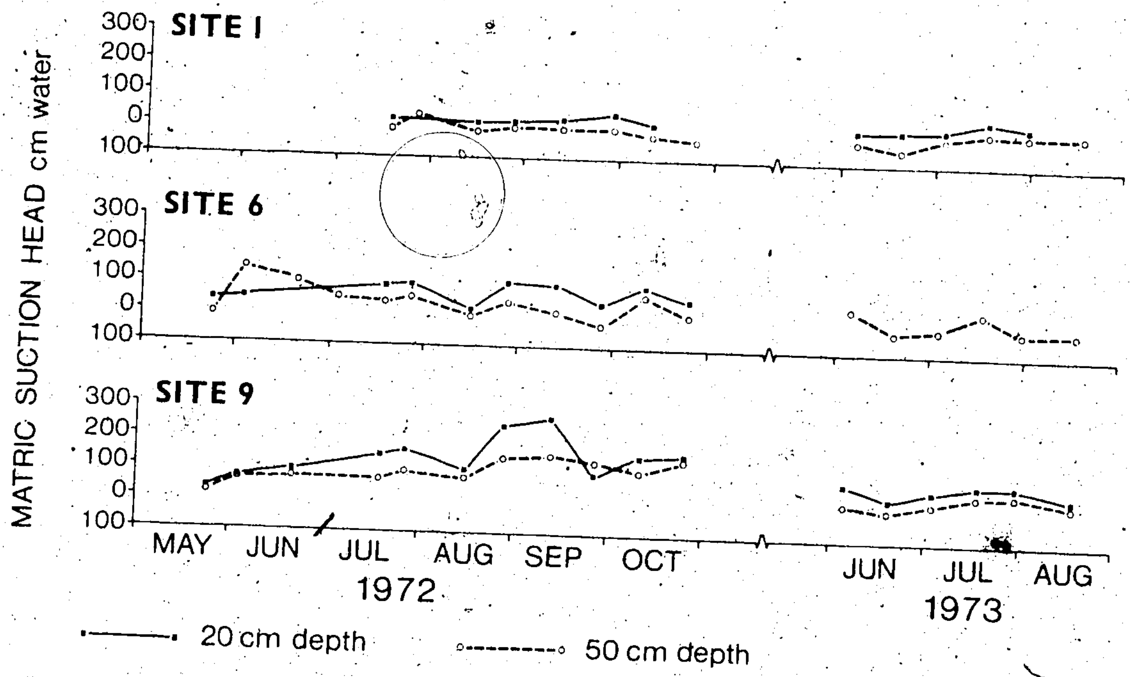


Figure 30. Matric suction heads at 20 cm and 50 cm depth obtained using tensiometers at sites where the water table was close to the ground surface.

following storms suggested that the lesser suctions there may have resulted from additional moisture flowing from higher ground within the Ah horizon or along the ground surface. However a faulty psychrometer cannot be ruled out, since unlike the tensiometers, psychrometers were installed without duplication. Hydraulic gradients were not consistent during the very wet summer of 1973 and at most sites moisture infiltrations appeared to reach the water table following heavy rain in mid June and again in mid August. Site 5 where the soil is Black Solonetz, may have been an exception, and at Site 7 tensiometer failure resulted in lack of information (Figure 28).

At Sites 1, 6 and 9, the water table is sufficiently close to the ground surface to maintain matric suctions within tensiometer range throughout summer. Except for brief periods, matric suction heads were greater at 20 cm depth than at 50 cm depth by amounts which exceeded the 30 cm elevation head difference (Figure 30), so that hydraulic gradients indicated almost continual upward flow.

The results suggest that flow is normally upward above the water table during summer except following very prolonged rainfalls. The particularly large suctions at 20 cm depth in the Black Solonetz soils at Sites 7 and 8 during 1972, suggest that there may be long periods during which little moisture penetrates below the surface horizon in such soils.

Quantitative estimates of moisture movement between different depths which could be related to the very small rates of recharge and discharge would require knowledge of hydraulic conductivity-suction relationships of an accuracy greater than could be derived from determined pressure plate moisture-suction relationships using the method of Marshall (1958). The twice monthly neutron probe determinations also cannot provide direct moisture information of much quantitative value during summer, particularly without detailed information on rainfall and evapotranspiration at each site. Correlation between moisture suctions obtained in situ and those derived from neutron probe moisture contents using pressure plate relationships gave a coefficient 'r' of only 0.63 for 150 values. Sample variation is involved in both direct tension measurements and in obtaining cores for the pressure plate while additional error results from core disturbance, and the neutron probe's Sphere of Influence intersecting layers outside those of interest. Further treatment of readings obtained during the summer is therefore not warranted.

Moisture changes during Winter

The effect of upward moisture movement has already been mentioned in connection with its effect on water tables close to the ground surface (see p.95). The neutron probe normally gives little useful information over winter where the water table is very close to the surface, as at Sites 1, 6 and 9, because measurements in the region of interest involve intersection of the ground surface and snow cover by the instrument's Sphere of Influence. It is also difficult to ascribe moisture increases to a particular source, since movements into the ground can occur from above, particularly in the vapour phase when air temperatures exceed ground temperatures (Longley 1967). At other sites the period between late October and late February was chosen to evaluate whether significant upward moisture movements occurred (Figure 31), because there was little thawing in the two winters of study during this period, while day-time thawing started in early March.

Large increases in moisture above the water table occurred in both winters only at Site 2. At Site 3, an increase appears to have occurred in the first winter, but not in the second. Possibly the high initial moisture level just above the water table is the reason for lack of additional moisture increase in the second winter. At Sites 5 and 7 neutron probe information was limited in depth by the water level in the access tubes, and moisture increases close to the ground surface which occurred at Site 5 in the first winter and at Site 7 in the second winter could have been caused by moisture movements into the ground from above. Information on the water table at these two sites is lacking because of freezing. At Sites 4 and 8, where the water table, at around 3 metres below the surface, was relatively deep, moisture changes over winter appear small. Slight moisture increases between 50 cm and 100 cm depth at Site 4 are of an order that could easily be ascribed to experimental error, particularly since low temperatures sometimes affected readings in winter.

Moisture movements from above do not appear to be the cause of most of the moisture increase above the water table at Site 2, since in the second winter little accompanying increase

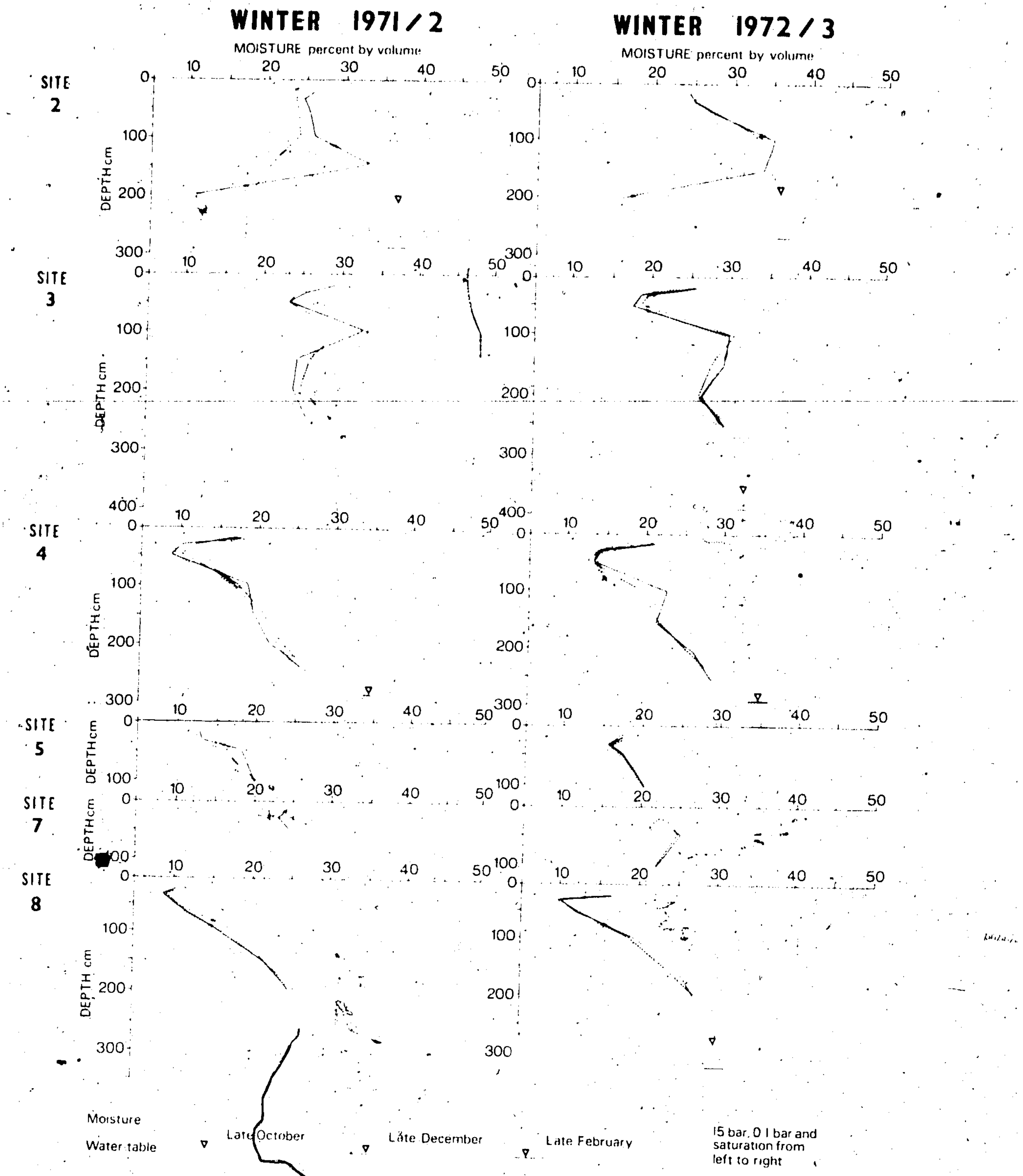


Figure 31. Moisture changes over winter in relation to 0.1 bar and 15 bar moisture contents (pressure plate) and saturation moisture content.

occurred close to the ground surface. A feature distinguishing this site from the others is the highly permeable loamy sand which forms a discontinuity at about 100 cm beneath the ground surface (see Plate 7) and it is within this layer or just above it that moisture increases to a level much greater than would be likely under unfrozen conditions, presumably by the mechanism of upward migration towards growing ice surfaces (Hoekstra 1966) discussed in Results section IV. In the first winter, the moisture gain above the water table was calculated as 8.7 cm water, while the moisture loss below the initial water table, as a result of water table decline, was 16.0 cm water. In the second winter the gain was 6.9 cm and the loss below 13.2 cm. Moisture losses resulting from a fall in water table, therefore more than account for any increase above.

Upward moisture movements, measurable under conditions of high permeability, must presumably occur to a lesser extent where the permeability is lower. The increase in moisture at around 100 cm below the surface at Site 4, though perhaps not significant, coincided approximately with the zone of salt accumulation, and it is possible that upward moisture movements into the frost zone, which are probably largely in the liquid phase (Jumikis 1962, Cary 1965, Hoekstra 1966), could be a mechanism for transfer of salts.

Moisture changes during Spring

In spite of soil temperatures below 0°C during the thaw period, much water from melting snow appears to enter the ground (Figure 32). Total amounts entering the ground calculated from neutron probe and water table information (Table 11) are however only approximate. Observation suggests that when the snow melts, the thawed soil surface is close to saturation, and this moist layer must influence readings at greater depth due to its interception by the instrument's Sphere of Influence. Moisture increases calculated from water table rise are based on the assumption that the moisture content below the measured water table is at saturation and that this is equal to the determined porosity. Determinations of soil water increase are therefore most accurate where the water table is low, where a large depth range is involved in moisture readings and where little change in the level of the water table occurs. In spite of limitations, comparison of moisture increases over the thaw period with calculated amounts of water available (Table 11), where the water table was more than one metre beneath the surface, suggests that, on average, a relatively high proportion of the meltwater entered the soil. Smaller moisture increases at Sites 5 and 7 than at other sites in 1973 are probably due to fairly high water tables and relatively impervious Bnt horizons. At Site 2 water in the underlying sandy material originating from the nearby slough, is probably the cause of an excess of moisture increase over that available in 1973.

In general, the data suggest that spring snow meltwater is important in replenishing soil moisture, and in some years it may be the only time of the year during which a downward flow gradient exists between soil surface and the water table.

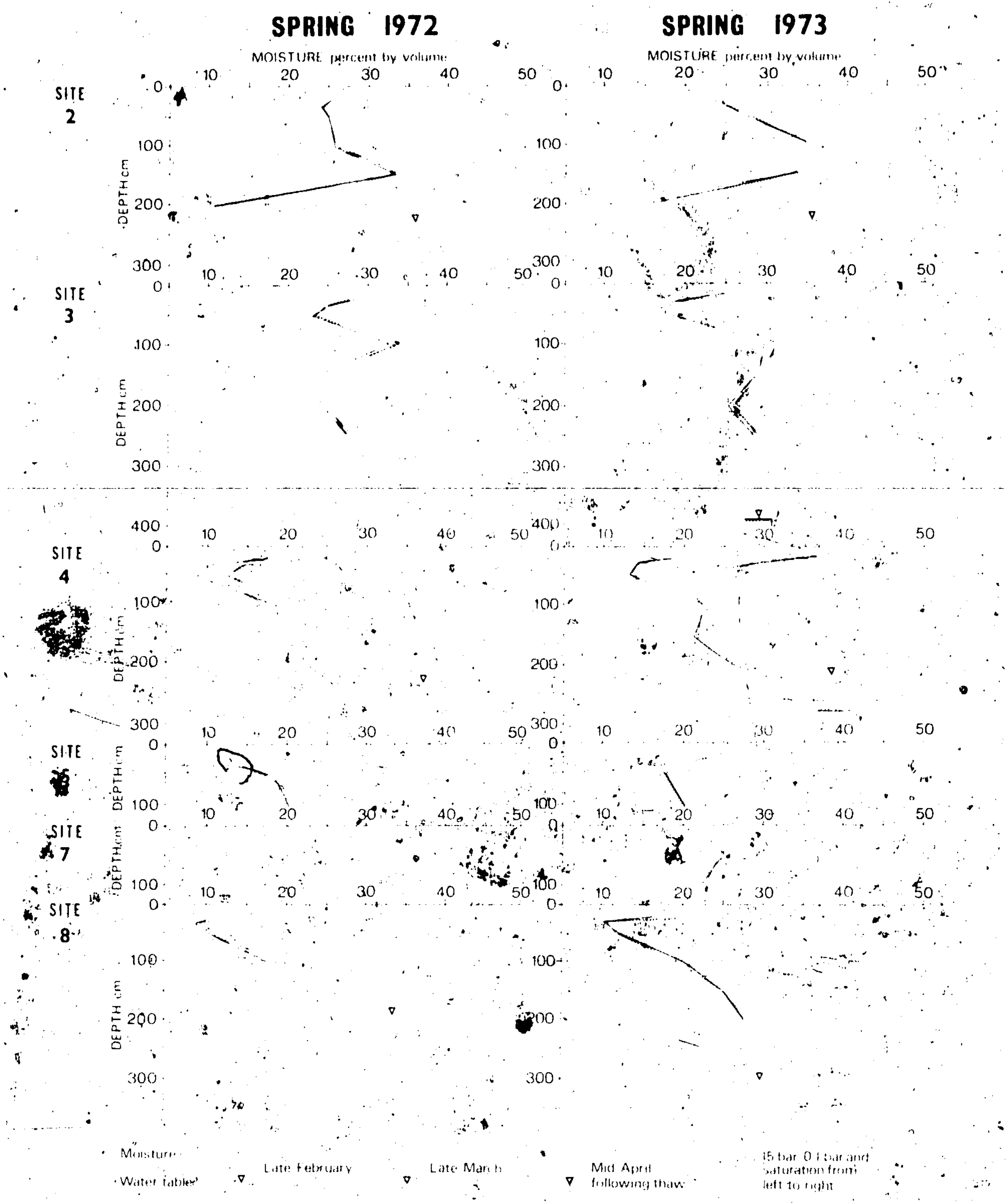


Figure 32. Moisture changes during spring in relation to 0.1 bar and 15 bar moisture contents (pressure plate) and saturation moisture content.

Table 11. Soil water increase from infiltration and water table rise compared with water available from melting and precipitation during the thaw period at six sites where the depth to the water table exceeded one metre.

Site	Water* Available cm	Water increase during thaw within indicated soil depths, cm 0-50 cm	50-150 cm	150 cm	Total	Water Table Rise cm
			1972			
2	13.8	1.1	3.3	7.3	11.7	54
3	29.1	6.7	10.4	5.9	23.0	197
4	24.2	9.8	7.3	4.9	22.0	45
5	13.8	5.2	0.0	0.0	5.2	F
7	12.2	1.3	0.0	0.0	1.3	F
8	13.8	10.0	7.4	4.9	22.3	-6
Mean	17.8				14.3	
			1973			
2	5.5	2.2	3.4	5.8	11.4	26
3	11.1	6.3	2.9	0.7	9.9	-3
4	17.6	11.7	1.7	4.0	17.4	61
5	3.2	1.7	0.0	0.0	1.7	F
7	2.7	2.6	0.0	0.0	2.6	F
8	4.2	2.0	0.0	0.0	2.0	-8
Mean	7.4				7.5	

* Water in snow at the beginning of the thaw period (March 11, 1972 and March 13, 1973) plus precipitation between then and the end of the thaw period (April 26, 1972 and April 10, 1973) minus evaporation. Water in snow was based on depth measurements at each site and one overall density mean of ten measurements. Precipitation was the mean of that at Vegreville, Ranfurly and Warwick. Evaporation estimates (0.9 cm in 1972, 0.8 cm in 1973) were based on the Penman equation (Penman 1948) using sunshine, wind, temperature and humidity at surrounding stations, radiation tables of Brunt (1934) and an assumed value for albedo of 0.75 for continuous snow cover and 0.50 for the last 16 days of the thaw period.

F means frozen.

VI - SOILS AND THEIR RELATIONSHIP TO GROUNDWATER CHARACTERISTICS

Upper soil study area

The dominant soil in this area is Eluviated Black Chernozem (Figure 33), while smaller areas of Humic Eluviated Gleysol occur around topographic depressions. Orthic Humic Gleysols are largely confined to land covered by water for periods each year. At Site 1, where the water table varied from above the surface to about 1 m below the surface, and near surface groundwater discharge was indicated, the soil is Orthic Humic Gleysol. With increase in depth of the water table at Site 2, and a change to groundwater recharge, the soil becomes Humic Eluviated Gleysol. At this site, the change in lithology, to sand beneath the solum (see Plate 7), appeared to be the reason, over winter and spring, for accumulation of moisture near the soil surface which must account for prominant mottling well above the recorded water table. Further up-slope at Site 3, where the water table is normally deeper and the recharge gradient stronger, than at Site 2, a change to Eluviated Black Chernozem occurs. Although the water table at this site is close to the surface for short periods, mainly following snow melting, rapid dissipation of this water, together perhaps with low microbial activity in cool spring soil temperatures, probably ensures that the water remains well oxygenated and significant mottling is not initiated.

Detectable salinity and gypsum are absent in these soils. Presumably, even at Site 1, where discharge originating from the slough is suggested, the deeper downward groundwater flow, of the

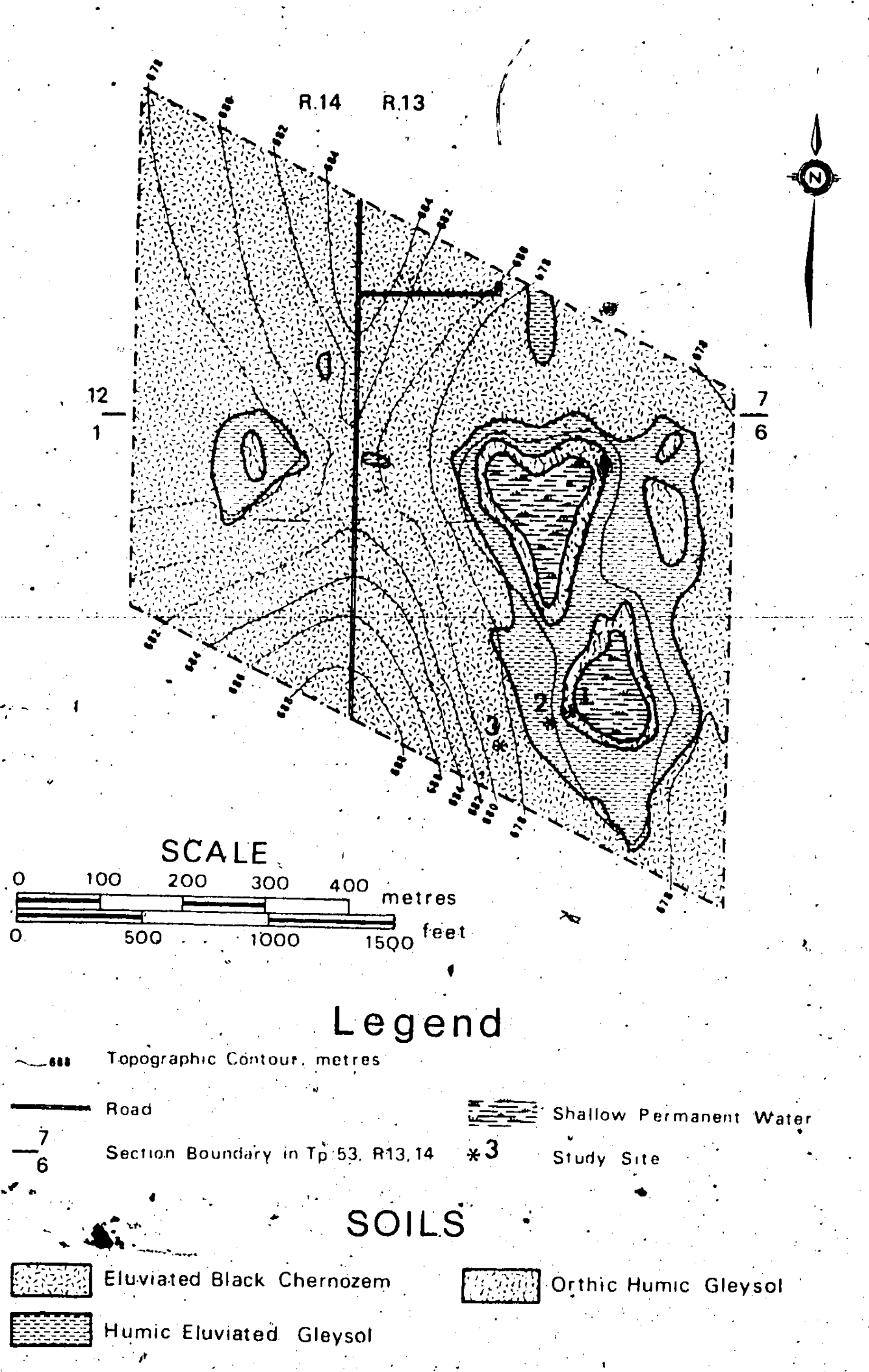


Figure 33. Soil map of Upper study area with locations of study sites.

order of 0.2 cm per year, ensures that salts are continually removed from circulation (Figure 27). Carbonates are absent from the top 1 m or so of all three soils (Figure 34), presumably because of leaching in the case of Sites 2 and 3, but perhaps aided by accumulation of colluvium and washing out at Site 1 where discharge, which prevails except when the site is under water, and the high water table should discourage leaching.

Lower soil study area

Soils change down the slope from Orthic Black Chernozem at Site 4, through a narrow strip of Solodic Black Chernozem to dominantly Black Solonetz intersected by small bands of Alkaline Solonetz and Saline Carbonated Gleyed Regosol in seepages and drainageways (Figure 35). The rise in ground level to the west of Site 6 is reflected in a changed soil situation. Although Black Solonetz still predominates, small areas of shallow water evident following snow melting or summer rains, willow-ringed where undisturbed, give rise to islands of Gleyed Black Solonetz, also Orthic Humic Gleysols and occasionally Humic Eluviated Gleysols. Fairly large areas of Solodic Black Chernozem are also in evidence. A fringe of white surface salts around the open water at Site 9 (see Plate 11) is associated with a narrow band of Saline Black Solonetz soil, while closer to the water's edge this merges into Orthic Humic Gleysol. Because sites in the lower study area are spread over a considerable distance and therefore affected by groundwater characteristics which differ considerably, each site

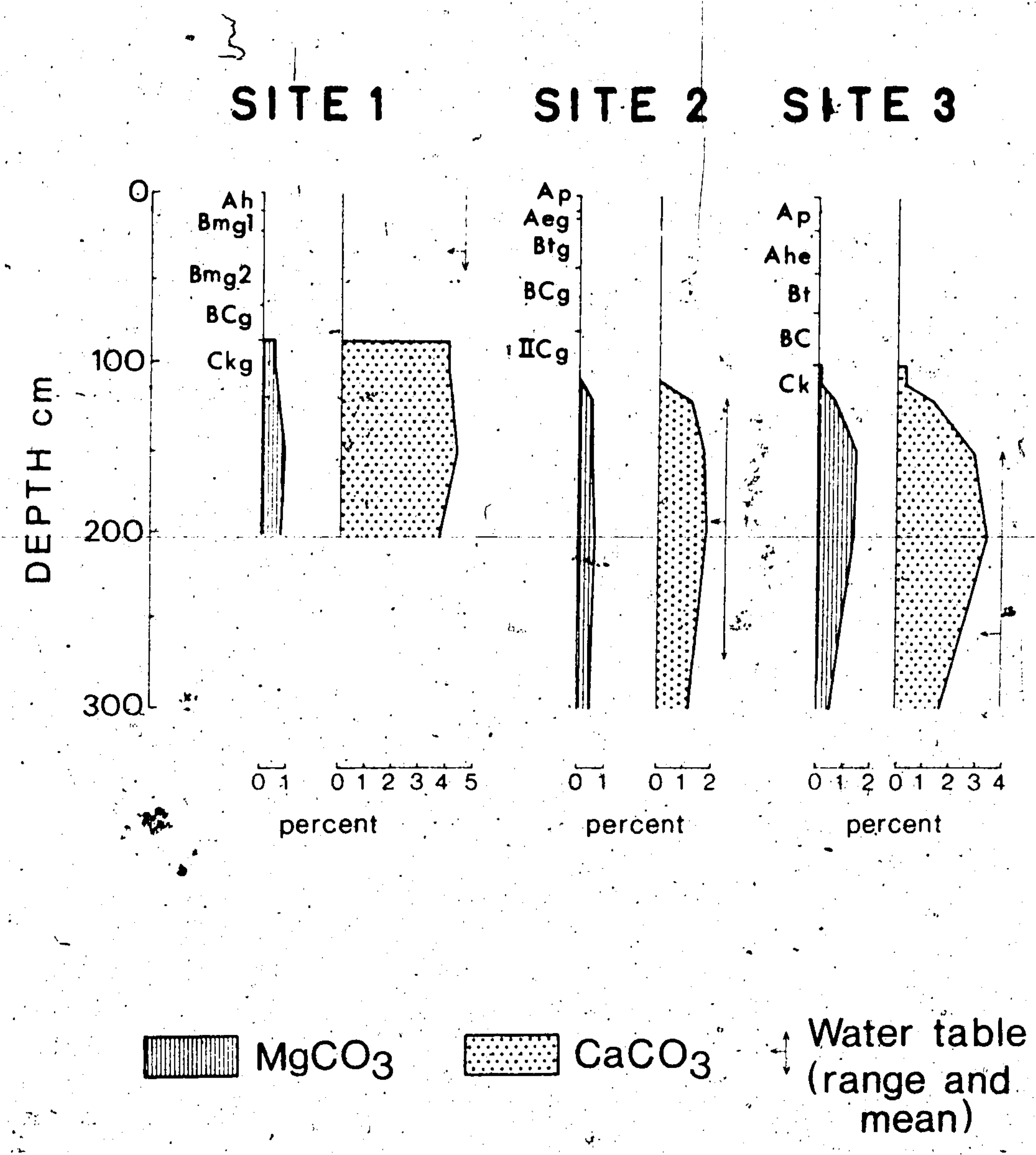


Figure 34. Magnesium and Calcium carbonate distributions in relation to depth, horizons and the water table, in soils of the Upper study area.

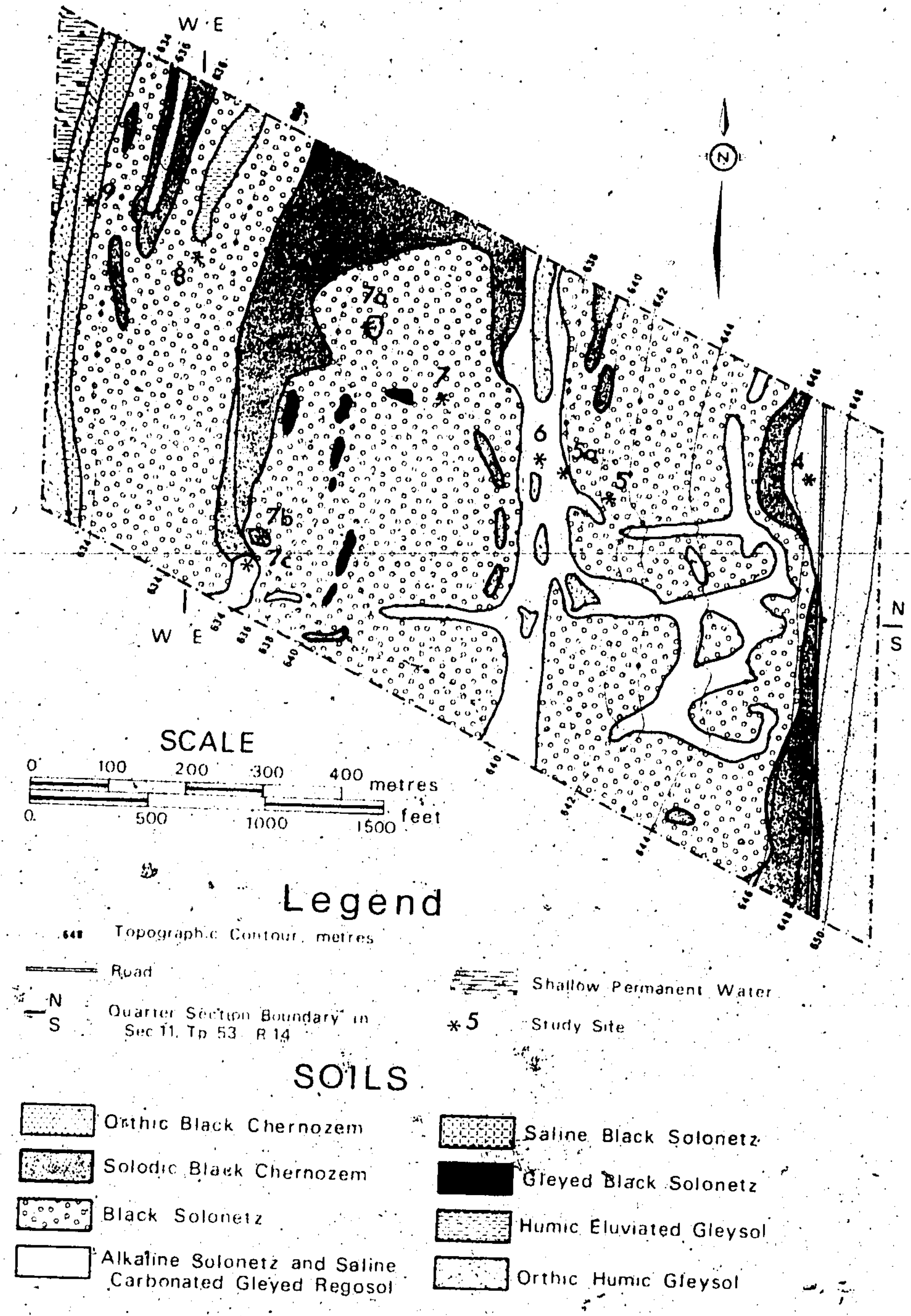


Figure 35. Soil map of Lower study area with locations of study sites.

is discussed individually below.

Site 4

All evidence suggests groundwater discharge at this site, and the soil, although Orthic Black Chernozem, is close to the boundary with soils showing solonetzic features. Effects of discharge on the soil are evident in the content of soluble salts, dominantly magnesium, which have accumulated together with gypsum at the position of maximum carbonate content in the top of the C horizon (Figure 36). The electrical conductivity of the saturation extract at this position was 4.5 mmhos/cm. Salt contents are low in both A and B Horizons and the Ca : Na ratio on the exchange complex of the B horizon ranges between 20 : 1 and 50 : 1 with calcium exceeding magnesium in the ratio 3 : 1. Several factors have probably combined to produce a Chernozemic soil rather than a solonetzic soil at this site. The most important of these is probably the content of sodium in the groundwater and the proportion of sodium relative to divalent ions, both of which, although high compared to waters in the upper study area, were much less than from sites at lower elevations (Figure 10). This is presumed to be because of proximity of Site 4 to the theoretical 'midline', and consequent shallow short groundwater flow paths. A fairly deep water table presumably discourages salts from accumulating higher in the profile where they would cause salinization of the B horizon. The lower bulk densities in this soil than at other sites, whether partially a consequence of a non-solonetz soil, or a cause of this condition, encourage a combination of rapid moisture infiltration

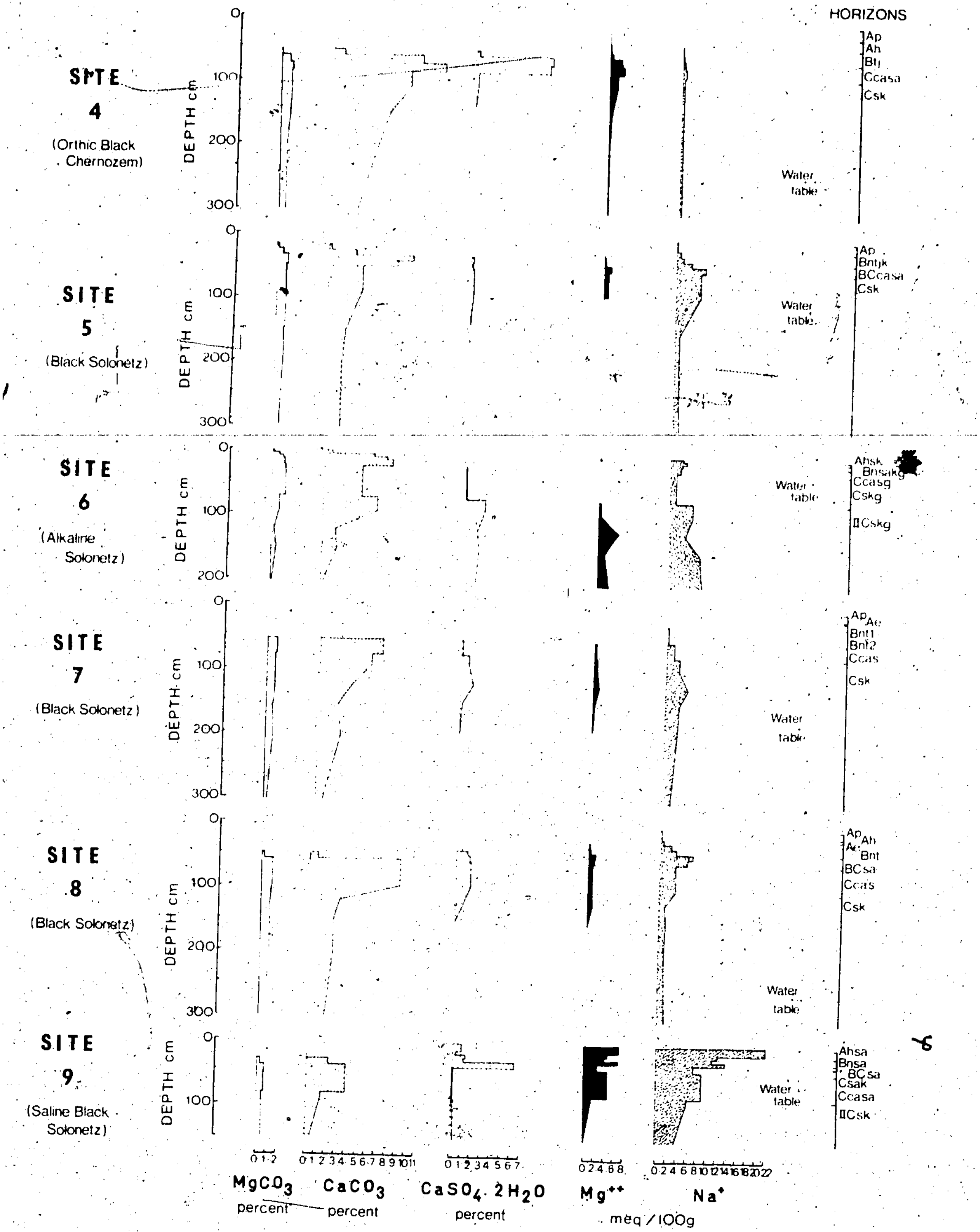


Figure 36. Carbonate, Gypsum and water extractable Magnesium and Sodium distributions in soil profiles of the Lower study area.

and deep rooting, both of which ensure a cycling of non-saline surface water in the upper soil horizons which also discourages upward migration of salts. Finally, the slope encourages a lateral flow of water through more permeable surface horizons (interflow) which should contribute to a gradual depletion of salts in the solum. Since the saturated hydraulic conductivity in the Ah horizon is more than 2000 times that of the till, the effects of interflow, particularly following snow melting when lower horizons are still below 0°C, should not be underestimated as a mechanism of de-salinization.

Site 5

The highest content of sodium salt is in the lower B and upper C horizons closely coinciding with the position of maximum carbonate accumulation (Figure 36). Gypsum content is low in this soil. The highest saturation extract electrical conductivity, 8.1 mmhos/cm, was in the BC horizon but values of 1.4 and 2.2 mmhos/cm occurred in the upper and lower portions of the Bnt horizon respectively. The high salt content close to the soil surface is presumably largely a consequence of a combination of discharge from a saline source of water in a sand lens 2 m below the surface, and a water table which remains around 1 m below the surface all year round. In the process of formation of such a soil, a high water table, by limiting the depth of soil available for retention of infiltration water, slowing infiltration rates, and at the same time limiting rooting depth, thereby reduces the depth of soil available for cycling non-saline surface

A Bnt horizon, once formed, acts as a further barrier to moisture penetration as evidenced by very high matric suctions (calculated from psychrometer readings) at 20 cm depth, in spite of the high water table and low tensions below the Bnt, at 50 cm depth. The fact that the position of the sodium maximum is close to that of carbonate in the soil profile, if not slightly below it however suggests an increasing depth of influence of surface water, though this does not necessarily imply reduced discharge. It could anyway be a consequence of short term moisture flow variations.

Site 6

The Alkaline Solonetz soil with both carbonates and sodium salts present to the soil surface appears to have been affected by the following factors in its formation. First, discharging groundwaters bring considerable salts upwards as evidenced by a fairly high water salinity (Figure 10). However the position of this site in a drainageway probably results in some dilution by surface water, as evidenced by a decline in soil salt content within 20 cm and 1 m of the soil surface (Figure 36). This is probably aided by a gravel layer, the IICskg horizon, 70 cm below the surface, which if continuous may conduct the mixture of waters downstream along the drainageway. Much salinity however obviously reaches the soil surface as a result of evapotranspiration above a very shallow water table when the drainageway is not flooded, but periodic incursions of surface water may be partly the cause, through alkaline hydrolysis and removal of sulphates, of high alkalinity in the upper 70 cm, though this may be aided by biological sulphate reduction in the frequently waterlogged soil surface where microbial activity should be greatest (Gotoh and Yamashita 1966, Daragan 1967).

Site 7

The soil is a Black Solonetz (see Plate 10), but little soluble salt is present in the Bnt horizon, the maximum of both salts and gypsum occurring below that of carbonates in the C horizon. The Bnt appeared to be physically tougher than in the other Black Solonetz soils, presumably reflecting the greater bulk density of this soil. The Ca : Mg : Na ratio on the exchange complex was around 7 : 4 : [illegible] throughout the Bnt horizon, so that although lacking free salts, and in spite of a pH ranging from 5.4 at the top to 7.0 at the bottom, the horizon nevertheless makes the chemical definition of a Bnt. The soil suggests that a gradual leaching out of salts is in process, but although groundwater flow at depths greater than 4 m below the ground surface is undoubtedly downwards, and the position of the site near the summit of a slight rise suggests local recharge, upward flow from a source of water very high in sodium (Figures 23, 24) apparently occurs near the water table, at least temporarily during the summer months. Perhaps over the long term, recharge predominates or perhaps lateral flow moving above the water table towards lower ground, has been responsible for the depletion of salts in the upper soil horizons.

Site 8

The Black Solonetz soil shows a large accumulation of sodium and magnesium salts in the BC horizon (Figure 36) where electrical conductivity of the saturation extract reached 10 mmhos/cm. Appreciable amounts of salts also occur in the Bnt horizon as at Site 5, but unlike at that site, the maximum accumulation zone of soluble sodium and magnesium salts is above that of gypsum and carbonates suggesting upward movement of salts even though an Ae horizon extending into the top of the Bnt horizon (see Plate 10) suggests gradual breakdown of the Bnt from above. A consistent groundwater discharge pattern throughout the year provides an explanation for upward movement of salts. The water table however fluctuates at similar depths to that at Site 4 (Figure 37), where in spite of a similar consistent discharge pattern, the soil was an Orthic Black Chernozem. Groundwater discharge rates based on rough estimates of hydraulic conductivity (Figure 37) are not sufficiently different to provide evidence for the differences in soil and the main explanation probably lies with the ion content of the discharging water, since groundwater samples from the water table showed a content of sodium at Site 8, three times as great as at Site 4 while the ratio of sodium to divalent cations was 4.9 at Site 8 compared to only 0.7 at Site 4. Less interflow from higher ground at Site 8 than at Site 4 where the slope is steeper, may have also contributed to soil differences between the two sites.

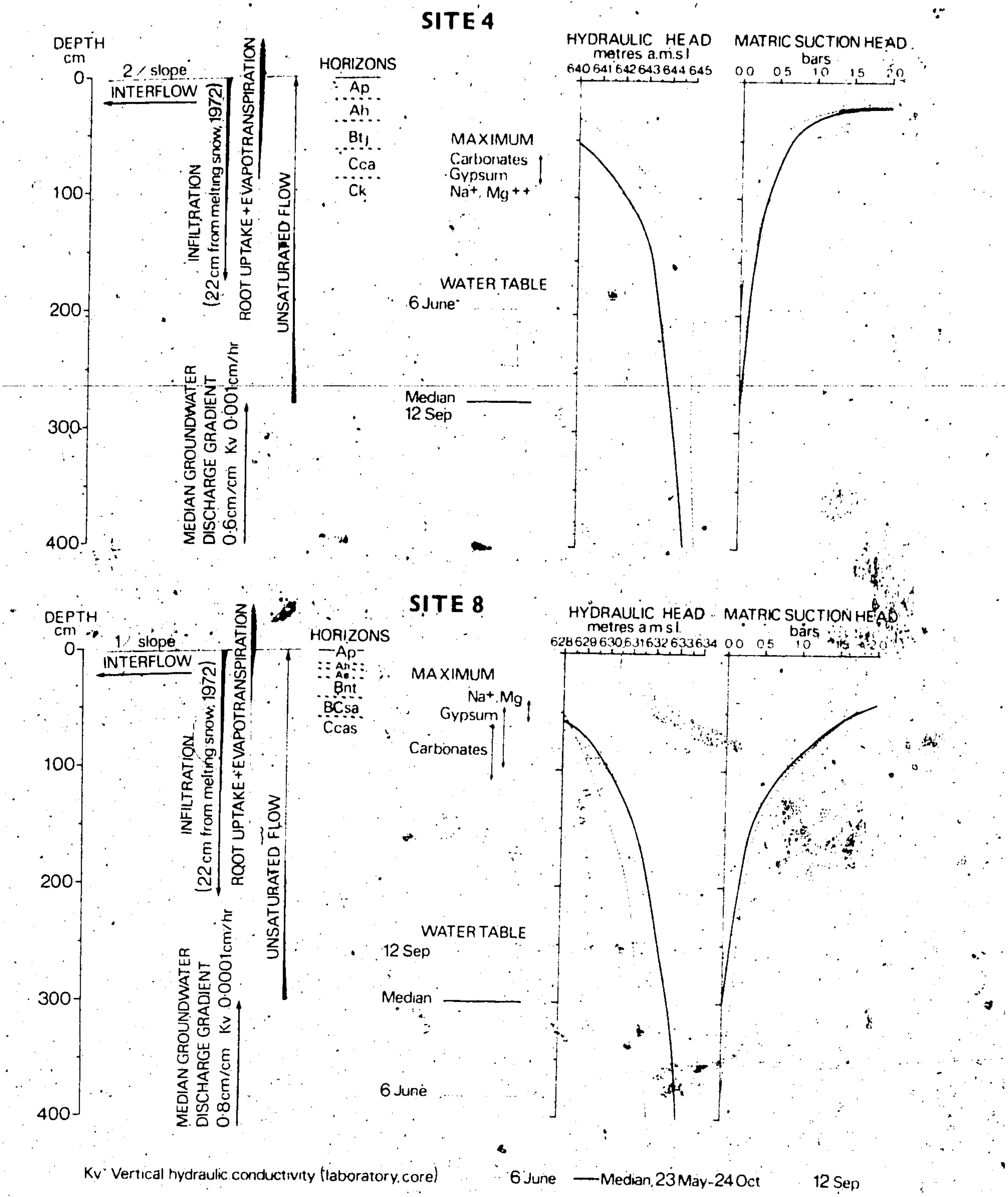


Figure 37. Schematic presentation of moisture flows influencing soil genesis, in relation to water table, hydraulic head and matric suction changes at Sites 4 and 8 during Summer 1972.

Site 9

The Saline Solonetz soil at this site is extremely high in salts (Figure [illegible]). The saturation extract electrical conductivity of the Ah horizon was 24 mmhos/cm while the immediate surface crust was found to be still more saline. A low pH, 5.6 in the Ah and 6.7 in the Bn horizon is presumably largely a result of salts being mainly sodium and magnesium sulphates, which have risen in the slowly discharging groundwaters from considerable depth, but it may also be aided by oxidation of reduced salts, for oxidation-reduction potential measurement (see Appendix 16) showed that the bedrock 3 m below the surface was 'much reduced' while the water table, which is lower than at Site 6, allows oxidizing conditions to prevail near the soil surface. The water table is however sufficiently high to maintain a fairly moist condition at the soil surface which together with a high sodium content limits infiltration and encourages the movement of salts right to the surface where they become concentrated by evapo-transpiration. The permanent water in the adjacent depression supplements the discharge, but because this water is fairly saline, accumulating mainly through overland flow across a saline surface soil, it is much less effective in reducing salt concentrations than at Site 6, but instead aids in flushing existing salts to the surface.

SUMMARY AND CONCLUSIONS

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The deeper groundwater flow is downward throughout the west slope which includes the soil study sites, but superimposed on this flow is a complex pattern of shallower flow systems which are greatly influenced by permeability contrasts both within the bedrock and surficial materials. In this area of normally low permeabilities, topographic depressions (sloughs) accumulate water mainly by overland flow producing 'groundwater mounds' within both recharge and discharge areas which act as a source of water for local discharge around depression fringes. Seasonal variations in potential are considerable within shallow flow systems, but it is difficult to draw conclusions regarding seasonal changes in flow direction because of reduction in amplitude of fluctuations with depth, lag, frost, and other effects. The main source of water for infiltration and recharge is melting snow in spring. During summer little water reaches the water table except following exceptionally prolonged rains and the vertical flow gradient above the water table is normally upward. An upward flow gradient continues through the winter and becomes enhanced by effects of frost, but except where permeabilities are high, and the water table is close enough to the surface to be penetrated by frost, amounts of moisture moved upward during winter are probably small.

In the upper study area, the only discharge appears to originate from a slough, and is confined to its fringes, whereas beneath the area as a whole, a steady recharge takes place into the bedrock and is presumably responsible for a low content of total dissolved solids and sodium as a proportion of cations in the groundwater. Soils reflect this situation showing no zones of salt or gypsum accumulation and range from Eluviated Black Chernozem through Humic Eluviated Gleysol to Orthic Humic Gleysol with increasing proximity of the water table to the ground surface.

In the lower study area, vertical flow directions often show inconsistencies presumably because of the effect of high permeability lenses within the material of overall low permeability. Tensiometers and study of near surface lithology have however helped in revealing the flow situation close to the water table in such cases. Groundwater discharge appears to predominate at all these sites, with the possible exception of one situated on a slight rise in the ground close to small willow-ringed temporarily water-filled depressions. Salinity of the groundwater is much greater than in the upper study area, the concentration of salts being greatest in topographic depressions where discharge of deep origin occurs and to the west of one such depression where it is presumably transported by strong lateral flow within more permeable layers. Soils at all the sites in the lower study area show salt and gypsum accumulation at some distance above the water table though not all are solonetzic. Alkaline Solonetz, Saline - Carbonated Gleyed Regosol, and Saline Black Solonetz soils occur where the water table is usually within 0.5 metres of the surface and discharging groundwaters are very saline. Black Solonetz soils predominate where discharge still occurs, but the water table is at least 0.5 metres beneath the surface. With a water table averaging 2 metres or more beneath the surface the zone of salt accumulation is sufficiently deep that occasionally soils of the Chernozemic order occur in spite of groundwater discharge. In such cases, a low sodium to calcium ratio in the discharging groundwater may discourage formation of a Solonetzic B horizon. A lack of salinity in the A and B horizons is then presumably partially maintained by a combination of high surface permeability and deep rooting which together encourage cycling of surface water, while lateral flow through the more permeable near-surface horizons encouraged by slope, is probably also an important de-salinization mechanism. Effects of such lateral flow should not be underestimated since the saturated hydraulic conductivities of Ah and A horizons is several thousand times as great as the underlying till and bedrock.

[illegible] alone are useful in providing information on groundwater flow over the broader area, the addition of tensiometers is neccessary in order to accurately define the water table position and to characterise the shallow flow situation relating to soil genesis at individual sites. This is particularly so where underlying materials are of very variable permeability. Most information is probably obtained where sites are in close proximity, but on different soils, so that unknown influences are minimized and flow conditions can be closely defined.

REFERENCES

REFERENCES

AHMAD, N. 1964. A review of salinity - alkalinity status of Irrigated soils of West Pakistan. pp.117-150 Proc. Symposium on Sodic soils, Budapest. Edit. Office Budapest 114.

AL-DHAHIR, Z.A. and MORGENSTERN, N.R. 1968. Intake factors for cylindrical piezometer tips. Soil Sci. 107 : 17-21.

ALLAN, J.A. 1943. Geology of Alberta soils. Rep. 34. Part III. Dept. of Geol. Univ. Alberta.

ARSHAD, M.A. and PAWLUK, S. 1966. Characteristics of some Solonetzic soils in the Glacial Lake Edmonton Basin of Alberta. I Physical and Chemical. J. Soil Sci. 17 : 36-47.

AUSTENSEN, H.M. and ANDERSON, C.H. 1969. Winter wheat in Saskatchewan : A new frontier. Agr. Inst. Can. Rev. 24/6 : 22-24.

BACK, W. 1966. Hydrochemical Facies and Groundwater flow patterns in Northern part of Atlantic coastal plain. Geol. Surv. Prof. Paper. 498A.

BASCOMB, C.L. 1961. A Calcimeter for routine use on soil samples. Chem. and Ind., Part 2, 1826.

BAVER, L.D. 1956. Soil Physics. John Wiley and Sons, Inc. New York. 489 pp.

BENTLEY, C.F. and ROST, C.O. 1947. A study of some Solonetzic Soil complexes in Saskatchewan. Sci. Agr. 27 : 293-313.

BENZ, L.C., WILLIS, W.O., SANDOVAL, F.M. and MICKELSON, R.H. 1968. Soil water translocation in a high water table area. Water Resources Res. 4 : 95-101.

BETTENAY, E., BLACKMORE, A.V. and HINGSTON, F.J. 1964. Aspects of the Hydrologic cycle and related salinity in the Belka Valley, Western Australia. Aust. J. Soil Res. 2 : 187-210.

BLAKE, G.R. 1965. Particle Density. pp.371-373 in Methods of Soil Analysis, Part I. Amer. Soc. Agron. Inc. Madison.

BOWER, C.A., REITEMEIER, R.F. and FIREMAN, M. 1952. Exchangeable cation analysis of saline and alkali soils. Soil Sci. 73 : 251-261.

BOWSER, W.E., KJEARSGAARD, A.A., PETERS, T.W. and WELLS, R.E. 1962 Soil Survey of Edmonton Sheet. Rep. No. 21 of Alberta Soil Survey. Univ. Alberta. 66 pp.

BRAY, R.H. 1935. The origin of horizons in clay-pan soils. Amer. Soil Survey Assoc. Bul. 16 : 70-75.

BRUNT, D. 1934. Physical and Dynamical meteorology, Cambridge Univ. Press. 411 pp.

CANADA DEPT. TRANSPORT. 1968. Climatic Normals. 5. Wind. Meteorological Office, Toronto.

CARSON, J.E. 1961. Soil Temperature and weather conditions. Argonne Nat. Lab., Univ. Chicago.

CARY, J.W. 1965. Water flux in moist soil : Thermal versus suction gradients. Soil Sci. 100 : 168-175.

CARY, J.W. 1966. Soil moisture transport due to thermal gradients : Practical aspects. Soil Sci. Soc. Amer. Proc. 30 : 428-433.

CARY, J.W. and TAYLOR, S.A. 1967. The dynamic of soil water, II - Temperature and solute effects, pp. 245-253 in Irrigation of agricultural lands, Agronomy 11, Amer. Soc. Agron. Madison.

CHEBOTAREV, I.I. 1955. Metamorphism of Natural waters in the crust of weathering. Geochimica Cosmochimica Acta 8 : 22-48, 137-170, 198-212.

CHESNIN, L. and YIEN, C.H. 1951. Turbimetric determination of available sulphates. Soil Sci. Soc. Amer. Proc. 15 : 149-151.

CHILDS, E.C. 1957. The anisotropic hydraulic conductivity of soil. J. Soil Sci. 8 : 42-47.

CHILDS, E.C. and COLLIS-GEORGE, W. 1950. Permeability of porous materials. Proc. Roy. Soc. A 202 : 392-405.

DARAGAN, A.Y. 1967. Microbiology of the Gley process. Soviet Soil Sci. Part 1 : 228-236.

de SIGMOND, A.A. 1938. The principles of Soil Science. Thomas Murby and Co. London. 362 pp.

DICKEY, D.D., FERGUSON, H. and BROWN, P.L. 1964. Influence of neutron meter access tubes on soil temperature and water under winter conditions. Soil Sci. Soc. Amer. Proc. 28 : 134-135.

DORSEY, N.E. 1940. Properties of ordinary water-substance. Reinhold Publ. Corp. N.Y.

DOUGHTY, J.L. 1941. The advantages of soil paste for routine pH determinations. Sci. Agr. 22 : 135-158.

ELLWOOD, R.B. 1961. Surficial Geology of the Vermilion area, Alberta, Canada. Unpublished Ph.D. thesis. Univ. Illinois. 131 pp.

ENVIRONMENT CANADA. 1973a. Canadian Normals. 1. Temperature 1941-1970. Atmospheric Environment Service, Downsview, Ontario.

ENVIRONMENT CANADA. 1973b. Canadian Normals. 2. Precipitation 1941-1970. Atmospheric Environment Service, Downsview, Ontario.

EVANS, D.D. 1965. Gas movement. pp. 319-330 in Methods of soil analysis, part I, Agronomy 9, Amer. Soc. Agron. Madison, Wisc.

FERGUSON, H., BROWN, P.L. and DICKEY, D.D. 1964. Water movement and loss under frozen soil conditions. Soil Sci. Soc. Amer. Proc. 28 : 700-703.

FERRIS, J.G., KNOWLES, D.B., BROWN, R.H. and STALLMAN, R.W. 1962. Theory of Aquifer tests. In Groundwater Hydraulics. Geological water supply paper 1536E : 69-171.

FIREMAN, M. 1944. Permeability measurements on disturbed soil samples. Soil Sci. 58 : 337-353.

FOLK, R.L. 1954. The distinction between Grain size and mineral composition in Sedimentary rock Nomenclature. J. Geol. 62 : 345-359.

FREEZE, R.A. 1967. The continuity between groundwater flow systems and flow in the unsaturated zone. pp. 205-2[illegible]. In Proc. Hydrol. Symp. No. 6. Dept. Energy, Mines and Resources, Ottawa.

FREEZE, R.A. 1969. Theoretical analysis of Regional Groundwater flow. Dept. Energy, Mines and Resources, Inland Waters Branch, Canada. Sci. Series No. 3. 196 pp.

FREEZE, R.A. and WITHERSPOON, P.A. 1966. Theoretical analysis of regional groundwater flow, I. Analytical and numerical solutions to the mathematical model. Water Resources Res. 2 : 641-657.

FREEZE, R.A. and BANNER, J.A. 1970. An instrumental experimental site for the investigation of soil moisture, frost, and groundwater discharge. Inland Waters Branch, Dept.

Energy, Mines and Resources, Ottawa. Rep. Series 3. Tech. Bul. 21.

GEDROIZ, K.K. 1925. Soil absorbing complex and the absorbed soil cations as a basis of genetic soil classification (Russian). Nossov Agr. Exp. Sta. Agro chemical div. paper No. 38. Leningrad.

GOTOH, S. and YAMASHI[illegible]. 1966. Oxidation-reduction potential of a paddy soil <u>in situ</u> with special reference to production of ferrous iron, manganous manganese and sulphide. Soil Sci. and Plant Nutr. 12 : 230-238.

GRADWELL, M.W. 1955. The determination of specific gravities of soils as influenced by clay-mineral composition. N.Z. J. Sci. Tech. 37B : 283-289.

GRAVENOR, G.P. and BAYROCK, L.A. 1956. Stream-trench systems in east-central Alberta; Research Council of Alberta Prelim. Rep. 56-4. 11 pp.

HESSE, P.R. 1971. A textbook of Soil Chemical Analysis. John Murray, London. p. 74.

HODGMAN, C.D., WEAST, R.C., SELBY, S.M. 1961. Handbook of Chemistry and Physics. 43rd Edit. The chemical rubber. Publ. Co.; Cleveland. pp. 602, 659, 2044, 2078.

HOEKSTRA, P. 1966. Moisture movement in soils under temperature gradients with the cold-side temperature below freezing. Water Resources Res. 2 : 241-250.

HUBBERT, M.K. 1940. The theory of groundwater motion. J. Geol. 158 : 785-944.

HUME, G.S. and HAGE, C.O. 1941. The Geology of East-Central Alberta. Canada Dept. Mines and Resources, Mines and Geology Branch, Geol. Memoir 232. 101 pp.

HVORSLEV, M.J. 1951. Time lag and soil permeability in groundwater observations. U.S. Army Corps of Engineers. Waterways Exp. Station, Vicksburg, Miss. Bul. 36. 50 pp.

JACKSON, M.L. 1958. Soil Chemical Analyses. Prentice-Hall Inc. N.J. p. 266.

JACKSON, R.D., REGINATO, R.J. and VAN BAVEL, C.H.M. 1965. Comparison of measured and calculated hydraulic conductivities of unsaturated soils. Water Resources Res. 1 : 375-380.

JOFFE, J.A. 1936. Pedology. Rutgers Univ. Press. New Brunswick. 575 pp.

JUMIKIS, A.R. 1962. Effective soil moisture transfer mechanisms upon freezing. Highway Res. Board Bul. 317 : 1-8.

KAISER, H. 1960. Investigations on the effect of shelterbelts on soil climate. Z. Acker-u. PfBau. 111 : 47-72. (Soil and Fert. Abs. 23 : 2863.)

KELLEY, W.P. 1951. Alkali soils, their formation, properties and reclamation. Reinhold. New York. 176 pp.

KEMPER, W.D. and MAASLAND, D.E.L. 1964. Reduction in salt content of solution on passing through thin films adjacent to charged surfaces. Soil Sci. Soc. Amer. Proc. 28 : 318-373.

KILMER, V.J. and ALEXANDER, L.T. 1949. Methods of making mechanical analysis of soils. Soil Sci. 68 : 15-24.

KLUTE, A. 1952. Some theoretical aspects of the flow of water in unsaturated soils. Soil Sci. Soc. Amer. Proc. 16 : 144-148.

KLUTE, A. 1965. Laboratory measurement of hydraulic conductivity of saturated soil. pp. 253-261 in Methods of Analysis, Part I. Amer. Soc. Agron. Madison.

KORVEN, H.C. and TAYLOR, S.A. 1959. Peltier effect and its use for determining relative activity of soil water. Can. J. Soil Sci. 39 : 76-85.

KUZMENKO, I.T. 1968. Seasonal variations in the temperature and moisture content of bottomland derno-meadow soils in relation to their agricultural utilization. Vest. Mosk, Univ. Ser. Biol. Pochv. No. 4. 78-85. (Soil and Fert. Abs. 32, 1139).

LAMBE, T.W. and WHITMAN, R.V. 1969. Soil Mechanics. John Wiley and Son, Inc. 553 pp.

LAVKULICH, L.M. 1969. Soil Dynamics in the Interpretation of Paleosols. pp. 25-38. In Pedology and Quaternary Research. Univ. Alberta. Edmonton.

LAWLESS, G.P., MACGILLIVRAY, A. and NIXON, P.R. 1963. Soil moisture interface effects upon readings of Neutron moisture probes. Soil Sci. Soc. Amer. Proc. 27 : 502-507.

LEBEDEFF, A.F. 1927. The movement of ground and soil waters. Trans. 1st Int. Congr. Soil Sci. 1 : 450-494.

Le BRETON, G.E. 1963. Groundwater geology and hydrology of East Central Alberta. Res. Council Alberta, Bull. 13.

LESKIW, L.A. 1971. Relationship between soils and groundwater in field mapping near Vegreville, Alberta. M.Sc. thesis. Univ. Alberta.

LIAKOPOULOS, A.C. 1965. Variation of the permeability tensor ellipsoid in homogenous anisotropic soils. Water Resources Res. 1 : 135-141.

LISSEY, A. 1968. Surficial mapping of groundwater flow systems with application to the Oak River Basin, Manitoba. Ph.D. thesis, Univ. Saskatchewan.

LONGLEY, R.W. 1967. Temperature increases under snow during a mild spell. Soil Sci. 104 : 379-382.

LUTHIN, J.N. and KIRKHAM, D. 1949. A piezometer method for measuring permeability of soil *in situ* below a water table. Soil Sci. 68 : 349-358.

MAASLAND, M. 1957. Soil anisotropy and land drainage. pp. 216-285 in Drainage of Agricultural lands. Amer. Soc. Agron. Madison.

MacGREGOR, J.M. and WYATT, F.A. 1945. Studies on Solonetz soils of Alberta. Soil Sci. 59 : 419-435.

Mac[illegible] D.C. 1970. Macroclimatic zonation in northern Alberta. M.Sc. thesis. Univ. Alberta, Edmonton.

MAGISTAD, O.C., REITEMEIER, R.F. and WILCOX, L.V. 1945. Determination of soluble salts in soils. Soil Sci. 59 : 65-75.

MARSHALL, T.J. 1958. A relation between permeability and size distribution of pores. J. Soil Sci. 9 : 1-8.

MASSOUMI, [illegible] and CORNFIELD, A.H. 1963. A rapid method for determining sulphate in water extracts of soils. Analyst 88 : 321-322.

MERRIAM, R.A. and KNOERR, K.R. 1961. Counting times required with neutron soil moisture probes. Soil Sci. 92 : 39[illegible]-395.

MEYBOOM, P. 1966. Groundwater studies in the Assiniboine River Drainage basin, Part I. The evaluation of a flow system in south central Saskatchewan. Geol. Surv. Canada Bul. 139. 65 pp.

MEYBOOM, P. 1967a. Groundwater studies in the Assiniboine River Drainage basin, Part II. Hydrologic characteristics of Phreatophytic vegetation in south central Saskatchewan. Geol. Surv. Canada Bul. 139. 64 pp.

MEYBOOM, P. 1967b. Estimates of groundwater recharge on the Prairies. pp. 128-153 in Water Resources of Canada. Roy. Soc. Can. Symposium.

MEYER, A.F. 1960. Effect of temperature on groundwater levels. J. Geophys. Res. 65 : 1747-1752.

MILLINGTON, R.J. and QUIRK, J. 1961. Permeability of porous solids. Trans. Farad. Soc. 57 : 1200-1206.

MITCHELL, J., MOSS, H.C., CLAYTON, J.S. 1944. Soil Survey Report No. 12. Dept. of Soils. Univ. Saskatchewan.

MONTEITH, J.L. and OWEN, P.C.V. 1958. A thermocouple method for measuring relative humidity in the range 95-100%. J. Sci. Instr. 35 : 443-446.

MORTIER, P., De BOODT, M., DANSERCOER, W. and De LEENHEER, L. 1960. The resolution of the neutron scattering method for soil moisture determination. Trans. 7th Int. Congr. Soil Sci. 1 : 321-329.

MOSS, E.H. 1955. The vegetation of Alberta. Bot. Rev. 21(9); 493-567.

MUELLER, O.P. 1970. Soil temperature regimes in a forested area of the Northern Rockies. Soil Sci. [illegible] : 40-47.

MURATOVA, V.S. 1958. Salt accumulation processes in soils and groundwater of the Mil'sk Plain, Kura-Araks Lowland. Soviet Soil Sci. 613-622.

NIKIFOROFF, C.C. 1937. The Solonetz-like soils in Southern California. J. Amer. Soc. Agron. 9 : 781-797.

NUCLEAR-CHICAGO CORPORATION. 1962. Model P19. Depth moisture gauge. Instruction manual. Nuclear-Chicago Corp. Des Plaines, Illinois.

ODYNSKY, W. 1945. Solonetz soils in Alberta. Sci. Agr. 25-12 : 780-790.

PATTEN, H.E. 1909. Heat transference in soils. U.S. Dept. Agr. Bur. Soils Bul. 59.

PAWLUK, S., DUMANSKI, J. and TOTH, J. 1969. Notes from the field tour held in c[illegible]tion with the Symposium, May 14, 1969. In Pedology [illegible]rnary Research, University of Alberta. 18[illegible]

PELTON, W.L., CAMPBELL, [illegible] and NICHOLAICHUK, W. 1967. The influence of freezing and thawing on soil moisture. pp. 241-265 in Proc. Hydrol. Symp. No. 6. Dept. Energy, Mines and Resources, Ottawa.

PENMAN, H.L. 1948. Natural evaporation from open water, bare soil and grass; Royal Soc. London Proc. Series A, 193 : 120-146.

PEYTON, A.D. and TURNER, J.C.R. 1962. Soret coefficients and heats of transport of some salts of alkaline earth metals in water at 25°C. Trans. Farad. Soc. 58 : 55-59.

PHILIP, J.R. 1957. The theory of infiltration : 1. The infiltration equation and its solution. Soil Sci. 83 : 345-357.

PHILIP, J.R. and De VRIES, D.A. 1957. Moisture movement in porous materials under temperature gradients. Trans. Amer. Geophys. Union. 38 : 222-232.

QUASHU, H.K. and ZINKE, P.J. 1964. The influence of vegetation on soil thermal regime at the San Dimas lysimeters. Soil Sci. Soc. Amer. Proc. 28 : 703-706.

RAWLINS, S.L. 1971. Some new methods for measuring the components of water potential. Soil Sci. 112 : 8-16.

RAWLINS, S.L. and DALTON, F.N. 1967. Psychrometric measurement of soil water potential without precise temperature control. Soil Sci. Soc. Amer. Proc. 31 : 297-301.

RICHARDS, L.A. 1931. Capillary conduction of liquids through porous mediums. Physics. 1 : 318-333.

RICHARDS, S.J., HAGAN, R.M. and McCALLA, T.M. 1952. Soil Temperature and plant growth. pp. 304-336 in Soil Physical Conditions and Plant Growth. Amer. Soc. Agron. Inc. Madison.

ROSE, D.A. 1965. Water movement in unsaturated porous materials. Inter. Assoc. Testing and Res. Lab. for Materials and Structures (RILEM) 29 : 119-124.

ROSE, D.A. 1968. Water movement in soils. 1. Physical factors affecting sorption of water by dry soil. J. Soil Sci. 19 : 81-93.

ROST, C.O. and MAEHL, K.L. 1943. Some solodized soils of the Red River Valley. Soil Sci. 55 : 301-312.

SCHNEIDER, R. 1961. Correlation of groundwater levels and air temperatures in the winter and spring in Minnesota. U.S. Geol. Surv. Water-supply paper 1539-D.

SCHOELLER, H. 1959. Arid zone hydrology, recent developments. UNESCO arid zone research series, 12, 125 pp.

[illegible] 1932. Measuring the salinity of irrigation waters and of soil solutions with a Wheatstone br U.S. Dep. Agr. Circ. 232.

SHAW, E.W. and HARDING, S.R. 1949. Lea Park and Belly Riv Formations of East-Central Alberta. Bul. Amer. As Petrol. Geol. 33 : 487-499.

SHEPARD, D.S. 1970. Symap interpolation characteristics. Laboratory for Computer Graphics and Spatial Anal Harvard University, Cambridge, Mass. 49 pp.

SIMONSEN, R.W. 1959. Outline of a generalized theory of so genesis. Soil Sci. Soc. Amer. Proc. 23 : 152-156.

SPAN[illegible] D.C. 1951. The Peltier effect and its use in the measurement of suction pressure. J. Exp. Bot. 2 : 145-168.

STONE, J.F., SHAW, R.H and KIRKHAM, D. 1960. Statistical parameters reproductivity of the neutron metho measuring soil moisture. Soil Sci. Soc. Amer. Pro 24 : 435-438.

SYMAP MANUAL. 1971. Laboratory for Computer Graphics and S Analysis, Harvard University, Cambridge, Mass. 15

SZABOLCS, I. 1965. Salt-affected soils in Hungary. pp. 275 in Proc. Symposium on Sodic soils, Budapest. Edit. Offices. Budapest 14.

TAYLOR, S.A. and CARY, J.W. 1960. Analysis of the simultane flow of water and heat or electricity with the the dynamics of irreversible processes. Trans. 7th Int Congr. Soil Sci. 1 : 80-90.

TAYLOR, S.A. and JACKSON, R.D. 1965. Temperature. pp 331-34 in Methods of Soil Analysis. Part I. Amer. Soc. Agr Madison.

TIMAR, E. 1965. The effect of organic matter on sulphate reduction occurring in Alkali (Szik) soils. pp. 195 in Proc. Symhosium on Sodic soils, Budapest. Edit. Office. Budapest 114.

TOOGOOD, J.A. 1958. A simplified textural classification di Can. J. Soil Sci. 38 : 54-55.

TOOGOOD, J.A. and PETERS, T.W. 1953. Comparison of methods mechanical analysis of soils. Can. J. Agr. Sci. 33 159-171.

67 : 4375-4387.

TOTH, J. 1963. A theoretical analysis [illegible] groundwater flow in small drainage basins. J. G[illegible]ys. Res. 68 : 4795-4812.

TOTH, J. 1966. Mapping and interpretation of field phenomena for groundwater reconnaissance in a prairie environment, Alberta, Canada. Bul. Int. Ass. Sci. Hydrol. 11 : 20-68

TREWARTHA, G.T. 1954. An Introduction to Clim[illegible]. McGraw-Hill Inc. N.Y. 402 pp.

U.S. LABORATORY STAFF. 1954. Diagnosis and improvement [illegible]ne and alkali soils. Agr. Handbook 60. U.S. Dept [illegible] 160 pp.

VAN BAVEL, C.H.M. 1969. The three phase domain in hydrology. pp 23-30 in Water in the Unsaturated Zone. [illegible]ningen symposium proceedings, IASH-UNESCO 1.

VAN EVERDINGEN, R.O. 1963. Groundwater flow-diagrams in sections with exaggerated vertical scale. Geol. Surv. Can. paper 63-27. 24 pp.

VAN SCHAIK, J.C. and RAPP, E. 1970. Water table behavior and soil moisture content during the winter. Can. J. Soil Sci. 50 : 361-366.

VAN WIJK, W.R. [illegible] Physics of Plant Environment. North Holla[illegible] Co., Amsterdam. 382 pp.

VARALLYAY, G. 1968. Salt [illegible]cumulation processes in the Hungarian Danube valley. [illegible] Int. Congr. Soil Sci. 1 : 374-380.

VISVALINGHAM, M. and TANDY, J.D. 1972. The Neutron method for measuring soil moisture content - A review. J. Soil Sci. 23 : 499-511.

VREDENBURG, R.T. and WILLIS, W.O. 1970. Effects of snow on soil water measurement by neutron moderation. Can. J. Soil Sci. 50 : 463-464.

VZNUZDAYEV, N.A. 1967. Temperature regime of gray forest soils of foothills of the north-west Caucasus. Sov. Soil Sci. Part 1 : 524-538.

WALDEN, A.R. 1972. Quantitative comparison of automatic contouring alogorithms. Kansas Geological Survey. 108 pp.

WALKELEY, A. and BLACK, I.A. 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the Chromic acid titration method. Soil Sci. 37 : 29-38.

WEBSTER, R. 1966. The measurement of soil water tension in the field. New Phytol. 65 : 249-258.

WHITTIG, L.D. and JANITZKY, P. 1963. Mechanisms of formation of sodium carbonate in soils. 1. Manifestation of biological conversions. J. Soil Sci. 14 : 322-333.

WILLIS, W.O., PARKINSON, H.L., CARLSON, C.W. and HAAS, H.J. 1964. Water table changes and soil moisture loss under frozen conditions. Soil Sci. 98 : 244-248.

WOODSIDE, W. and KUZMAK, J.M. 1958. Effect of temperature distribution on moisture flow in porous materials. Trans. Amer. Geophys. Union. 39 : 676-680.

WYATT, F.A., NEWTON, J.D., BOWSER, W.E. and ODYNSKY, W. 1944. Soil Survey of Wainwright and Vermilion sheets. Soil Survey Bul. 42. Alberta Soil Survey, Univ. Alberta. 122 pp.

YORKE, D.J. and KENDALL, G.R. 1972. Daily bright sunshine 1941-1970. CL 1-6-72. Atmospheric Environment Service, Downsview, Ontario.

PHOTOGRAPHIC PLATES

1. Plant community surrounding a water-filled depression showing features of salinity and groundwater discharge. Red Samphire (*Salicornia rubra* L.) is prominent in the foreground.

te 2. Landscape features of the Upper soil study area. Sites 1, 2 and 3 (L. to R.) are arrowed.

3. View towards the west from Nest III (installed as part of Leskiw's (1971) study) towards the Vermilion River.

Plate 4. Site 6 flo
during spr
thaw.

Plate 5. View from near Site 7 eastwards towards Sites 6, 5a and 5 (arrowed L. to R.).

6. Willow-ringed depression in late winter, with drifted snow (above) in contrast to the same depression in spring (below). Site 7a is seen to the left of the depression.

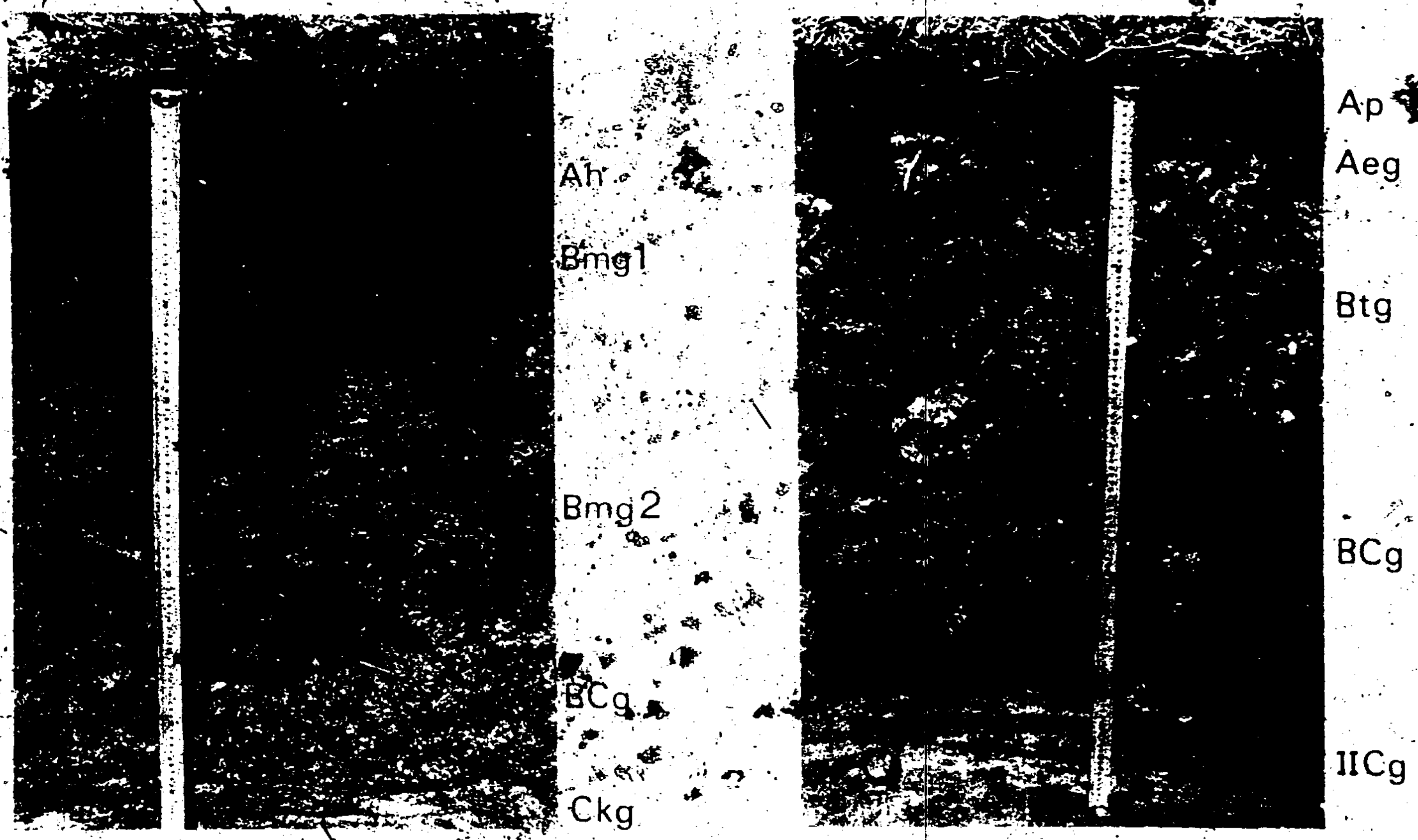


Plate 7. Orthic Humic Gleysol profile at Site 1 (left) and Humic Eluviated Gleysol profile at Site 2 (right).

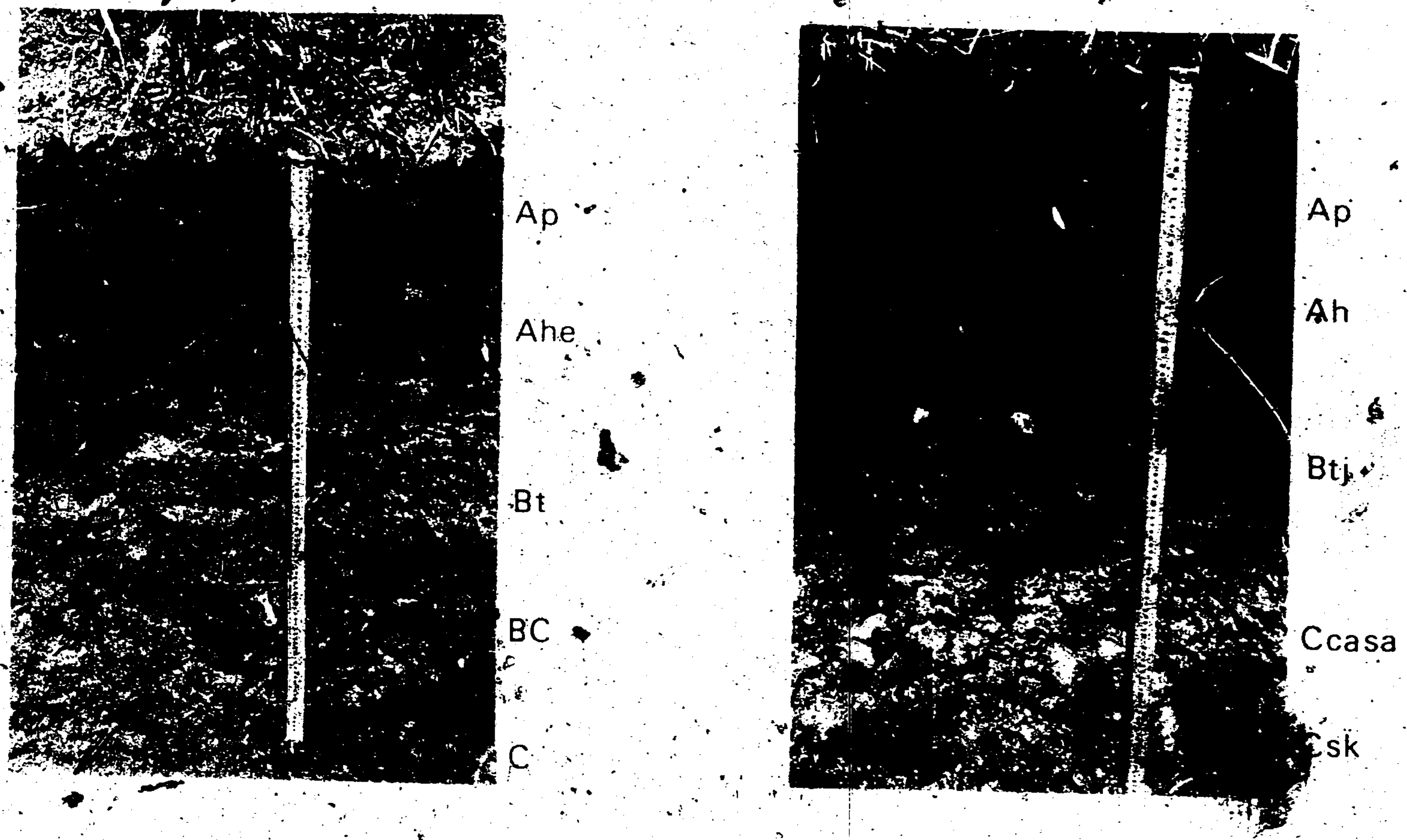


Plate 8. Eluviated Black Chernozem profile at Site 3 (left) and Orthic Black Chernozem profile at Site 4 (right).

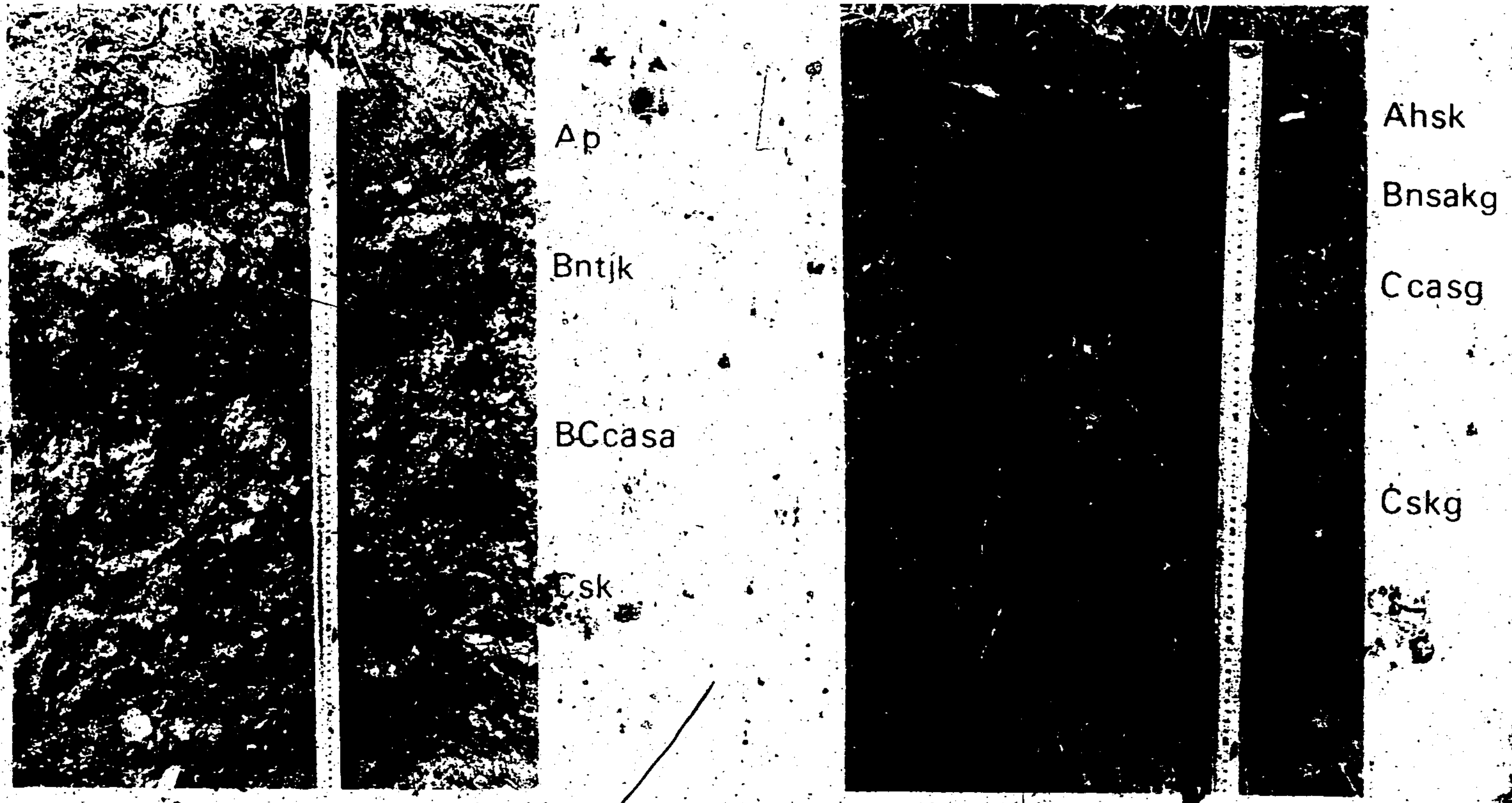


Plate 9. Black Solonetz profile at Site 5 (left) and Alkaline Solonetz profile at Site 6 (right).

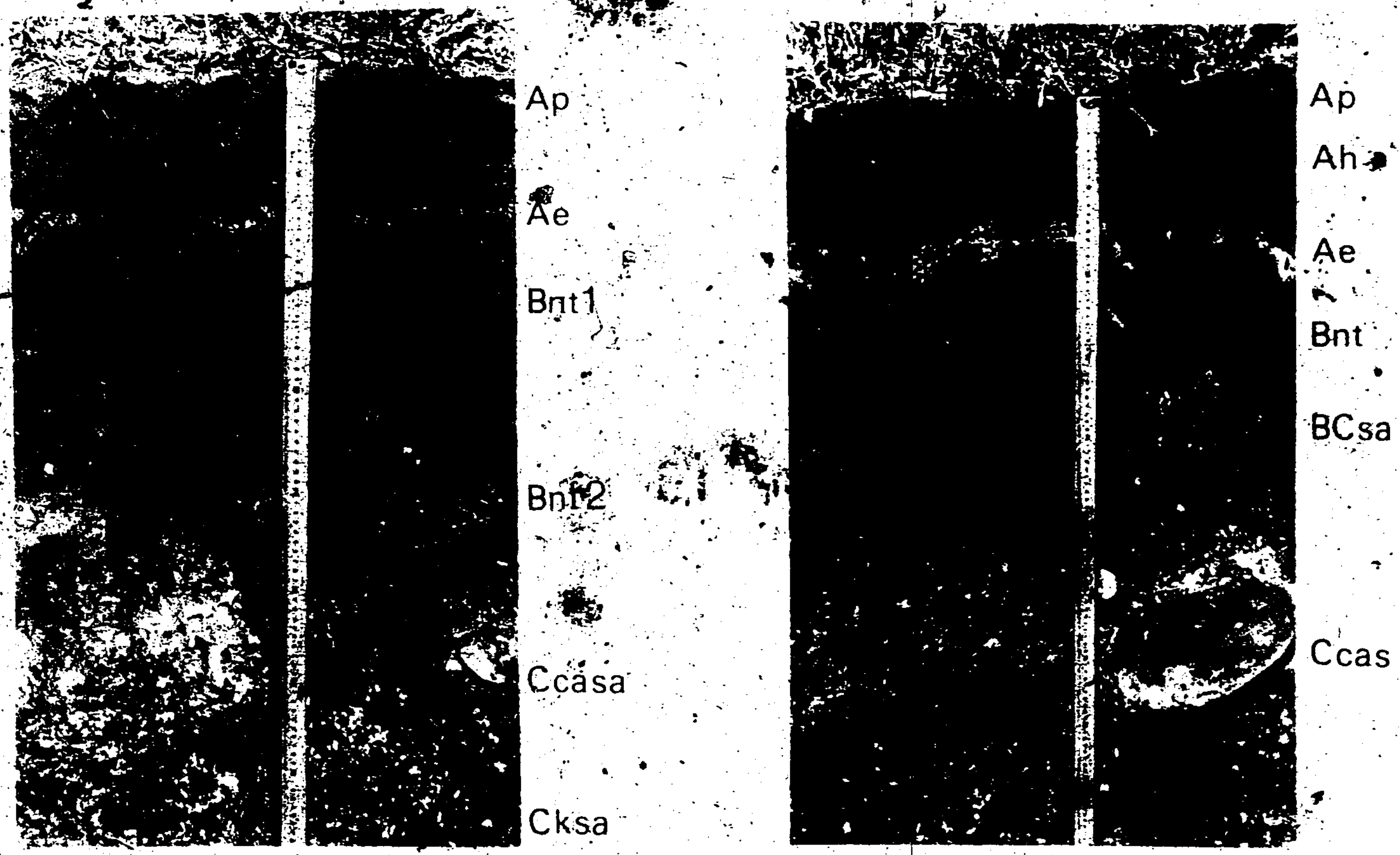
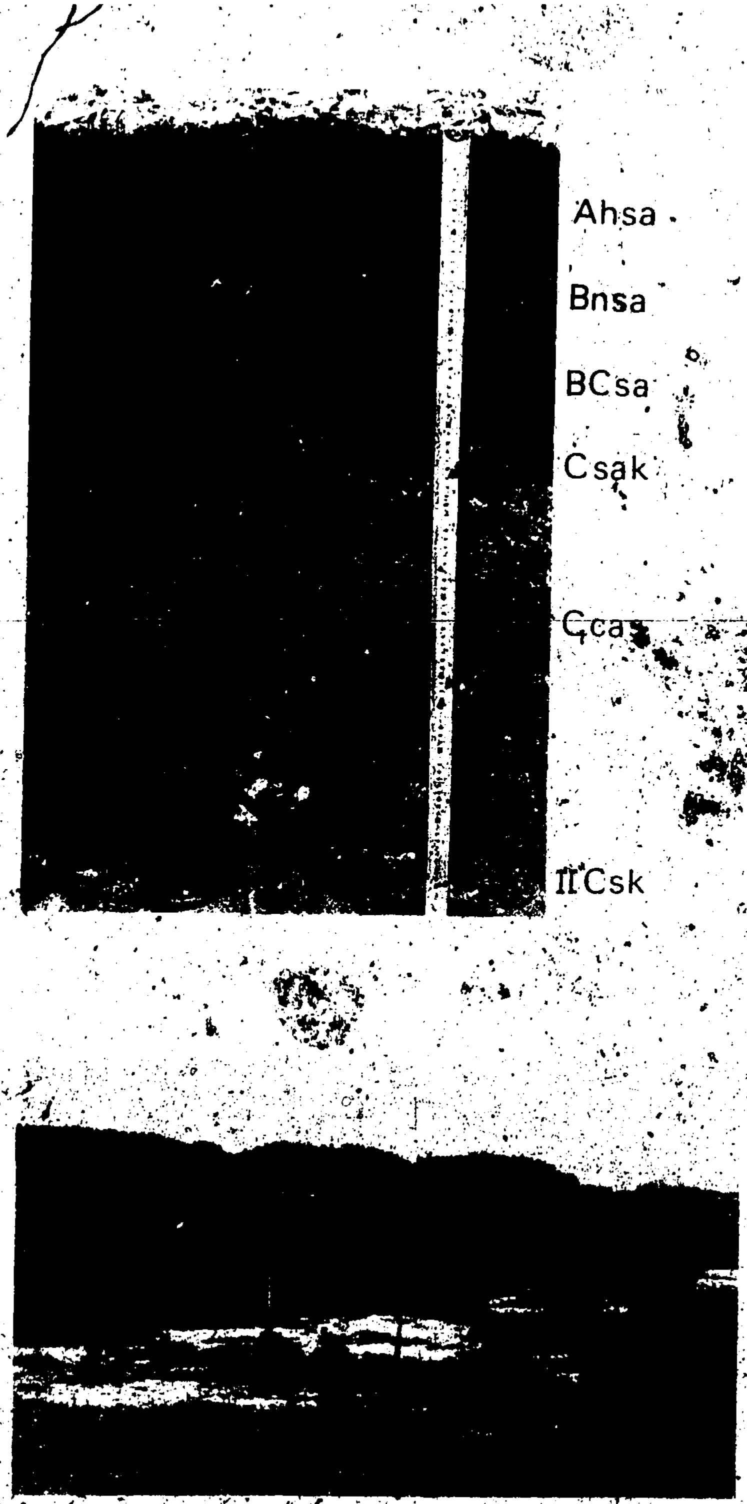


Plate 10. Black Solonetz soil profiles at Site 7 (left) and Site 8 (right).



ate 11. Saline Black Solonetz soil profile at Site 9 (above) and location (below).

APPENDICES.

Appendix 1. Soil and lithological descriptions at the nine study sites.

Site 1

DESCRIPTION OF SOIL

Classification.	Orthic Humic Gleysol	Elevation	675 m
Parent material.	Colluvium from Till	Slope	1%
Drainage Class.	Poorly drained	Aspect	NE
Vegetation.	Common plantain *Plantago major* Tartary buckwheat, *Fagopyron tartaricum* Toad rush, *Juncus bufonis* Water sedge, *Carex aquatilis*	Water table	0.3 to 1.5m
Location.	NW - 6 - 53 - 13 - 4. Edge of water-filled depression.		

Horizon, Depth	Description
Ah 0- 10 cm	Very dark gray (10YR3/1m) sandy loam; moderate medium subangular blocky structure; friable; abundant fine roots and pores; clear smooth boundary; ~~8-12 cm thick~~; pH 5.7.
Bmg1 10- 22 cm	Dark gray (10YR4/1m) loam; common fine prominant yellowish red (5YR4/6m) mottles; weak fine and medium prismatic breaking to weak platy structure; friable; plentiful fine roots; common medium and fine pores; clear smooth boundary; 12-16 cm thick; pH 7.0.
Bmg2 22- 65 cm	Light bluish gray (5BY7/1m) clay loam; common fine prominant strong brown (7.5YR5/8m) mottles; weak medium subangular blocky structure; very sticky; few very fine roots; common very fine pores; diffuse irregular boundary; 41-45 cm thick; pH 7.5.
BCg 65- 86 cm	Light gray (5Y6/1m) clay loam, common fine prominant yellowish brown (10YR5/8) mottles; amorphous; sticky; few stones; clear wavy boundary; 19-23 cm thick; pH 7.7.
Ckg 86 cm+	Very dark grayish brown (10YR3/2m) variably textured, mainly loam; amorphous; friable to firm; few stones; calcareous; pH 7.8.

DESCRIPTION OF LITHOLOGY

Depth	Description
0.9 - 2.5 m	Light brownish grey till; very few pebbles.
2.5 - 6.7 m	Brownish grey slightly silty sand.
6.7 - 11.9 m	Dark grey till; very few pebbles.
11.9 - 12.2 m+	Shaly sandstone bedrock.

Site 2

DESCRIPTION OF SOIL

Classification.	Humic Eluviated Gleysol.	Elevation	676 m
Parent material.	Till with lenses of water sorted material	Slope	5%
		Aspect	NE
Drainage class.	Imperfectly drained	Water table	1.2 to 3.0m
Vegetation.	Alfalfa, <u>Medicago sativa</u> Brome grass, <u>Bromus inermis</u>		
Location.	NW - 6 - 53 - 13 - 4. 20 m SW of Site 1.		

Horizon, Depth	Description
Ap 0- 9 cm	Very dark grayish brown (10YR3/2m), dark gray (10YR4/1d) sandy loam; few fine distinct dark yellowish brown (10YR3/4md) mottles; moderate medium subangular blocky structure; friable; abundant fine roots and pores; abrupt wavy boundary; 8-10 cm thick; pH 6.3.
Aeg 9- 13 cm	Dark grayish brown (10YR4/2m), light gray (10YR6/1d) sandy loam; many fine and medium distinct yellowish brown (10YR5/6md) mottles; weak platy structure; friable; plentiful fine and very fine roots; abundant very fine pores; clear wavy boundary; 1-7 cm thick; pH 6.0.
Btg 13- 42 cm	Light olive gray (5Y6/2m) loam; many fine and medium prominant yellowish red (5YR4/2m) mottles; weak medium prismatic breaking to moderate medium subangular blocky structure; few very fine roots; abundant fine and very fine pores; diffuse smooth boundary; 25-33 cm thick; pH 5.5.
BCg 42- 80 cm	Dark grayish brown (2.5Y4/2m) loam; common medium and coarse distinct yellowish brown (10YR5/4m) mottles; weak coarse prismatic breaking to moderate medium subangular blocky structure; friable to firm; very few fine roots; common fine and very fine pores; few stones; 34-42 cm thick; abrupt smooth boundary; pH 6.4.
IICg 80 cm+	Light yellowish brown (2.5Y6/4m), with light gray (2.5Y7/2m) bands and along root channels, bedded loamy sand; structureless; loose; non-calcareous; pH 7.0.

DESCRIPTION OF LITHOLOGY

Depth	Description
0.8 - 8.0 m	Brownish grey silty sand; some small pebbles.
8.0 - 13.4 m+	Shale bedrock.

Site 3

DESCRIPTION OF SOIL

Classification.	Eluviated Black Chernozem	Elevation	679 m
Parent material.	Till	Slope	5%
Drainage class.	Well drained	Aspect	NE
Vegetation.	Alfalfa, *Medicago sativa* Brome grass, *Bromus inermis*	Water table	0.6 to 3.7m
Location.	NW - 6 - 53 - 13 - 4 65 m SW of Site 2.		

Horizon, Depth	Description
Ap 0- 20 cm	Very dark grayish brown (10YR3/2m), grayish brown (10YR5/2d) loam; moderate coarse subangular blocky breaking to moderate fine subangular blocky structure; friable; abundant fine and very fine roots; many fine pores; clear smooth boundary; 18-21 cm thick; pH 6.4.
Ahe 20- 45 cm	Very dark brown (10YR4/2m), pale brown (10YR6/3d) loam; weak medium prismatic breaking to moderate fine granular structure; friable; plentiful very fine roots; many very fine pores; gradual smooth boundary; 24-31 cm thick; pH 6.4.
Bt 45- 68 cm	Yellowish brown (10YR5/4m), with grayish brown (2.5Y5/2m) ped coatings and dark grayish brown (2.5Y4/2m) ped interiors, clay loam; moderate medium prismatic breaking to moderate medium subangular blocky structure; friable; plentiful very fine roots; many fine and very fine pores; diffuse smooth boundary; 24-28 cm thick; pH 6.0.
BC 68-100 cm	Grayish brown (2.5Y5/2m) loam; weak coarse prismatic breaking to weak medium subangular blocky structure; friable; few very fine roots; common fine pores; diffuse smooth boundary; 30-34 cm thick; pH 5.7.
Ck 100 cm+	Grayish brown (2.5Y5/2m) loam till; fragmented; friable to firm; some stones; calcareous; pH 7.1.

DESCRIPTION OF LITHOLOGY

Depth	Description
1.0 - 7.6 m	Brownish gray till.
7.6 - 9.1 m	Dark gray till.
9.1 - 12.2 m	Silt; a few pebbles.
12.2 - 14.3 m+	Bluish gray reworked shale bedrock containing a few pebbles.

Site 4

DESCRIPTION OF SOIL

Classification.	Orthic Black Chernozem.	Elevation	647 m
Parent material.	Till	Slope	2%
Drainage class.	Well drained	Aspect	W
Vegetation.	Brome grass, *Bromus inermis* Crested wheatgrass, *Agropyron cristatum* Well fertilized pasture.	Water table	1.8 to 2.7m
Location.	NE - 11 - 53 - 14 - 4. - Upper member of lower sequence.		

Horizon, Depth	Description
Ap 0- 18 cm	Black (10YR2/1m), dark gray (10YR4/1d) loam; moderate fine granular structure; friable abundant fine roots; many fine pores; abrupt smooth boundary; 17-19 cm thick; pH 6.1.
Ah 18- 36 cm	Very dark brown (10YR2/2m), grayish brown (10YR5/2d) loam; weak coarse prismatic breaking to fine and medium subangular blocky structure; friable; plentiful very fine roots; many fine pores; clear smooth boundary; 16-20 cm thick; pH 6.1.
Btj 36- 60 cm	Dark yellowish brown (10YR3/4m) loam; moderate medium prismatic breaking to moderate fine and medium subangular blocky; firm; few very fine roots; common fine and very fine pores; gradual wavy boundary; 21-28 cm thick; pH 7.1.
Ccasa 60- 85 cm	Light olive brown (2.5Y5/4m) loam; fragmented; firm; stones; gradual wavy boundary; 20-30 cm thick; stones: calcareous; pH 8.0.
Csk 85 cm+	Yellowish brown (10YR5/4m) loam till; fragmented; firm; stones; calcareous; pH 7.8.

DESCRIPTION OF LITHOLOGY

Depth	Description
0.9 - 4.6 m	Brownish grey till: very few pebbles.

Depth	Description
4.6 - 7.3 m	Grey, very sandy till.
7.3 - 15.0 m	Interbedded shaly sandstone and shale bedrock.

Site 5

DESCRIPTION OF SOIL

Classification.	Black Solonetz	Elevation	640 m
Parent material.	Till	Slope	3%
Drainage class.	Moderately well drained	Aspect	W
Vegetation.	Brome grass, *Bromus inermis* Crested wheatgrass, *Agropyron cristatum* Well fertilized pasture.	Water table	1.1 to 1.5m
Location.	NE - 11 - 53 - 14 - 4 233 m W of Site 4.		

Horizon, Depth	Description
Ap 0- 17 cm	Black (10YR2/1m), gray (10YR5/2d) sandy loam; moderate fine and medium subangular blocky structure; friable; abundant fine and very fine roots; many fine pores; abrupt smooth boundary; 16-18 cm thick; pH 5.7
Bntjk 17- 33 cm	Very dark gray (7.5YR3/1m) ped surfaces, with dark yellowish brown (10YR4/4m) ped interiors, clay loam; strong coarse columnar breaking to strong fine and medium blocky structure; very firm; very few roots; few pores; clear smooth boundary; 15-18 cm thick; pH 7.8.
BCcasa 33- 50 cm	Dark grayish brown (2.5Y4/2m) clay loam; common medium distinct pale yellow (2.5Y7/4m) salt precipitates; moderate coarse columnar structure to amorphous; very firm; very few roots; few pores; abrupt smooth boundary; 16-18 cm thick; pH 8.3
Csk 50 cm+	Yellowish brown (10YR5/4m) to dark brown (10YR4/1m) loam till; amorphous; very firm; stones; calcareous; pH 8.2

DESCRIPTION OF LITHOLOGY

Depth	Description
0.5 - 4.3 m	Brownish gray, becoming gray below, till containing layers of sand.

Depth	Description
4.3 - 13.7 m.	Interbedded shaly sandstone and shale bedrock, with a hard layer at 105 m depth.

Site 6

DESCRIPTION OF SOIL

Classification.	Carbonated Gleyed Alkaline Solonetz	Elevation	638 m
Parent material.	Till	Slope	Flat
Drainage class.	Poorly drained	Aspect	None
Vegetation.	Nuttals salt meadow grass *Puccinellia nuttaliana* Red Samphire, *Salicornia rubra*	Water table	0 to 0.6 m
Location.	NE - 11 - 53 - 14 - 4. 100 m NW of Site 5		

Horizon, Depth	Description
Ahsk 0- 4 cm	Very dark grayish brown (10YR3/2m) loam; moderate fine and medium granular and subangular blocky structure; friable; abundant fine roots; many fine pores; abrupt smooth boundary; 3-5 cm thick; pH 7.8.
Bnsakg 4- 12 cm	Dark gray (2.5Y5/2m) sandy clay loam; common coarse faint light brownish gray (2.5Y6/2m) mottles within peds; moderate medium columnar structure; firm; plentiful very fine roots; common fine pores; gradual wavy boundary; 5-14 cm thick; pH 9.2.
Ccasg 12- 22 cm	Light brownish gray (5Y6/2m) loam; common medium distinct yellowish brown (10YR6/2m) mottles; fragmented; few roots and pores; stones; clear smooth boundary; 8-13 cm thick; pH 9.5..
Cskg 22- 70 cm	Gray (5Y6/1m) sandy loam; many coarse prominant yellowish brown (10YR5/8m) mottles; amorphous; very few roots and pores; stones; abrupt smooth boundary; calcareous; pH 9.2.
IICsk 70 cm+	Black (10YR2/1m) gravelly sandy loam; few medium prominant dark reddish brown (5YR3/4m) mottles; Loose; 30% stones; non-calcareous; pH 6.1.

DESCRIPTION OF LITHOLOGY

Depth	Description
0.7 - 1.8 m	Brown and bluish grey till containing gravel layers.

Depth	Description
1.8 - 14.4 m	Interbedded shaly sandstone and shale bedrock.

Site 7

DESCRIPTION OF SOIL

Classification.	Black Solonetz	Elevation	639 m
Parent material.	Till	Slope	1%
Drainage class.	Moderately well drained	Aspect	Variable
Vegetation.	Brome grass, Bromus inermis Foxtail, Hordeum jubatum	Water table	0.3 to 1.5m
Location.	NE - 11 - 53 - 14 - 4 123 m NW of Site 6		

Horizon, Depth	Description
Ap 0- 12 cm	Very dark gray (10YR3/1m), gray (10YR5/1d) sandy loam; moderate fine granular structure; friable; abundant very fine roots; many fine pores; abrupt smooth boundary; 11-13 cm thick; pH 5.0.
Ae 12- 14 cm	Very dark grayish brown (10YR4/2m), light brownish gray (10YR6/1d) loam; moderate platy structure; friable; plentiful very fine roots; common very fine pores; clear irregular boundary; 1-4 cm thick; pH 5.0.
Bnt1 14- 24 cm	Dark brown (7.5YR3/2m) ped surfaces, with dark yellowish brown (10YR4/4m) ped interiors, clay loam; strong medium columnar structure; very firm; very few roots; few pores; gradual smooth boundary; 6-14 cm thick; pH 5.4.
Bn[illegible] 24- 51 cm	Very dark grayish brown (10YR3/2m) ped surfaces, with dark yellowish brown (10YR4/4m) ped interiors, clay loam grading to loam below; strong coarse columnar structure; very firm; very few roots; few pores; clear smooth boundary; 22-31 cm thick; pH 6.6.
Cca sa 51- 75 cm	Olive brown (2.5Y4/4m) loam; many medium distinct light gray (2.5Y7/2m) carbonate and salt precipitates; amorphous; very firm; roots and pores absent; stones; calcareous; gradual wavy boundary; 19-20 cm thick; pH 7.9.
Cksa 75 cm+	Olive brown (2.5Y4/4m) loam till; common medium distinct pale yellow (2.5Y7/4m) salt precipitates; amorphous; very firm; stones; calcareous; pH 7.9.

DESCRIPTION OF LITHOLOGY

Depth	Description
0.8 - 3.0 m	Brownish gray till
3.0 - 12.8 m	Interbedded shaly sandstone and shale bedrock, with shale predominant; carbonaceous layer at 4.5 m depth.

Site 8

DESCRIPTION OF SOIL

Classification.	Black Solonetz	Elevation	636 m
Parent material.	Till	Slope	1%
Drainage class.	Well drained	Aspect	W
Vegetation.	Brome grass, *Bromus inermis* Foxtail, *Hordeum jubatum*	Water table	1.8 to 3.0m
Location.	NW - 11 - 53 - 14 - 4 379 m NW of Site 7		

Horizon, Depth	Description
Ap 0- 12 cm	Very dark gray (10YR3/1m) dark gray (10YR4/1d) loam; moderate fine and medium subangular blocky; friable; abundant fine and very fine roots; many fine pores; abrupt smooth boundary; 11-13 cm thick; pH 5.7.
Ah 12- 16 cm	Very dark gray (10YR3/1m), dark gray (10YR4/1d) loam; moderate medium columnar breaking to medium subangular blocky structure; friable; plentiful fine and very fine roots; many fine pores; clear broken boundary; 0-7 cm thick; pH 5.6
Ae 16- 23 cm	Grayish brown (10YR5/2m), light gray (10YR6/1d) loam; moderate medium columnar breaking to platy structure; friable; plentiful fine and very fine roots; many very fine pores; clear wavy boundary; 4-11 cm thick; pH 7.2.
Bnt 23- 40 cm	Very dark gray (10YR3/1m) ped coatings, grayish brown (10YR5/2m) ped interiors, loam becoming clay loam below; strong coarse columnar structure; firm; few very fine roots; common very fine pores; gradual wavy boundary; 14-21 cm thick; pH 7.7.
BCsa 40- 57 cm	Gray (10YR5/1m) ped coatings, yellowish brown (10YR5/5m) ped interiors, clay loam; with few medium distinct white (10YR8/2) salt precipitates; moderate coarse columnar to amorphous; friable to firm; very few very fine roots; few fine pores; clear smooth boundary; 15-19 cm thick; pH 8.0.
Ccas	Yellowish brown (10YR5/4m) variously textured but predominantly loam till; many fine distinct white

(10YR8/2m) salt precipitates; fragmented; firm; stones; calcareous; pH 8.3.

DESCRIPTION OF LITHOLOGY

Depth	Description
0.6 - 4.3 m	Brownish gray till.
4.3 - 14.0 m	Interbedded shaly brownish gray sandstone and shale bedrock with shale predominant. Hard layer at 6.1 m depth.

Site 9

DESCRIPTION OF SOIL

Classification.	Saline Black Solonetz	Elevation	633 m
Parent material.	Till and Bedrock	Slope	1%
Drainage class.	Poorly drained	Aspect	W
Vegetation.	Foxtail, *Hordeum jubatum* Nuttals salt meadow grass *Puccinellia nuttalliana* Red Samphire, *Salicornia rubra*	Water table	0 to 0.6 m.
Location.	NW - 11 - 53 - 14 - 4 Lowest member of lower sequence and adjacent to water-filled depression.		

Horizon, Depth	Description
Ahsa 0- 13 cm	Black (2.5YR2/1m) loam; thin white (10YR9/1d) layer of salt at soil surface; weak medium subangular blocky breaking to fine granular structure; friable; abundant fine and very fine roots; many fine pores; abrupt smooth boundary; 12-14 cm thick; highly saline; calcareous only at soil surface; pH 5.6, but pH 7.2 in surface ½ cm.
Bn sa 13- 25 cm	Dark grayish brown (10YR4/2m) ped surfaces becoming very dark brown (10YR2/2m) below, very dark grayish brown ped interiors, loam; common fine distinct white (10YR8/1) salt precipitates; strong medium columnar structure; firm; few very fine roots; common very fine pores; clear wavy boundary; 11-14 cm thick; pH 6.7.
BCsa 25- 29 cm	Very dark grayish brown (10YR2.5/2m) clay loam; Common coarse distinct light gray (2.5Y7/2m) salt precipitates; weak subangular blocky structure; friable; very few roots; few fine pores; clear smooth boundary; 3-6 cm thick; calcareous; pH 7.5.
Csak 29- 40 cm	Dark grayish brown (2.5Y5/6) clay loam; common fine distinct light olive brown (2.5Y5/6m) mottles and common coarse prominant light gray (2.5Y7/2m) precipitates; fragmented; friable; roots and pores absent; stones; calcareous; clear smooth boundary; 9-12 cm thick; pH 8.2
Ccas 40- 83 cm	Olive brown (2.5Y4/4m) loam; fragmented; friable; clear wavy boundary; 38-48 cm thick; pH 8.3.

Horizon, Depth	Description
IICsk 83 cm+	Bluish gray (5BY5/1m) sandy clay loam; common fine prominent yellowish brown (10YR5/8) mottles; amorphous; extremely hard; calcareous; partially weathered bedrock; pH 8.1.

DESCRIPTION OF LITHOLOGY

Depth	Description
0.8 - 3.0 m	Bluish gray sandstone bedrock with a hard layer between 3.0 and 3.4 m.
3.4 - 22.9 m	Shale containing hard bands at 5.8 m, 14.0 m and 18.3 m depth and a carbonaceous layer at 8.8 m depth.

Appendix 2. Particle size analysis of soil and underlying materials at the soil sites using the pipette method, Bracketed values are on a carbonate-free basis, otherwise carbonates were not excluded. (U=upper, L=lower, M=middle)

SITE	HORIZON OR DEPTH cm	TEXTURE	PERCENTAGE WITHIN INDICATED SIZE FRACTIONS							
			Sand Fractions in mm					Total sand	Silt	Clay
			2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.10	0.10-0.05			
1	Ah	SL	2.2	11.8	11.7	25.1	10.4	61.2	28.1	10.7
	Bmg1(U)	L	1.9	6.3	7.0	20.1	10.1	45.4	36.3	18.3
	Bmg1(L)	L	1.6	4.9	6.2	17.9	13.0	43.6	34.1	22.4
	Bmg2(U)	L	0.9	3.4	4.9	14.2	10.7	34.1	37.7	28.2
	Bmg2(L)	L	0.9	3.8	4.8	16.9	11.7	38.1	35.0	26.9
	BCg	L	0.8	3.9	4.5	17.5	11.4	38.1	35.0	26.9
	Ckg	L	1.9	6.2	4.7	17.9	10.9	40.6	32.9	26.4
	150	SL	1.5	10.5	15.3	27.8	7.2	62.3	21.9	15.7
	200	SCL	1.0	8.9	12.1	24.2	9.5	55.7	23.6	20.6
2	Ap	SL	2.6	11.5	11.3	22.4	9.2	57.0	25.1	17.9
	Aeg	SL	1.1	8.6	10.7	23.0	11.0	54.4	28.1	17.4
	Btg(U)	L	1.3	5.7	5.6	21.3	11.0	44.9	30.4	24.6
	Btg(L)	L	1.3	4.4	6.2	18.3	9.6	39.8	33.0	27.1
	BCg(U)	L	0.8	5.3	6.8	23.2	9.3	45.4	32.6	22.1
	BCg(L)	L	1.2	5.7	5.8	21.8	10.7	45.2	29.2	25.7
	IICg	LS	1.2	15.3	20.2	37.5	3.3	77.5	16.6	5.9
	120	-	-	-	-	-	-	-	-	-
	150	SL	0.1	7.2	21.4	40.1	4.6	73.4	14.5	12.0
	200	-	-	-	-	-	-	-	-	-
	300	S	1.2	26.3	34.7	23.0	2.6	87.8	5.5	6.7
3	Ap	L	1.2	4.5	5.7	15.9	10.9	38.2	40.4	21.3
	Ahe(U)	L	1.3	3.7	5.1	20.1	12.1	42.3	36.9	20.9
	Ahe(L)	L	0.9	3.6	5.5	20.9	11.0	41.9	34.7	23.5
	Bt(U)	CL	0.8	4.3	5.7	14.3	10.3	35.4	36.2	28.3
	Bt(L)	CL	0.3	3.1	6.3	17.6	9.7	37.0	32.0	31.0
	BC	L	0.8	3.2	3.8	18.5	14.7	41.0	34.6	24.4
								(44.5)	(31.1)	(24.5)
	Ck	L	0.8	3.5	7.3	23.3	10.7	44.6	30.0	25.5
	120	CL	0.4	2.9	3.8	18.6	11.1	36.8	33.9	29.3
	150	L	[illegible]	9.3	9.2	[illegible]	10.5	52.0	28.8	19.2
	200	CL	1.3	6.0	5.5	16.0	7.6	36.4	32.3	31.3
	300	CL	1.3	5.7	5.0	16.5	9.3	37.8	31.7	30.5
4	Ap	L	1.2	6.3	9.4	22.6	9.0	48.6	27.2	24.1
	Ah(U)	L	1.0	7.0	7.6	23.5	8.8	47.9	29.2	22.9
	AH(L)	L	2.0	7.8	9.6	23.2	7.4	50.0	29.8	20.3
	Btj(U)	L	1.2	7.3	9.8	21.4	8:8	48.5	28.0	23.5
	Btj(M)	SCL	2.1	8.1	9.7	20.7	7.6	48.2	25.3	26.5
	Btj(L)	L	1.0	7.3	9.5	19.0	8.9	45.7	30.1	24.3
	Cca(U)	L	1.2	6.4	12.1	16.7	6.9	43.3	30.2	26.5
								(48.3)	(31.5)	(20.2)
	Cca(L)	L	1.0	7.7	8.9	19.7	7.0	44.3	28.7	26.9
								(48.8)	(28.1)	(23.1)
	Ck	SCL	0.7	9.9	10.0	22.9	6.1	49.6	26.2	24.2
								(52.1)	(25.4)	(22.5)
	150	SCL	2.0	8.1	9.6	24.1	8.4	52.2	28.6	21.1
	200	L	1.8	8.3	8.4	20.2	8.0	46.7	33.5	19.9
	300	L	1.0	7.5	9.1	20.3	11.1	49.0	34.0	16.9
5	Ap	SL	1.0	18.0	7.4	19.3	10.7	56.4	29.2	14.4
	Bntjk(U)	CL	1.3	7.3	7.0	14.5	10.9	41.2	30.2	28.6
	Bntjk(L)	CL	0.9	6.0	6.4	15.3	10.9	39.5	30.8	29.8
								(36.9)	(36.0)	(27.1)
	BCcasa(U)	CL	1.5	5.9	6.3	14.5	10.5	38.8	31.5	30.1
								(36.7)	(36.7)	(26.7)
	BCcasa(L)	CL	2.5	5.7	10.7	12.9	6.3	38.1	31.2	30.7
								(36.8)	(33.8)	(29.4)
	Csk	CL	1.2	6.4	8.3	19.9	7.2	43.0	26.8	30.2
								(44.2)	(32.7)	(23.0)
	150	L	1.3	6.2	8.0	20.2	10.4	46.1	33.2	20.6
	200	L	1.2	7.9	8.3	19.6	10.8	47.8	32.6	19.7
	300	SL	0.8	7.3	6.1	24.9	13.2	52.3	34.5	13.2

(Continued)

SITE	HORIZON OR DEPTH cm	TEX-TURE	PERCENTAGE WITHIN INDICATED SIZE FRACTION							
			Sand Fractions in mm					Total sand	Silt	Clay
			2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.10	0.10-0.05			
6	Ahsk	L	1.9	9.1	9.5	17.6	7.6	45.7	32.4	21.8
	Bnsakg(U)	SL	2.8	13.7	13.1	24.3	8.1	62.0	23.6	14.4
	Bnsakg(L)	SCL	2.3	10.5	12.5	23.3	8.2	56.8	22.7	20.5
	Ccasg	L	2.3	9.0	9.7	18.0	7.4	46.4	32.7	20.9
	Csk	SL	1.2	12.8	19.1	34.9	5.8	73.8	15.4	10.8
	IICsk	SL	6.4	18.8	10.4	12.6	4.0	52.2	31.7	16.1
	120	-	-	-	-	-	-	-	-	-
	150	CL	0.8	3.5	4.1	9.1	5.7	23.2	43.2	33.6
	200	SiL	0.1	0.5	0.4	4.2	18.0	23.2	55.0	21.7
7	Ap	SL	0.7	9.6	10.8	19.1	11.4	51.6	37.1	11.3
	Ae	L	0.7	7.4	8.2	17.7	9.4	43.4	33.7	22.9
	Bnt1	CL	0.8	6.6	7.6	16.6	8.2	39.6	28.3	32.2
	Bnt2(U)	SCL	1.3	7.8	8.0	20.3	9.4	46.8	24.7	28.5
	Bnt2(L)	L	2.3	6.9	8.2	20.5	9.9	47.8	27.8	24.4
	Ccasa	L	1.2	6.2	8.0	20.1	10.4	45.9 (50.4)	29.8 (29.2)	24.2 (20.4)
	Cksa	L	1.3	7.4	8.3	20.9	10.2	48.1 (50.2)	27.8 (29.5)	24.1 (20.2)
	120	L	1.5	7.9	7.8	21.1	11.0	49.3	30.6	20.1
	150	L	0.6	7.4	8.2	20.6	11.6	48.4	29.7	21.9
	200	L	1.5	7.7	8.9	19.8	11.1	49.0	36.1	14.9
	300	CL	1.2	4.7	5.8	12.9	11.0	35.6	31.7	32.7
8	Ap	L	0.8	4.0	13.2	13.1	9.7	40.8	41.1	18.1
	Ah	L	1.4	5.2	6.0	15.8	12.6	41.1	43.8	15.1
	Ae	L	0.8	5.5	4.7	13.7	12.8	37.5	49.7	12.9
	Bnt(U)	L	0.7	3.7	4.8	9.0	10.5	28.7	45.5	25.7
	Bnt(L)	CL	3.5	7.4	7.1	11.1	9.2	38.3	31.4	30.2
	BCsa(U)	SCL	1.3	6.6	9.5	18.9	9.8	46.1	25.8	28.2
	BCsa(L)	SCL	1.0	6.4	7.8	20.2	10.2	45.6	24.9	29.5
	Ccas	L	1.1	5.2	7.3	17.9	11.5	43.0 (46.0)	32.4 (34.6)	24.5 (19.3)
	120	L	1.0	5.1	8.3	21.7	13.3	49.4	31.1	19.5
	150	L	1.0	5.5	5.3	20.3	12.5	44.6	37.6	17.8
	200	L	1.4	4.6	4.7	20.7	11.6	43.0	40.1	16.9
	300	L	1.6	3.9	4.0	16.5	10.5	36.5	42.6	20.8
9	Ahsa	L	1.6	6.8	5.8	14.0	14.3	42.5	43.4	14.1
	Bnsa(U)	L	0.8	3.3	3.4	10.5	15.3	33.3	43.0	23.7
	Bnsa(L)	L	1.0	3.2	4.0	12.5	15.7	36.5	42.0	21.6
	BCsa	CL	0.6	2.3	3.6	8.7	12.8	28.0	37.9	34.1
	Csak	CL	0.5	7.3	10.7	19.6	7.7	45.8	36.0	31.4
	Ccas	L	0.6	2.4	3.6	9.2	15.4	30.7	30.0	26.0
	IICsk	SCL	0.1	0.2	0.3	37.8	17.6	56.0	17.5	26.4
	150	SCL	0.0	0.1	0.2	38.8	19.5	58.6	17.0	24.4
	180	SCL	0.1	0.5	0.5	52.4	9.9	63.4	15.8	20.7

Appendix 3. Bulk density, particle density, calculated porosity and pressure plate moisture retention values for various depths at the soil study sites.

SITE	DEPTH cm	BULK DENS. gm/cc	PART. DENS. gm/cc	PORO-SITY %	MOISTURE CONTENT, wt/wt at indicated bars suction 0.05	0.10	0.33	0.85	1.0	5.0	15.0
1	10	1.35	2.62	48.5	-	-	-	-	-	-	-
	20	1.50	2.66	43.6	-	19.8	17.9	-	16.7	14.3	12.9
	30	1.50	2.68	44.0	-	20.2	18.1	-	16.8	14.3	13.1
	50	1.60	2.69	40.5	-	23.4	21.7	-	20.2	17.0	14.5
	~~100~~	~~1.60~~	~~2.70~~	~~40.7~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~
	150	1.50	2.68	44.0	-	-	-	-	-	-	-
2	10	1.45	2.63	44.9	-	-	-	-	-	-	-
	20	1.40	2.69	48.0	-	27.3	21.4	-	18.6	15.8	14.7
	30	1.30	2.70	51.9	-	27.3	20.9	-	18.4	15.6	14.1
	50	1.45	2.70	46.3	-	24.6	19.2	-	17.0	14.2	12.9
	100	1.60	2.67	40.1	-	20.6	18.9	-	16.9	15.0	12.3
	150	1.70	2.66	36.1	-	10.3	7.6	-	-	-	-
	200	1.75	2.65	34.0	11.9	-	-	3.8	-	-	-
3	10	1.05	2.55	58.8	-	-	-	-	-	-	-
	20	1.25	2.61	52.1	-	30.9	23.7	-	21.0	17.6	16.3
	30	1.40	2.68	47.8	-	26.5	20.4	-	18.5	14.9	13.6
	50	1.40	2.68	47.8	-	23.5	18.6	-	15.9	13.0	11.5
	100	1.55	2.70	42.6	-	22.3	19.0	-	18.6	15.5	13.9
	150	1.85	2.69	31.2	-	-	-	-	-	-	-
	200	1.90	2.69	29.4	14.6	14.2	12.3	9.2	-	-	-
	250	1.90	2.69	29.4	14.8	14.5	12.9	9.2	-	-	-
4	10	0.85	2.59	67.2	-	-	-	-	-	-	-
	20	0.90	2.47	63.6	-	42.3	28.3	-	24.5	21.1	19.7
	30	1.05	2.61	59.8	-	38.0	23.0	-	19.0	15.2	14.5
	50	1.25	2.68	51.4	-	20.9	17.2	-	13.9	12.6	10.7
	100	1.65	2.71	39.1	-	22.4	17.5	-	15.1	12.1	10.0
	150	1.65	2.69	38.7	20.2	19.3	17.0	12.1	-	-	-
	200	1.70	2.69	36.8	18.2	17.5	15.9	12.2	-	-	-
	250	1.80	2.68	32.8	17.3	16.6	15.1	11.3	-	-	-
5	10	1.10	2.55	56.9	-	-	-	-	-	-	-
	20	1.40	2.66	47.4	-	22.0	18.1	-	16.6	14.4	13.1
	30	1.55	2.67	41.9	-	19.7	16.2	-	14.3	11.6	10.0
	50	1.70	2.72	37.5	-	18.0	15.5	-	14.2	11.5	9.7
	100	1.90	2.70	29.6	-	17.3	14.9	-	13.2	11.0	9.2
	150	2.00	2.69	25.7	-	-	-	-	-	-	-
6	10	1.30	2.65	50.9	-	-	-	-	-	-	-
	20	1.40	2.69	48.0	-	17.0	15.1	-	12.0	9.1	6.2
	30	1.50	2.68	44.0	-	19.0	17.5	-	15.8	12.9	10.2
	50	-	-	-	-	22.3	19.5	-	20.5	15.4	12.1
	150	1.77	2.67	33.7	-	-	-	-	-	-	-
7	10	1.10	2.57	57.2	-	-	-	-	-	-	-
	20	1.55	2.67	41.9	-	22.5	21.1	-	19.4	16.3	14.7
	30	1.60	2.65	39.6	-	22.4	19.8	-	18.0	15.4	14.0
	50	1.80	2.69	33.1	-	20.0	17.0	-	15.5	12.9	10.6
	100	2.00	2.71	26.2	-	15.0	13.1	-	12.2	10.1	8.4
8	10	1.00	2.53	60.5	-	-	-	-	-	-	-
	20	0.90	2.64	65.9	-	30.3	23.9	-	19.5	15.8	13.7
	30	1.20	2.69	55.4	-	24.8	20.5	-	18.5	14.1	11.8
	50	1.55	2.70	42.6	-	22.1	16.6	-	14.4	11.7	10.8
	100	1.70	2.70	37.0	-	20.0	16.5	-	14.1	10.4	8.5
	150	1.80	2.68	32.8	-	17.2	15.6	-	-	-	-
	200	1.90	2.69	29.4	17.3	-	-	12.6	-	-	-
9	10	1.15	2.59	55.6	-	-	-	-	-	-	-
	20	1.30	2.71	52.0	-	25.5	23.1	-	21.5	17.5	14.9
	30	1.45	2.74	47.1	-	25.8	22.6	-	20.9	16.8	14.6
	50	-	-	-	-	22.9	20.9	-	19.2	16.5	14.1
	150	1.77	2.67	33.7	-	-	-	-	-	-	-

Appendix 4. pH, exchangeable cations, cation exchange capacity, electrical conductivity of saturation extracts, organic carbon, calcium carbonate equivalent and gypsum analyses of soil and underlying materials at the study sites.

SITE	HORIZON OR DEPTH cm	pH	EXCHANGEABLE CATIONS meq/100 g Na+	K+	Ca++	Mg++	C.E.C. meq/100 g	E.C. mmhos/cm	ORG. CARB %	CaCO3 Equiv.%	GYPSUM % Deb*	USDA**
	Ah	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.53	2.04	-	0.00	0.03
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	0.60	Tr	-	-
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	16.8	[illegible]	[illegible]	Tr	0.00	0.02
	[illegible]	[illegible]	[illegible]	[illegible]	16.6	[illegible]	[illegible]	[illegible]	[illegible]	Tr	0.00	0.02
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	20.1	[illegible]	[illegible]	Tr	0.00	0.02
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Tr	0.00	0.02
	[illegible]	[illegible]					[illegible]		[illegible]	Tr	[illegible]	[illegible]
	[illegible]						[illegible]	[illegible]		[illegible]	0.00	0.06
	[illegible]	[illegible]					[illegible]	[illegible]		[illegible]	0.00	0.08
	[illegible]	[illegible]					[illegible]	[illegible]		[illegible]	0.01	[illegible]
	A[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					
	Ae[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.88	[illegible]	-	[illegible]		-	-
	Bt[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	15.[illegible]		[illegible]	-	-	-
	Bt[illegible]	[illegible].8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.30	-	0.00	0.01
	Btg[illegible]	[illegible]	0.11	[illegible]	[illegible]	[illegible]	[illegible]	-	0.71	-	-	-
	[illegible]	[illegible]	0.11	[illegible]	13.18	5.56	[illegible]	[illegible]	0.40	-	0.00	0.02
	IIC[illegible]	[illegible]	0.08	[illegible]	[illegible]	-	20.8	-	0.28	Tr	-	-
	[illegible]	7.[illegible]					[illegible]	[illegible]	[illegible]	[illegible]	0.00	0.0[illegible]
	150	8.[illegible]					[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]					[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]					[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]					[illegible]	[illegible]		[illegible]	0.00	[illegible]
	Ap	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					
	Ahe[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.28	[illegible]		[illegible]	[illegible]
	Ahe[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	18.[illegible]	-	[illegible]		-	-
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]		-	-
	[illegible]	[illegible]	[illegible]	[illegible]	17.71	8.1[illegible]	[illegible]	0.16	[illegible]		[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	17.[illegible]	[illegible]	[illegible]	-	[illegible]		-	
	[illegible]	[illegible]					[illegible]		[illegible]		-	-
	[illegible]	[illegible]					[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]							[illegible]	[illegible]	-	-
	[illegible]	7.6					[illegible]	[illegible]	-	[illegible]	0.00	[illegible]
	[illegible]	7.[illegible]					-	[illegible]	-	5.1	0.01	0.0[illegible]
	[illegible]						[illegible]	[illegible]	-	[illegible]	0.01	0.08
	Ap	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					
	Ah[illegible]	[illegible]	[illegible]	1.6[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	-	-	-
	Ah[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	7.50	-	0.00	0.02
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		-	-
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	10.5	0.60	[illegible]	Tr	0.01	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible].88	[illegible]	Tr	0.02	[illegible]
	[illegible]	8.[illegible]					[illegible]	[illegible]	0.60	[illegible]	[illegible]	[illegible]
	[illegible]	8.[illegible]						[illegible]	[illegible]	[illegible]	7.81	[illegible]
	[illegible]	[illegible]						[illegible]	[illegible]	[illegible]	7.60	[illegible]
	[illegible]	8.[illegible]					[illegible]	[illegible]	[illegible]	8.8	[illegible]	[illegible]
	[illegible]								-	[illegible]	-	
	[illegible]	8.[illegible]					[illegible]	[illegible]	-	[illegible]	[illegible]	[illegible]
	[illegible]	8.[illegible]					[illegible]	[illegible]	-	[illegible]	0.01	[illegible]
	[illegible]							[illegible]	-	[illegible]	0.01	[illegible]
	A[illegible]											
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	0.00	0.01
	[illegible]	8.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.00	[illegible]
	[illegible]	8.[illegible]	-		-		[illegible]	[illegible]	[illegible]	[illegible]	0.00	0.18
	[illegible]	8.[illegible]	-		-	-	-	[illegible]	[illegible].58	[illegible]	[illegible]	[illegible]
	[illegible]	8.[illegible]	-	-	-	-	-	8.1	0.16	8.0	[illegible]	0.28
	[illegible]		-	-	-	-	[illegible]	6.[illegible]	0.12	[illegible]	[illegible]	[illegible]
	150	8.[illegible]	-	-	-	-	-	-	-	-	-	-
	200	8.[illegible]	-	-	-	-	11.0	[illegible]	-	[illegible]	0.00	0.29
	[illegible]	8.[illegible]	-	-	-	-	-	1.6	-	[illegible]	0.00	0.19
						-	[illegible]	1.8	-	[illegible]	0.00	0.09
6	Ahsk	7.8	-	-	-	-						
	Bnsakgj	8.[illegible]	-	-	-	-	[illegible]	[illegible]	[illegible]	[illegible]	0.01	0.25
	Bnsakg[illegible]	[illegible]	[illegible]	-	-	-	-	[illegible]	1.2[illegible]	3.7	[illegible]	0.27
	Csakg	[illegible]	-	-	-	-	10.8	[illegible]	0.55	[illegible]	0.00	0.22
	Csk	[illegible]	-	-	-	-	-	[illegible].8	[illegible]	8.1	0.00	0.30
	IICsk	[illegible]	-	-	-	-	[illegible]	[illegible]	0.27	[illegible]	0.06	[illegible]
	120	[illegible]	-	-	-	-	-	[illegible]	1.2[illegible]	6.[illegible]	1.08	1.19
	150	[illegible]	-	-	-	-	-	11.1	0.79	1.6	1.29	1.4[illegible]
	200	[illegible]	-	-	-	-	[illegible]	[illegible]	1.12	[illegible]	1.46	1.40
							[illegible]	11.[illegible]	1.82	0.5	1.18	[illegible]

(Continued)

SITE	HORIZON OR DEPTH cm	pH	EXCHANGEABLE CATIONS meq/100 g Na	K	Ca	Mg	C.E.C. meq/100g	E.C. mmhos/cm	ORG. CARB %	CaCO3 Equiv.%	GYPSUM % Det.*	USDA**
7	Ap	5.0	0.68	0.36	5.09	2.03	17.2	0.19	1.87	-	0.00	0.01
	Ae	5.0	1.02	0.35	6.13	3.36	16.[illegible]	[illegible]	1.66	-	-	-
	Bnt1	5.6	1.34	0.22	9.27	5.60	18.7	0.32	0.92	-	0.00	0.05
	Bnt2(U)	6.2	1.27	0.25	7.56	6.24	19.2	0.52	0.75	Tr	0.00	0.61
	Bnt2(L)	7.0	1.66	0.22	9.41	5.53	16.7	0.52	[illegible]	Tr	0.00	0.03
	Ccasa	7.9	-	-	-			1.3	[illegible]	[illegible]	0.06	0.52
	Cksa	7.9	-				1[illegible]	6.1	0.41	5.1	0.84	0.65
	120	8.1	-	-	-	-	[illegible]	7.8	-	5.3	1.2[illegible]	1.[illegible]
	150	8.2	-	-	-	-	1[illegible]	5.9	-	2.8	0.19	0.16
	200	8.5	-	-	-	-		5.[illegible]	-	[illegible]	[illegible]	0.21
	300	8.5	-	-	-	-	[illegible]	[illegible]	-	1.2	0.01	0.49
8	Ap	5.7	1.50	0.12	9.12	2.71	18.7	0.38	3.77	-	0.00	[illegible]
	Ah	5.6	2.68	0.17	9.09	3.09	21.6	-	3.28	-	-	-
	Ae	7.2	3.62	0.13	5.65	2.74	13.7	2.0	1.15	Tr	0.00	0.00
	Bnt(U)	7.6	6.87	0.12	5.23	6.1	13.9	4.3	0.83	Tr	0.01	0.16
	Bnt(L)	7.8	8.59	0.15	5.50	7.75	21.4	5.2	0.61	Tr	0.01	0.5
	BCsa(U)	8.1	-	-	-	-	-	9.2	0.36	Tr	1.12	1.05
	BCsa(L)	8.0	-	-	-	-	-	10.1	0.20	0.8	1.27	0.70
	Ccas	8.3	-	-	-	-	1[illegible]	7.5	0.29	3.8	1.[illegible]	1.06
	120	7.9	-	-	-	-	-	5.2	-	.7	[illegible].8	0.50
	150	8.1	-	-	-	-	15.2	[illegible]	-	[illegible]	0.02	0.09
	200	8.3	-	-	-	-	-	1.8	-	[illegible].1	0.00	0.11
	300	8.1	-	-	-	-	23.7	1.4	-	[illegible].5	0.00	0.11
9	Ahsa	5.6	-	-	-	-	27.6	2[illegible]	5.19	-	0.01	0.20
	Bnsa(U)	6.7	-	-	-	-	-	20	1.96	-	0.33	0.00
	Bnsa(L)	6.7	-	-	-	-	25.0	18.6	1.83	-	1.97	0.00
	BCsa	7.5	-	-	-	-	-	14.1	1.25	-	1.11	0.00
	Csak	8.2	-	-	-	-	-	12.6	0.28	2.5	6.28	5.60
	Ccas	8.3	-	-	-	-	26.3	13.6	0.60	.7	0.12	0.00
	IICsk	8.3	-	-	-	-	19.9	5.6	0.28	2.1	0.19	0.06
	120	-	-	-	-	-	-	-	-	-	0.22	0.58
	150	8.5	-	-	-	-	6.[illegible]	1.9	-	1.0	-	-
	200	-	-	-	-	-	-	-	-	-	-	-

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* Difference between $SO_4^{=}$ in the large water volume extract over that in the saturation extract, plus Ca^{++} or $SO_4^{=}$, whichever is smaller, in the saturation extract.

** Difference between Ca^{++} plus Mg^{++} in the large water volume extract over that in the saturation extract.

Appendix 5. Cations and anions in soil extracts expressed as content in soil. (Tr=trace, L=less than 0.5 meq/100 g $SO_4^{=}$)

SITE	HORIZON OR DEPTH cm	IONS IN SATURATION EXTRACT meq/100 g soil Ca^{++}	Mg^{++}	Na^{+}	K^{+}	$SO_4^{=}$	Cl^{-}	HCO_3^{-}	IONS IN LARGE WATER VOLUME EXTRACT* meq/100 g soil Ca^{++}	Mg^{++}	Na^{+}	K^{+}	$SO_4^{=}$	IONS IN % HCl EXTRACT** meq/100 g soil Ca^{++}	Mg^{++}
1	Ah	0.09	0.06	0.02	0.01	0.05	Tr	0.12	0.13	0.41	0.08	0.07	L	-	-
	Bmg1(U)	-	-	-	-	-	-	-	0.58	0.17	0.06	0.04	L	-	-
	Bmg1(L)	0.06	0.04	0.01	0.00	0.00	0.00	0.03	0.22	0.10	0.06	0.03	L	19.9	8.1
	Bmg2(U)	0.06	0.04	0.02	0.00	0.02	Tr	0.06	0.22	0.12	0.09	0.03	L	18.0	13.3
	Bmg2(L)	0.06	0.05	0.02	0.00	0.03	0.00	0.08	0.25	0.15	0.07	0.04	L	16.2	12.1
	BCg	0.08	0.07	0.03	0.00	0.02	Tr	0.12	0.21	0.15	0.07	0.03	L	16.0	[illegible]
	Ckg	0.09	0.10	0.03	0.00	0.03	0.00	0.14	0.55	0.31	0.11	0.02	L	[illegible]	[illegible]
	150	0.04	0.10	0.02	0.00	0.06	0.00	0.08	0.81	0.26	0.11	0.02	L	[illegible]	42.8
	200	0.13	0.16	0.04	0.00	0.08	0.01	0.14	0.41	0.32	0.11	0.02	L	84.9	27.5
2	Ap	-	-	-	-	-	-	-	0.40	0.13	0.08	0.09	L	-	-
	Ae	-	-	-	-	-	-	-	0.21	0.08	0.02	0.02	L	-	-
	Btg(U)	0.01	0.00	0.01	0.00	0.02	0.00	0.02	0.08	0.04	0.03	0.02	L	-	-
	Btg(L)	-	-	-	-	-	-	-	0.12	0.06	0.04	0.02	L	-	-
	BCg(U)	0.05	0.01	0.01	0.00	0.01	Tr	0.05	0.22	0.11	0.06	0.04	L	-	-
	BCg(L)	-	-	-	-	-	-	-	0.26	0.12	0.07	0.04	L	14.3	11.5
	IICg	0.03	0.02	0.01	0.00	0.02	0.00	0.03	0.22	0.11	0.05	0.04	L	8.6	6.9
	120	0.06	0.06	0.01	0.00	0.05	0.00	0.05	0.30	0.11	0.06	0.05	L	19.5	12.4
	150	0.03	0.04	0.01	0.00	0.02	0.00	0.04	0.27	0.17	0.05	0.04	L	31.3	18.5
	200	0.05	0.05	0.02	0.00	0.06	0.00	0.05	0.74	0.75	0.06	0.04	L	41.8	20.2
	300	0.08	0.06	0.02	0.00	0.03	[illegible]	0.06	0.47	0.35	0.04	0.03	L	26.8	14.4
3	Ap	0.11	0.05	0.01	0.01	0.08	0.00	0.08	0.64	0.13	0.09	0.05	L	-	-
	Ahe(U)	-	-	-	-	-	-	-	0.38	0.14	0.12	0.03	L	-	-
	Ahe(L)	-	-	-	-	-	-	-	0.32	0.17	0.08	0.04	L	-	-
	Bt(U)	0.03	0.03	0.01	0.00	0.02	0.00	0.04	0.18	0.10	0.04	0.04	L	-	-
	Bt(L)	-	-	-	-	-	-	-	0.20	0.17	0.06	0.04	L	-	-
	BC	-	-	-	-	-	-	-	0.18	0.15	0.06	0.03	L	-	-
	Ck	0.14	0.14	0.03	0.01	0.05	0.00	0.18	0.73	0.36	0.08	0.04	L	23.3	16.9
	120	-	-	-	-	-	-	-	[illegible]	0.15	0.06	0.02	L	55.5	23.6
	150	0.06	0.05	0.03	0.01	0.04	0.00	0.08	[illegible]	0.18	0.07	0.04	L	71.9	50.2
	200	0.13	0.09	0.03	0.01	0.09	0.00	0.10	0.51	0.26	0.10	0.07	L	77.1	54.5
	300	0.14	0.18	0.05	0.01	0.17	0.01	0.09	0.80	0.42	0.12	0.08	L	63.3	41.2
4	Ap	-	-	-	-	-	-	-	0.31	0.20	0.12	0.12	L	-	-
	Ah(U)	0.11	0.14	0.05	0.07	0.00	0.00	0.06	0.32	0.17	0.12	0.26	L	-	-
	Ah(L)	-	-	-	-	-	-	-	0.21	0.19	0.11	0.08	L	-	-
	Btj(U)	0.16	0.25	0.07	0.01	0.33	0.01	0.11	0.47	0.38	0.16	0.07	L	-	-
	Btj(M)	0.19	0.31	0.15	0.03	0.25	0.01	0.10	2.54	1.94	0.32	0.22	L	7.9	2.4
	Btj(L)	1.02	0.83	0.21	0.03	1.79	0.01	0.09	5.23	2.32	0.43	0.25	4.4	12.4	2.3
	Cca(U)	1.33	2.58	0.60	0.04	1.86	0.01	0.13	97.7	5.96	1.00	0.29	91	220	35.2
	Cca(L)	1.16	2.97	0.77	0.03	1.81	0.01	0.11	88.1	5.97	1.17	0.25	88	244	41.4
	Ck	0.95	1.92	0.72	0.02	2.43	Tr	0.08	8.48	2.52	1.19	0.23	4.9	168	39.1
	150	0.43	0.55	0.46	0.01	1.06	0.01	0.08	1.55	1.09	0.93	0.15	0.9	133	37.2
	200	0.07	0.36	0.50	0.01	0.32	0.01	0.31	1.52	1.01	0.73	0.15	L	103	26.6
	300	0.14	0.20	0.35	0.02	0.55	Tr	0.11	1.29	0.83	1.17	0.26	L	73.3	33.3
5	Ap	0.01	0.00	0.09	0.00	0.00	0.00	0.05	0.07	0.06	0.35	0.04	L	7.02	3.6
	Bntjk(U)	0.04	0.04	2.83	0.00	0.33	0.00	0.47	0.41	1.10	1.14	0.19	L	12.6	14.6
	Bntjk(L)	0.04	0.08	1.30	0.00	0.73	Tr	0.27	1.58	0.60	5.34	0.16	L	89.5	32.3
	BCcasa(U)	0.26	0.35	3.05	0.00	2.34	0.01	0.19	3.38	1.44	8.30	0.10	4.5	187	40.8
	BCcasa(L)	1.47	1.41	5.91	0.00	9.14	0.00	0.17	4.08	2.11	9.12	0.12	8.2	147	39.9
	Csk	0.93	0.87	5.02	0.00	4.80	Tr	0.14	3.72	2.10	9.54	0.11	6.3	72.5	36.7
	120	0.01	0.01	0.90	0.00	0.61	0.01	0.29	0.90	2.52	5.62	0.37	L	38.9	30.6
	[illegible]	0.02	0.01	0.91	0.01	0.47	0.01	0.24	0.68	1.57	4.88	0.32	L	35.3	29.9
	[illegible]	0.02	0.02	1.18	0.01	0.57	0.01	0.32	0.50	0.59	3.63	0.14	L	34.0	19.7
6	[illegible]	0.14	0.11	2.64	0.03	1.58	0.01	0.58	1.04	2.10	7.27	0.41	L	25.2	12.0
	Bnsakg(U)	0.00	0.03	3.27	0.01	2.25	0.04	1.00	1.58	1.55	6.75	0.26	L	78.4	17.7
	Bnsakg(L)	[illegible]	0.04	2.46	0.01	1.22	0.01	0.77	1.23	1.35	8.03	0.38	L	91.9	26.4
	Ccasg	0.02	0.04	2.23	0.00	0.87	0.02	0.90	1.73	1.77	10.3	0.72	L	100	56.1
	IICsk	0.23	5.43	4.72	0.00	2.97	0.04	0.20	13.2	1.67	7.82	0.11	25	95.4	22.9
	120	0.71	4.24	3.28	0.00	7.38	0.01	0.36	15.7	5.78	4.88	0.99	22	24.8	8.38
	150	1.32	4.44	6.12	0.06	7.30	0.02	0.03	14.1	5.08	10.8	0.39	23	39.7	23.5
	200	1.34	[illegible]	6.78	0.01	8.61	0.05	0.00	9.77	5.42	11.7	0.11	21	15.4	16.0

(Continued)

SITE	HORIZON OR DEPTH cm.	IONS IN SATURATION EXTRACT meq/100 g soil Ca^{++}	Mg^{++}	Na^{+}	K^{+}	$SO_4^{=}$	Cl^{-}	HCO_3^{-}	IONS IN LARGE WATER VOLUME EXTRACT* meq/100 g soil Ca^{++}	Mg^{++}	Na^{+}	K^{+}	$SO_4^{=}$	IONS IN 2N HCl EXTRACT** meq/100 g soil Ca^{++}	Mg^{++}
7	Ap	0.01	0.00	0.05	0.00	0.00	0.00	0.04	0.08	0.07	0.24	0.04	L	-	-
	Ae	-	-	-	-	-	-	-	0.13	0.27	0.67	0.06	L	-	-
	Bnt1	0.02	0.00	0.09	0.00	0.00	0.00	0.03	0.20	0.42	0.64	0.08	L	-	-
	Bnt2(U)	0.02	0.01	0.13	0.00	0.00	0.00	0.07	0.10	0.09	0.70	0.02	L	-	-
	Bnt2(L)	0.02	0.01	0.13	0.00	0.00	0.00	0.07	0.14	0.19	0.69	0.05	L	13.8	11.1
	Ccasa	0.44	0.32	1.41	0.00	1.56	0.00	0.11	3.91	1.68	3.43	0.09	1.8	139	36.1
	Cksa	1.08	0.71	2.67	0.01	3.22	0.00	0.12	6.84	2.52	6.41	0.11	11	117	30.2
	120	1.30	1.10	4.91	0.01	7.29	0.00	0.12	15.0	2.72	9.07	0.13	21	77.1	31.8
	150	0.29	0.25	2.81	0.01	3.19	0.00	0.16	1.01	1.20	6.82	0.21	5.1	46.0	38.6
	200	0.07	0.09	2.63	0.01	2.28	0.00	0.19	0.76	1.20	6.72	0.30	2.1	52.4	30.4
	300	0.06	0.03	1.77	0.01	1.72	0.00	0.32	0.48	1.78	6.60	0.22	L	25.2	20.0
~~8~~	~~Ap~~	~~0.03~~	~~0.00~~	~~0.17~~	~~0.00~~	~~0.00~~	~~0.00~~	~~0.11~~	~~0.07~~	~~0.05~~	~~0.51~~	~~0.04~~	~~L~~	~~-~~	~~-~~
	Ah	-	-	-	-	-	-	-	0.07	0.05	0.76	0.01	L	-	-
	Ae	0.04	0.04	0.72	0.00	0.46	0.00	0.17	0.15	0.36	2.64	0.16	L	-	-
	Bnt(U)	0.09	0.14	2.04	0.00	1.38	0.01	0.20	0.80	1.30	4.90	0.56	L	6.39	8.12
	Bnt(L)	0.12	0.24	3.21	0.00	2.08	0.01	0.20	1.12	2.08	6.55	0.93	1.1	4.67	8.65
	BCsa(U)	1.37	1.25	6.61	0.02	9.38	Tr	0.12	10.9	3.88	12.4	0.19	21	18.8	11.1
	BCsa(L)	1.19	1.10	5.65	0.02	4.96	Tr	0.12	7.75	2.71	11.8	0.17	19	19.5	13.1
	Ccas	1.17	0.78	3.24	0.01	5.91	0.00	0.13	11.6	2.68	10.8	0.14	21	171	31.8
	120	1.24	0.97	1.20	0.01	2.44	0.01	0.11	6.15	1.93	4.65	0.11	10	58.5	29.8
	150	0.19	0.11	1.28	0.01	1.01	0.01	0.13	0.76	0.59	4.78	0.12	L	47.8	30.7
	200	0.03	0.03	1.02	0.01	0.50	0.01	0.20	0.56	0.81	5.45	0.15	L	47.8	32.8
	300	0.03	0.02	1.16	0.01	0.58	0.01	0.29	0.76	0.59	5.45	0.16	L	39.5	30.4
9	Ahsa	1.33	7.01	21.9	0.13	26.20	0.33	0.14	4.01	6.71	30.5	0.40	35	-	-
	Bnsa(U)	0.89	4.70	12.2	0.05	20.0	0.12	0.11	0.87	3.33	18.5	0.23	23	-	-
	Bnsa(L)	1.01	4.02	11.1	0.01	14.8	0.45	0.09	0.91	3.54	17.6	0.57	30	-	-
	BCsa	1.49	6.82	13.7	0.01	19.8	0.02	0.22	1.54	3.62	22.4	0.14	31	13.0	8.26
	Csak	0.97	2.57	7.44	0.01	9.36	0.01	0.13	58.6	9.90	21.3	0.12	81	63.1	16.6
	Ccas	1.36	4.62	9.15	0.03	15.3	0.01	0.20	2.67	2.32	12.8	0.11	11	117	37.2
	IICsk	1.14	1.38	6.15	0.02	9.65	0.01	0.36	1.43	1.76	13.7	0.07	10.7	38.9	24.0
	150	0.03	0.05	3.00	0.01	2.61	0.02	0.59	3.34	3.43	12.2	0.17	5.2	11.0	19.7

* Sufficient water to dissolve all gypsum.

** Following Large Water Volume extraction.

Appendix 6. Analysis of water samples from piezometers at soil study sites and at piezometer nests installed as part of Leskiw's (1971) study (overleaf).

SITE	DEPTH* metres	pH	E.C. mmhos/cm	CATIONS meq per litre				ANIONS meq per litre				
				Na^+	K^+	Ca^{++}	Mg^{++}	$SO_4^=$	HCO_3^-	$CO_3^=$	Cl^-	OH^-
1	WT	8.4	0.61	1.1	0.02	5.8	4.0	0.0	8.3	0.00	0.00	0.00
	3.0	8.5	0.20	0.9	0.10	0.8	0.7	0.0	1.8	0.00	0.14	0.00
	6.1	8.6	0.20	1.0	0.14	0.3	0.2	0.0	1.1	0.00	0.79	0.00
	12.2	8.9	0.50	1.1	0.14	2.9	2.6	0.7	5.3	0.00	0.03	0.00
2	WT	-	1.3	4.6	0.08	8.2	5.8	18.4	2.9	0.00	0.00	0.00
	4.3	9.1	0.30	1.1	0.13	0.1	0.9	0.0	2.5	0.00	0.14	0.00
	7.3	8.9	0.25	0.6	0.09	0.3	2.0	0.5	2.5	0.00	0.00	0.00
	13.4	8.6	0.51	1.1	0.15	2.9	2.8	1.1	5.3	0.00	0.00	0.00
3	WT	8.5	0.50	0.7	0.10	3.1	1.9	0.7	4.7	0.00	0.00	0.00
	5.2	8.4	1.5	2.2	0.23	13.1	6.2	24.9	1.9	0.00	0.00	0.00
	8.2	8.5	0.70	1.7	0.19	2.7	3.3	5.9	2.5	0.00	0.00	0.00
	14.3	8.9	0.56	1.3	0.16	2.4	2.9	1.4	4.9	0.00	0.06	0.00
4	WT	8.6	3.0	16.3	0.35	12.7	9.5	31.1	10.8	0.00	0.06	0.00
	6.7	9.7	1.1	8.7	0.18	0.2	0.2	6.9	4.7	0.00	0.17	0.00
	12.8	9.5	1.8	15.2	0.19	0.2	0.6	5.6	9.0	0.00	0.00	0.00
	25.0	8.9	0.40	1.9	0.06	0.6	2.4	1.2	3.3	0.05	0.00	0.00
5	WT	9.0	2.8	27.2	0.17	1.7	1.6	12.5	14.1	0.00	0.03	0.00
	4.6	10.1	1.5	13.6	0.17	0.1	0.0	5.1	10.7	0.00	0.93	0.00
	7.6	9.5	1.5	16.3	0.13	0.2	0.1	5.6	9.2	0.00	0.00	0.00
	13.7	9.4	1.8	21.7	0.09	0.2	0.1	9.0	10.9	0.00	0.00	0.00
5a	1.8	-	2.3	23.7	0.17	0.1	0.0	17.0	6.6	0.00	1.00	0.00
[illegible]	4.3	-	1.6	17.5	0.07	0.1	0.0	5.3	11.5	0.00	1.00	0.00
6	1.8	9.8	3.0	31.0	0.18	0.1	0.0	17.2	11.8	0.00	0.00	0.00
	4.6	9.1	1.4	39.0	0.32	0.1	0.1	6.4	15.2	0.00	10.0	0.00
	6.1	9.0	1.5	13.6	0.06	0.4	0.2	9.6	6.4	0.06	0.00	0.00
	12.2	9.3	0.82	7.1	0.12	0.2	1.2	2.2	6.3	0.05	0.00	0.00
	24.4	9.8	1.5	17.4	0.06	0.1	0.0	3.1	10.8	0.00	0.14	0.00
7	3.7	8.2	7.0	78	0.13	1.9	1.1	66	4.2	0.00	20.7	0.00
	6.7	8.8	1.8	16.3	0.54	0.4	0.3	0.7	10.0	0.00	6.29	0.00
	12.8	9.7	2.4	23.4	0.09	0.2	0.2	12.2	8.5	0.05	0.00	0.00
	25.0	9.0	0.60	3.6	0.13	1.2	2.1	1.2	5.3	0.07	0.00	0.00
7a	4.6	9.7	1.5	13.6	0.07	0.1	0.1	3.6	10.6	0.00	0.06	0.00
7b	5.2	9.1	1.5	14.1	0.14	0.2	0.2	3.1	13.3	0.00	0.34	0.00
7c	4.9	9.9	1.7	18.5	0.07	0.1	0.1	3.2	12.3	0.00	1.21	0.00
8	WT	9.4	3.7	44.4	0.21	5.1	3.9	25.6	16.7	1.00	0.00	0.00
	5.2	8.4	2.9	30.4	0.17	0.8	0.6	28.7	4.6	0.00	1.61	0.00
	8.2	9.1	1.6	17.4	0.05	0.4	0.4	8.0	7.9	0.12	0.00	0.00
	14.5	9.0	0.82	8.2	0.06	0.9	1.6	4.9	5.1	0.07	0.00	0.00
9	WT	8.8	7.4	87	0.79	5.2	8.1	100	17.9	0.00	0.03	0.00
	2.4	9.2	5.4	63	0.21	0.3	0.8	62	8.3	0.00	0.99	0.00
	6.1	9.2	3.8	43.0	0.15	1.1	0.4	35.6	9.4	0.00	0.00	0.00
	12.2	9.3	3.4	38.1	0.18	0.2	0.3	24.9	11.2	0.00	0.08	0.00
	24.4	9.3	1.0	8.2	0.05	0.3	1.2	4.9	6.1	0.11	0.00	0.00

NEST	DEPTH metres	pH	E.C. mmhos/cm	CATIONS meq per litre				ANIONS meq.per litre				
				Na^+	K^+	Ca^{++}	Mg^{++}	$SO_4^=$	$HCO_3^=$	$CO_3^=$	Cl^-	OH^-
I	18.3	9.0	0.20	1.0	0.10	0.3	0.5	0.4	1.4	0.00	0.03	0.00
	46.0	8.6	0.27	0.9	0.38	0.6	0.7	0.5	[illegible].9	0.00	0.03	0.00
	83.8	8.9	0.40	2.0	0.26	1.1	0.8	0.3	3.4	0.00	0.00	0.00
	123.4	8.9	0.30	1.0	0.36	0.9	1.2	0.4	2.9	0.00	0.00	0.00
II	6.1	9.2	0.60	1.7	0.25	1.9	3.4	0.0	6.9	0.00	0.00	0.00
	14.6	8.6	0.52	1.2	0.23	4.0	2.3	0.0	5.9	0.00	0.00	0.00
	48.8	8.9	0.35	1.9	0.33	0.6	0.8	0.6	2.9	0.00	0.00	0.00
	79.2	11.9	2.15	16.3	0.49	0.1	0.0	0.3	0.0	7.70	0.00	6.71
	105.2	9.6	0.29	1.0	0.38	0.5	0.9	0.5	2.4	0.00	0.00	0.00
III	4.6	9.6	1.00	10.9	0.08	0.4	0.8	0.7	9.9	0.00	0.00	0.00
	46.6	9.8	1.20	13.0	0.77	0.2	0.2	0.0	12.9	0.00	0.06	0.00
	73.8	10.3	0.82	3.7	0.29	0.2	0.2	0.3	6.3	0.00	1.13	0.00
	96.6	10.2	0.70	2.8	0.51	0.4	0.8	0.4	6.1	0.00	0.42	0.00
IV	[illegible]1.4	9.5	2.41	27.2	0.08	0.3	0.3	13.7	15.3	0.00	0.06	0.00
	22.6	11.1	1.54	17.4	0.38	0.4	0.1	0.6	1.6	14.00	0.03	0.00
	47.9	12.2	4.20	24.5	0.45	0.7	0.0	0.0	0.0	6.50	0.93	16.46
	72.5	12.2	4.40	26.7	1.15	0.4	0.0	0.3	0.0	10.13	1.04	18.53
V	10.7	11.1	2.70	27.2	0.09	0.2	0.0	14.7	2.3	11.33	0.14	0.00
	[illegible]1.9	11.7	1.65	10.9	3.07	0.1	0.0	0.6	0.0	6.10	1.18	3.12
	[illegible].5	10.0	1.50	17.4	0.40	0.2	0.0	0.6	10.5	4.07	0.31	0.00
	[illegible].9	11.4	1.00	8.2	1.41	0.4	0.0	1.0	1.6	5.27	0.03	0.00

Appendix 7. Analysis of 1:5 water extracts of drill samples from the soil study sites.

SITE	DEPTH metres	LITHOLOGY	pH	E.C. mmhos/cm	CATIONS meq per litre Na⁺	K⁺	Ca⁺⁺	Mg⁺⁺	ANIONS meq per litre $SO_4^=$	HCO_3^-	Cl^-
1	2.9	Till	7.8	0.10	0.13	0.05	0.29	0.39	0.0	0.59	0.00
	4.4	Sand	7.1	0.10	0.06	0.05	0.25	0.11	0.0	0.39	0.00
	6.9	Till	8.1	0.15	0.12	0.17	0.80	0.41	1.5	0.98	0.00
	12.0	Bedrock	8.0	0.15	0.17	0.20	0.90	0.30	0.9	0.98	0.00
2	2.9	Sand	8.0	0.11	0.23	0.06	0.50	0.30	0.0	0.69	0.00
	12.8	Bedrock	8.0	0.15	0.27	0.24	0.70	0.16	1.5	1.08	0.00
3	4.9	Till	7.2	0.81	0.46	0.27	4.69	2.47	23.1	0.39	Tr
	7.9	Till	7.7	0.45	0.48	0.24	1.90	1.32	11.8	0.49	0.00
	9.7	Silt	7.7	0.21	0.41	0.19	0.80	0.41	16.8	0.69	0.00
	14.0	Till	7.8	0.20	0.39	0.27	0.89	0.36	1.9	0.98	0.00
4	4.7	Till	8.0	0.19	0.87	0.12	0.21	0.07	2.4	0.98	0.00
	12.5	Bedrock	8.0	0.26	2.0	0.08	0.15	0.04	4.7	0.78	0.00
	19.8	Bedrock	8.7	0.40	3.7	0.05	0.12	0.11	2.4	3.3	0.00
	24.7	Bedrock	8.9	0.80	7.5	0.11	0.12	0.06	5.6	5.5	0.00
5	[illegible]	Till	8.1	0.61	3.0	0.02	0.04	0.03	4.3	1.77	0.00
	4.1	Bedrock	8.4	0.30	3.0	0.08	0.06	0.03	2.6	2.06	0.00
	4.4	Bedrock	8.6	0.36	3.4	0.09	0.06	0.02	1.5	2.75	0.00
	6.4	Bedrock	8.7	0.45	4.4	0.14	0.11	0.04	1.9	3.7	0.00
	7.3	Bedrock	8.8	0.45	[illegible]	0.14	0.16	0.11	1.9	3.9	0.00
	13.4	Bedrock	8.6	0.50	4.9	0.07	0.06	0.03	2.6	4.1	0.00
6	2.3	Bedrock	8.5	0.40	3.8	0.05	0.02	0.02	2.1	3.0	0.00
	3.8	Bedrock	8.5	0.40	3.9	0.05	0.04	0.02	[illegible]	2.31	0.00
	5.9	Bedrock	9.1	0.39	3.8	0.04	0.06	[illegible]	[illegible]	3.4	0.00
	8.8	Bedrock	8.7	0.75	6.5	0.09	0.08	[illegible]	[illegible]	[illegible]	0.00
	24.1	Bedrock	8.4	0.90	7.4	0.09	0.07	[illegible]	11.9	[illegible]	0.00
7	2.3	Till	8.5	0.40	3.8	0.03	0.08	0.03	5.2	2.75	0.00
	[illegible]	Bedrock	8.9	0.60	5.6	0.08	0.10	0.06	[illegible]	4.7	0.00
	4.7	Bedrock	8.7	0.59	5.3	0.06	0.06	[illegible]	2.4	3.7	0.80
	9.3	Bedrock	8.9	0.50	4.6	0.06	0.07	0.02	1.9	4.7	0.00
	11.9	Bedrock	8.8	0.65	6.5	0.07	0.08	0.02	3.4	5.5	0.00
	12.5	Bedrock	8.8	0.50	5.0	0.06	0.09	0.04	1.9	4.4	0.00
	24.7	Bedrock	8.6	0.81	7.3	0.08	0.06	0.02	9.4	3.9	0.00
8	2.6	Till	7.8	0.25	1.9	0.05	0.22	0.10	3.7	0.79	0.00
	3.2	Bedrock	8.8	0.35	2.8	0.03	0.08	0.04	3.7	1.57	0.00
	5.2	Bedrock	8.5	0.36	3.4	0.06	0.09	0.05	2.6	2.75	0.00
	7.8	Bedrock	8.5	0.75	6.5	0.08	0.10	0.12	8.2	8.8	0.00
	13.7	Bedrock	8.9	0.80	6.9	0.07	0.09	0.04	6.2	4.6	0.00
9	2.6	Bedrock	8.5	1.0	7.9	0.06	0.18	0.12	19.8	2.06	Tr
	3.0	Bedrock	8.5	0.39	3.4	0.05	0.04	0.01	2.1	2.95	0.00
	4.4	Bedrock	8.5	0.90	7.7	0.08	0.15	0.16	15.0	3.3	0.00
	5.9	Bedrock	8.8	0.70	6.7	0.07	0.06	0.02	3.6	5.1	0.00
	8.8	Bedrock	8.7	0.66	6.7	0.06	0.09	0.02	5.1	4.1	0.00
	11.9	Bedrock	8.7	1.1	10.2	0.11	0.12	0.03	15.9	4.3	0.00
	16.8	Bedrock	8.8	0.70	8.8	0.07	0.12	0.04	7.5	3.1	0.00
	24.4	Bedrock	8.9	0.70	6.1	0.06	0.08	0.04	4.3	4.9	0.00

Appendix 8. Water levels in piezometers installed as part of Leskiw's (1971) study terminating at depths indicated.

NEST AND LEVEL m a.m.s.l	PIEZ. DEPTH m	WATER LEVELS metres above mean sea level										
		May 25/71	Jun 1/71	Jun 7/71	Jun 15/71	Jul 6/71	Jul 21/71	Aug 4/71	Aug 18/71	Aug 30/71	Sep 14/71	Sep 28/71
I	18.3	675.22	675.16	675.17	675.19	675.15	675.13	675.13	675.08	675.06	675.10	675.14
	46.0	667.44	667.44	667.45	667.46	667.49	667.50	667.52	667.50	667.50	667.52	667.54
	83.8	643.06	653.10	655.29	656.50	657.76	657.93	657.97	657.95	657.95	657.95	657.94
	123.4	602.18	603.67	605.01	606.29	609.80	611.93	613.75	615.99	617.77	618.15	619.44
II	6.1	671.08	671.02	671.02	671.01	671.08	671.03	671.06	670.93	670.89	670.79	670.74
	14.6	669.48	669.50	669.55	669.60	669.65	669.72	669.77	669.80	669.83	669.86	669.86
	48.8	644.96	647.93	650.24	652.09	659.85	660.34	660.35	660.33	660.33	660.33	660.31
	79.2	634.73	638.62	640.79	642.10	643.84	644.22	644.40	644.44	644.46	644.47	644.44
	105.2	601.71	604.29	606.56	608.59	613.66	616.28	618.33	620.77	622.67	623.00	624.20
III	4.6	656.48	656.46	656.44	656.44	656.46	656.39	656.37	656.14	655.95	656.02	655.92
	46.6	638.80	638.79	638.83	638.82	638.84	638.87	638.88	638.83	638.81	638.82	638.81
	73.8	637.74	639.00	639.32	639.49	639.62	639.64	639.67	639.64	639.63	639.66	639.66
	96.6	586.20	586.86	587.19	587.50	588.21	588.70	589.34	590.19	590.50	591.11	591.74
IV	3.4	638.43	-	-	637.45	638.79	638.95	639.12	639.28	639.34	639.43	639.41
	22.6	636.00	636.62	636.76	636.81	636.80	636.78	636.78	636.77	636.76	636.77	636.76
	47.9	614.27	619.08	622.33	624.73	629.17	630.93	631.96	632.85	633.14	633.53	633.82
	72.5	589.86	592.87	595.15	597.17	602.73	606.44	609.42	612.51	614.97	615.26	616.76
V	10.7	629.08	629.08	629.08	629.07	629.06	629.09	629.14	629.20	629.25	629.29	629.37
	21.9	627.50	627.58	627.64	627.67	627.68	627.70	627.72	627.69	627.67	627.72	627.71
	47.5	622.53	623.06	623.22	623.41	623.76	624.04	624.31	624.60	624.80	624.83	624.22
	68.9	598.28	603.80	607.61	610.39	615.61	617.33	618.45	619.48	620.16	631.55	620.57

NEST AND LEVEL m. a.m.s.l.	PIEZ. DEPTH m	WATER LEVELS metres above mean sea level										
		Oct 12/71	Oct 26/71	Nov 9/71	Nov 23/71	Dec 8/71	Dec 18/71	Jan 16/72	Feb 10/72	Mar 11/72	Apr 10/72	May 10/72
I	18.3	675.17	675.17	675.19	675.19	675.18	675.01	675.16	675.17	675.04	674.99	675.03
	46.0	667.55	667.55	667.54	667.52	667.46	667.49	667.52	667.55	667.58	667.60	667.60
	83.8	657.95	657.95	657.93	657.86	657.84	657.85	657.87	657.89	657.90	657.94	657.93
	123.4	620.57	621.57	622.49	623.30	624.09	624.61	625.96	626.93	627.84	628.77	634.29*
II	6.1	670.74	670.73	670.68	670.59	670.64	670.52	670.49	670.37	670.23	670.43	671.86*
	14.6	669.87	669.86	669.84	669.83	669.77	669.76	669.62	669.59	669.47	669.41	669.49
	48.8	660.32	660.32	660.32	660.32	660.22	660.24	660.29	660.30	660.34	660.34	660.39
	79.2	644.44	644.44	644.43	644.43	644.43	644.36	644.38	644.41	644.43	644.43	644.35
	105.2	625.07	625.80	626.36	626.80	627.09	627.35	627.91	628.33	628.76	629.09	630.73
III	4.6	655.86	655.83	655.82	655.76	655.71	655.67	655.60	655.45	655.33	655.57	656.76
	46.6	638.82	638.81	638.80	638.81	638.74	638.76	638.80	638.82	638.84	638.83	638.81
	73.8	639.67	639.65	639.63	639.64	639.53	639.56	639.60	639.62	639.64	639.67	639.66
	96.6	592.38	593.30	594.10	595.10	596.06	596.78	598.99	600.91	603.35	605.87	626.28*
IV	3.4	639.32	639.18	-	-	-	-	-	-	-	-	638.61
	22.6	636.76	636.77	636.77	636.78	636.74	636.75	636.79	636.81	636.85	636.86	636.89
	47.9	634.04	634.19	634.37	634.40	634.39	634.44	634.61	634.70	634.81	634.90	634.91
	72.5	618.00	619.21	620.03	620.78	621.41	621.79	622.70	623.36	623.93	624.32	625.57*
V	10.7	629.46	629.54	629.58	629.63	629.60	629.64	629.64	629.62	629.54	629.45	629.36
	21.9	627.72	627.73	627.72	627.73	627.71	627.74	627.78	627.82	627.84	627.85	627.86
	47.5	624.10	623.07	624.07	624.07	623.95	623.98	624.02	624.05	624.10	624.10	624.11
	68.9	620.83	620.94	620.99	621.03	621.02	621.07	621.15	621.14	621.15	621.18	621.18

* Following addition of water to pipe to hasten stabilization.

NEST AND LEVEL m. a.m.s.l.	PIEZ. DEPTH m	WATER LEVELS metres above mean sea level Jun 6-72	Jul [illegible]/72	* Jul 26-72	Aug 27/72	Sep 26.72	Oct 25.72	Nov 21.72	Dec 18.72	Jan [illegible]	Feb 10-73	Mar [illegible]
I	18.3	675.01	674.85	674.99	675.05	674.97	674.98	675.01	675.01	675.10	675.12	[illegible]
	46.0	667.61	667.60	667.66	667.61	667.62	667.64	667.66	667.68	667.71	667.72	667.75
	81.8*	657.90	657.89	657.8	657.88	657.88	657.88	657.89	657.89	657.91	657.92	[illegible]
	123.4	634.35	634.36	[illegible]	634.39	[illegible]	634.49	634.50	634.39	634.51	634.52	[illegible]
~~II~~	~~9.1~~	~~674.62~~		~~671.16~~	~~670.70~~	~~670.37~~	~~[illegible]~~	~~670.40~~	~~670.47~~	~~670.[illegible]~~	~~670.4[illegible]~~	~~670.49~~
	14.6	669.70	669.79	669.80	669.78	669.74	669.69	669.66	669.55	669.50	669.45	[illegible]
	48.8	660.29	660.29	660.27	660.27	[illegible]	660.26	660.27	660.29	660.30	660.32	[illegible]
	79.2	644.31	644.31	644.28	644.26	[illegible]	644.22	644.26	644.27	644.28	644.28	[illegible]
	105.2	630.84	630.90	630.90	631.07	631.17	631.19	631.25	631.31	631.36	631.41	[illegible]
III	23.6	656.54	656.58	656.16	655.99	655.87	655.80	655.74	655.71	655.65	655.51	[illegible]
	46.6	638.80	638.78	638.76	638.78	638.77	638.77	638.81	638.80	638.81	638.81	638.8[illegible]
	73.8	639.64	639.52	639.63	639.61	639.5[illegible]	639.59	639.59	639.60	639.61	639.61	639.61
	96.6	628.25	630.40	631.96	639.61*	650.[illegible]	650.98	651.55	[illegible]	[illegible]	652.78	[illegible]
IV	3.4	638.74	639.0[illegible]	639.16	639.10	[illegible]	639.2[illegible]	639.02	638.8[illegible]	638.7	638.65	639.0[illegible]
	22.6	636.88	636.85	636.85	636.92	636.9[illegible]	636.95	636.97	636.99	637.01	637.02	637.08
	47.9	634.9[illegible]	634.91	634.81	634.9[illegible]	[illegible]	634.97	635.00	635.02	635.0[illegible]	635.05	635.07
	72.5	625.67	625.87	626.[illegible]	626.[illegible]	[illegible]	626.53	626.68	626.78	626.88	626.98	627.10
V	10.7	629.2[illegible]	629.18	629.20	629.31	629.42	629.55	629.65	629.60	629.71	629.66	629.58
	21.9	627.85	627.87	627.91	627.93	627.93	627.9[illegible]	627.96	627.98	628.00	627.96	627.94
	47.5	624.10	624.06	624.06	624.03	623.98	623.97	623.99	623.98	623.98	624.00	624.02
	68.9	621.14	621.08	621.05	621.01	621.01	621.01	621.00	621.04	621.04	621.01	621.01

NEST AND LEVEL m. a.m.s.l.	PIEZ. DEPTH m	WATER LEVELS metres above mean sea level Apr 30-7[illegible]	May 8-7[illegible]	Jun 6-7[illegible]	Jul [illegible]	Jul [illegible]	Sep [illegible]
I	18.3	675.[illegible]7	675.1[illegible]	674.99	674.95	675.03	674.95
	46.0	667.77	667.7[illegible]	667.7[illegible]	667.73	667.74	667.77
	81.8	657.95	657.9[illegible]	657.94	658.00	657.96	658.0[illegible]
	123.4	634.4[illegible]	634.4[illegible]	634.44	634.45	634.5[illegible]	634.53
II	9.1	670.[illegible]	670.87	671.09	671.83	671.79	671.77
	14.6	669.[illegible]	669.[illegible]7	669.51	669.87	670.28	671.04
	48.8	660.38	660.39	660.38	660.43	660.41	660.49
	79.2	644.28	644.27	644.26	644.30	644.27	644.31
	105.2	631.50	631.56	631.60	631.66	631.72	631.79
III	23.6	655.26	656.02	656.25	656.33	656.57	657.42
	46.6	638.79	638.81	638.78	638.84	638.81	638.87
	73.8	639.6[illegible]	639.64	639.63	639.63	639.67	639.71
	96.6	643.29	643.50	643.68	643.83	643.96	644.08
IV	3.4	638.57	638.38	638.20	638.11	638.09	638.38
	22.6	636.81	636.94	636.92	637.05	637.00	637.15
	47.9	635.11	635.13	635.11	635.13	635.1[illegible]	635.45
	72.5	627.25	627.35	627.43	627.51	627.57	627.65
V	10.7	629.[illegible]	629.20	629.18	629.16	629.15	629.35
	21.9	627.7[illegible]	624.10	624.11	624.13	624.09	624.09
	47.5	624.09	624.07	624.08	624.10	624.06	624.06
	68.9	620.98	620.91	620.84	620.82	620.79	620.81

* Following addition of water to pipe to hasten stabilization.

Appendix 9. Hydraulic heads at the soil study sites given by sloughs, water table access tubes (WT), and piezometers terminating at depths indicated (below ground level at the water table access tube), with values corrected (C) where necessary for basic time lag.

SITE AND LEVEL m. a.m.s.l.	PIEZ. DEPTH m.	HYDRAULIC HEADS, metres above mean sea level									
		Jul 6/71	Jul 14/71	Jul 21/71	Jul 28/71	Aug 4/71	Aug 18/71	Aug 30/71	Sep 14/71	Sep 28/71	Oct 12/71
1	Slough	-	-	-	674.52	-	-	-	-	-	674.34
	WT	-	-	-	674.49	674.44	674.41	674.35	674.32	674.28	674.27
	3.05	674.64	674.60	674.51	674.25	674.49	674.30	674.25	674.25	674.25	674.24
	6.10	674.62	674.62	674.56	674.52	674.47	674.27	674.21	674.21	674.20	674.21
	12.19	-	-	-	-	-	-	672.57	672.57	672.59	672.60
	WT	-	-	-	-	674.18	674.07	673.96	673.93	673.93	673.96
	4.27	673.15	673.15	673.97	674.12	674.12	673.94	673.85	673.85	673.89	[illegible]
	7.32	-	-	-	-	-	-	-	-	-	-
	c	-	-	-	-	-	-	-	-	-	-
	13.41	-	-	-	-	-	-	-	672.33	672.11	672.29
	WT	-	-	-	676.57	676.56	676.52	676.52	677.21	677.06	676.89
	[illegible].18	-	-	-	-	-	-	677.76	677.43	676.89	676.49
	8.[illegible]	-	-	-	-	-	-	-	-	673.57	673.41
	15.[illegible]	-	-	-	-	-	-	-	-	-	-
	WT	-	-	644.39	644.36	644.33	644.19	644.14	644.06	644.06	643.98
	6.71	675.83	645.32	645.21	645.22	645.17	644.94	644.81	644.80	644.75	644.76
	12.80	-	-	-	-	-	-	-	645.31	645.26	645.23
	[illegible]	-	-	-	-	-	-	-	-	-	-
	WT	-	-	-	-	-	-	-	-	-	-
	4.57	639.45	639.45	639.45	639.45	639.45	639.42	639.40	639.37	639.32	639.27
	c	639.46	639.46	639.45	639.44	639.44	639.41	639.49	639.36	639.31	639.26
	7.[illegible]	-	-	-	-	-	-	-	-	639.11	639.11
	14.[illegible]	-	-	-	-	-	-	-	-	639.11	639.11
6	WT	-	-	637.53	-	-	-	-	-	-	-
	1.83	-	-	-	-	-	637.15	637.13	637.14	637.15	637.19
	4.27	-	637.18	637.20	637.23	637.21	637.15	637.13	637.13	637.10	637.13
	6.10	-	-	-	-	-	-	-	-	-	637.42
	c	-	-	-	-	-	-	-	-	-	637.46
	[illegible]	-	-	-	-	-	-	-	-	-	-
	c	-	-	-	-	-	-	-	-	-	637.74
	[illegible]8	-	-	-	-	-	-	-	-	637.70	637.72
7	WT	-	637.54	637.52	637.60	637.61	637.61	637.54	637.50	637.27	637.10
	[illegible]	-	-	-	-	-	-	-	-	-	-
	[illegible]	-	-	-	-	-	-	-	-	-	-
	[illegible].80	-	-	-	-	-	-	-	-	-	-
	[illegible]	-	-	-	-	-	-	-	-	-	-
8	WT	-	-	-	633.75	633.71	633.60	633.55	633.50	-	-
	[illegible].18(1)	-	-	-	-	-	-	-	633.67	633.67	633.58
	(2)	-	-	-	-	-	-	-	-	-	-
	(3)	-	-	-	-	-	-	-	-	-	-
	8.2[illegible]	-	-	-	-	-	-	-	-	-	-
	c	-	-	-	-	-	-	-	-	-	633.01
	14.33	-	-	-	-	-	-	-	-	-	632.79
	Slough	-	-	632.91	-	-	-	-	632.95	632.95	632.95
	WT	-	-	-	-	-	-	-	-	632.99	632.95
	2.44	-	-	-	-	-	-	-	-	632.96	632.91
	c	-	-	-	-	-	-	-	-	-	-
	[illegible]	-	-	-	-	-	-	-	-	-	-
	c	-	-	-	-	-	-	-	-	-	-
	12.19	-	-	-	-	-	-	-	-	-	-
	c	-	-	-	-	-	-	-	-	-	-
	24.38	-	-	-	-	-	-	-	-	-	-

SITE AND LEVEL m. a.m.s.l.	PIEZ. DEPTH m.	Oct 26/71	Nov 9/71	Nov 23/71	Dec 8/71	Dec 18/71	Dec 29/71	Jan 16/72	Jan 29/72	Feb 10/72	Feb 29/72
		HYDRAULIC HEADS metres above mean sea level									
1	Slough	674.34	-	-	674.30	-	-	-	-	-	-
	WT	674.21	674.17	674.13	674.02	673.96	673.89	673.80	673.71	673.64	673.52
	3.05	674.15	674.07	674.09	674.07	673.98	673.54	673.42	673.22	673.22	673.07
	6.10	674.24	674.03	674.03	674.85	673.69	673.57	673.37	673.30	673.22	673.14
	12.19	672.65	672.72	672.64	672.59	672.54	672.49	672.46	672.37	672.32	672.23
2	WT	673.94	673.89	673.86	673.82	-	-	-	-	-	-
	4.27	673.92	673.88	673.82	673.75	673.64	673.55	673.49	673.35	673.29	673.19
	7.32	-	673.80	673.79	673.78	673.75	673.71	673.65	673.58	673.50	673.41
	c	-	673.80	673.76	673.71	673.68	673.63	673.52	673.41	673.30	673.19
	14.41	672.34	672.33	672.34	672.32	672.32	672.28	672.27	672.23	672.17	672.15
3	WT	676.74	676.65	676.52	676.42	676.44	676.37	676.30	676.20	-	-
	5.18	676.01	675.58	675.52	675.48	675.39	675.35	675.36	675.35	675.35	675.32
	8.23	673.33	673.25	673.21	673.24	673.30	673.23	673.31	673.15	673.18	683.11
	14.33	-	-	-	-	-	-	-	-	-	-
	c	-	-	-	-	-	-	-	-	-	-
4	WT	643.95	643.91	644.36	643.89	643.88	643.89	643.92	643.91	643.94	643.95
	6.71	644.76	644.77	644.75	644.74	644.75	644.76	644.82	644.76	644.75	644.72
	12.80	645.23	645.23	645.24	645.24	645.24	645.24	645.26	645.24	645.23	645.22
	24.99	-	-	-	-	-	-	-	-	-	-
	c	-	-	-	-	-	-	-	-	-	-
5	WT	-	-	-	-	-	-	-	-	-	-
	4.57	639.24	639.14	639.11	639.08	639.06	638.97	639.06	639.05	639.04	639.07
	c	639.19	639.10	639.10	639.02	638.93	638.96	639.08	639.04	639.06	639.10
	7.62	638.47	638.45	638.46	638.48	638.49	638.50	638.55	638.57	638.58	638.62
	13.72	639.07	639.07	639.07	639.10	639.11	639.11	639.17	639.20	639.22	639.26
	c	639.06	639.07	639.07	639.10	639.11	639.11	639.17	639.20	639.22	639.32
6	WT	637.28	637.28	637.30	637.30	-	-	-	-	-	-
	1.83	637.19	637.20	637.18	637.20	-	-	-	-	-	-
	4.27	637.10	637.10	637.11	637.11	637.15	637.16	637.23	637.26	637.27	637.30
	6.10	637.36	637.36	637.37	637.38	637.39	637.39	637.43	637.44	637.46	637.48
	c	637.38	637.36	637.37	637.38	637.39	637.40	637.45	637.44	637.46	637.49
	12.19	-	-	-	-	-	-	-	-	-	-
	c	-	-	-	-	-	-	-	-	-	-
	24.38	637.70	637.71	637.74	637.76	637.77	637.80	637.85	637.84	637.84	637.86
	c	637.70	637.72	637.74	637.77	637.79	637.82	637.85	637.83	637.85	637.90
7	WT	-	-	-	-	-	-	-	-	-	-
	4.66	636.93	636.81	636.66	636.63	636.58	636.64	636.65	636.78	636.82	636.86
	6.71	-	-	-	-	-	-	-	-	-	-
	c	-	-	-	-	-	-	-	-	-	-
	12.80	-	-	-	-	-	-	-	-	-	-
	c	-	-	-	-	-	-	-	-	-	-
	24.99	635.97	635.95	635.94	635.94	635.93	635.92	635.94	635.94	635.96	635.95
	c	635.95	635.93	635.91	635.90	635.90	635.93	635.94	635.95	635.96	635.97
8	WT	-	-	-	-	-	-	-	-	-	-
	5.18(1)	633.50	633.40	633.26	633.11	633.04	632.90	632.82	632.70	632.68	632.61
	(2)	-	-	633.16	633.13	633.11	633.04	632.93	632.90	632.84	632.74
	(3)	-	-	-	633.06	633.05	632.99	632.94	632.90	632.89	632.78
	8.23	-	-	-	633.41	-	633.44	633.43	633.39	633.33	633.24
	c	-	-	-	633.50	633.50	633.47	633.38	633.30	633.22	633.09
	14.33	633.01	633.01	633.01	633.01	633.01	633.01	633.03	633.03	633.02	633.03
9	Slough	632.79	-	-	632.77	-	-	-	-	-	-
	WT	632.95	632.91	632.89	-	-	-	-	-	-	-
	2.44	632.91	632.87	632.76	632.69	632.66	632.62	632.56	632.48	632.44	632.36
	c	632.85	632.75	632.69	632.64	632.61	632.57	632.48	632.41	632.33	632.25
	6.10	-	632.99	632.93	632.87	632.81	632.78	632.73	632.66	632.62	632.53
	c	-	632.97	632.90	632.81	632.78	632.74	632.63	632.58	632.48	632.42
	12.19	-	-	-	-	-	-	-	-	632.85	632.89
	c	-	-	-	-	-	-	-	-	632.97	632.97
	24.38	-	-	-	-	-	-	-	-	-	-

SITE AND LEVEL m. a.m.s.l.	PIEZ. DEPTH m.	HYDRAULIC HEADS metres above mean sea level									
		Mar 11/72	Mar 24/72	Apr 10/72	Apr 26/72	May 10/72	May 23/72	Jun 6/72	Jun 20/72	Jul 3/72	Jul 18/72
1	Slough	-	-	674.47	675.14	675.12	675.06	674.95	674.84	674.79	674.75
	WT	673.46	673.42	673.38	673.45	674.48	674.71	674.72	674.74	674.71	674.68
	3.05	673.04	673.08	673.21	674.20	674.86	674.96	674.76	674.71	674.67	674.87
	6.10	673.08	673.08	673.19	673.99	674.93	674.92	674.77	674.65	674.61	674.52
	12.19	672.23	672.20	672.17	672.43	672.79	672.93	672.90	672.89	672.84	672.81
2	WT	-	-	-	-	674.21	674.50	674.49	674.40	674.32	674.29
	4.27	673.15	673.12	672.96	673.73	674.45	674.55	674.44	674.35	674.27	674.25
	7.32	673.37	673.33	673.25	673.33	673.54	673.79	673.97	674.08	674.13	674.17
	c	673.17	673.17	673.29	673.58	674.14	674.33	674.26	674.24	674.24	674.23
	13.41	672.08	672.04	672.01	672.11	672.27	672.46	672.52	672.56	672.57	672.54
3	WT	-	-	-	678.48	677.97	677.64	677.43	677.31	677.21	677.08
	5.18	675.34	675.34	675.32	677.29	677.19	677.24	677.05	676.88	676.67	676.55
	8.23	673.11	673.07	673.03	672.95	672.90	672.99	673.03	673.11	673.05	673.16
	14.33	-	-	-	-	672.22	672.22	672.22	672.22	672.24	672.23
	c	-	-	-	-	672.22	672.22	672.22	672.22	672.24	672.23
4	WT	643.98	644.00	644.41	644.40	644.69	644.96	644.94	644.70	644.50	644.33
	6.71	644.75	644.81	645.09	645.48	645.64	645.62	645.44	645.22	645.04	644.87
	12.80	645.21	645.21	645.45	645.69	645.86	645.88	645.83	645.74	645.66	645.58
	24.99	-	-	643.18	643.21	643.20	643.19	643.17	643.19	643.19	643.17
	c	-	-	643.23	643.21	643.20	643.18	643.16	643.15	643.14	643.18
5	WT	-	-	-	-	-	-	-	639.14	639.16	639.15
	4.57	639.08	639.10	639.11	639.14	639.16	639.18	639.20	639.20	639.20	639.20
	c	639.11	639.11	639.13	639.16	639.17	639.20	639.22	639.22	639.19	639.17
	7.62	638.64	-	-	-	-	638.66	-	-	638.56	638.56
	13.72	639.35	639.31	639.32	639.31	639.30	639.28	-	-	639.21	639.18
	c	639.37	639.31	639.32	639.31	639.29	639.28	639.25	639.24	639.21	639.18
6	WT	-	-	-	-	-	637.48	637.27	637.17	637.20	637.21
	1.83	-	-	-	-	-	-	637.22	637.19	637.18	637.20
	4.27	637.29	637.30	637.30	637.31	637.29	637.23	637.13	637.09	637.07	637.06
	6.10	637.50	637.52	637.52	637.53	637.57	637.56	637.56	637.53	637.50	637.49
	c	637.51	637.52	637.52	637.55	637.57	637.56	637.55	637.52	637.50	637.46
	12.19	-	-	-	-	-	-	-	-	-	-
	c	-	-	-	-	-	-	-	-	-	-
	24.38	637.89	637.89	637.90	637.91	637.89	637.87	637.82	637.82	637.82	637.82
	c	637.93	637.92	637.93	637.91	637.88	637.85	637.81	637.82	637.82	637.82
7	WT	-	-	-	-	-	-	-	-	637.54	637.53
	3.66	636.87	636.89	636.90	636.92	636.96	637.15	637.30	637.46	637.48	637.44
	6.71	-	-	-	-	636.70	636.70	636.70	636.69	636.68	636.67
	c	-	-	-	-	636.53	636.54	636.55	636.57	636.61	636.67
	12.80	-	-	-	-	-	636.66	636.75	636.64	636.62	636.61
	c	-	-	-	-	-	636.66	-	636.49	636.43	636.39
	24.99	635.97	635.98	635.98	636.00	636.60	635.99	636.01	636.02	636.03	636.03
	c	635.97	635.98	635.99	636.00	636.02	636.02	636.03	636.04	636.05	636.06
8	WT	-	-	-	633.70	633.71	633.65	633.58	633.54	633.50	-
	5.18(1)	632.61	632.59	632.57	632.55	632.52	632.62	632.77	633.01	633.17	633.30
	(2)	632.71	632.68	632.62	632.59	632.59	632.61	632.66	632.72	632.84	632.96
	(3)	632.76	632.71	632.67	632.65	632.61	632.70	632.64	632.68	632.78	632.89
	8.23	633.19	633.12	633.04	632.88	632.85	632.79	632.72	632.66	632.65	632.66
	c	633.03	632.97	632.84	632.73	632.65	632.59	632.58	632.60	632.63	632.72
	14.33	633.04	633.04	633.05	633.05	633.04	633.05	633.05	633.05	633.04	633.04
9	Slough	-	-	633.00	633.13	633.09	632.88	632.83	632.65	632.65	632.46
	WT	-	-	-	-	632.80	632.78	632.78	632.77	632.78	632.78
	2.44	632.32	632.27	632.23	632.28	632.36	632.46	632.55	632.64	632.69	632.74
	c	632.21	632.20	632.23	632.31	632.41	632.49	632.58	632.67	632.72	632.77
	6.10	632.42	632.41	632.37	632.43	632.46	632.50	632.50	632.59	632.67	632.76
	c	632.37	632.35	632.37	632.43	632.50	632.55	632.60	632.68	632.74	632.83
	12.19	632.91	632.91	632.91	632.91	632.89	632.87	632.87	632.77	632.72	632.67
	c	632.96	632.94	632.91	632.86	632.82	632.78	632.72	632.66	632.61	632.55
	24.38	-	-	-	-	-	-	-	-	-	-

(Continued)

SITE AND LEVEL m. a.m.s.l.	PIEZ. DEPTH m.	HYDRAULIC HEADS metres above mean sea level									
		Jul 26/72	Aug 15/72	Aug 27/72	Sep 12/72	Sep 26/72	Oct 10/72	Oct 24/72	Nov 6/72	Nov 21/72	Dec 9/72
1	Slough	674.67	674.67	674.60	674.53	674.55	674.51	674.46	674.45	674.44	-
	WT	674.75	674.73	674.71	674.60	674.57	674.57	674.55	674.53	674.52	-
	3.05	674.64	674.61	674.50	674.42	674.44	674.44	674.46	674.37	674.33	674.11
	6.10	674.55	674.55	674.42	674.39	674.44	674.39	674.36	674.35	674.28	674.15
	12.19	672.79	672.78	672.72	672.69	672.64	672.64	672.65	672.60	672.67	672.63
2	WT	674.32	674.32	674.23	674.17	674.23	674.25	674.23	674.24	674.20	674.12
	4.27	674.29	674.29	674.17	674.09	674.22	674.14	674.20	674.16	674.16	674.05
	7.32	674.18	674.20	674.20	674.17	674.14	674.17	674.17	674.08	674.05	674.04
	c	674.22	674.22	674.21	674.15	674.13	674.18	674.14	674.07	674.03	674.05
	13.41	672.55	672.55	672.55	672.53	672.52	672.55	672.55	672.61	672.57	672.55
3	WT	677.03	676.56	676.42	675.89	675.77	675.64	675.55	675.50	675.43	675.39
	5.18	676.51	676.43	676.30	675.34	675.34	675.34	675.35	675.35	675.34	675.32
	8.23	673.22	673.27	673.34	673.30	673.30	673.32	673.36	673.37	673.35	673.32
	14.33	672.26	672.25	672.28	672.25	672.24	672.26	672.26	672.25	672.26	672.26
	c	672.26	672.25	672.28	672.25	672.24	672.26	672.26	672.25	672.26	672.26
4	WT	644.26	644.13	644.07	644.01	644.03	644.00	643.99	643.99	643.98	643.98
	6.71	644.83	644.82	644.74	644.67	644.67	644.69	644.73	644.75	644.74	644.76
	12.80	645.54	645.45	645.41	645.35	645.17	645.19	645.20	645.21	645.21	645.23
	24.99	643.17	643.18	643.17	643.16	643.15	643.14	643.15	643.15	643.14	643.15
	c	643.12	643.12	643.12	643.12	643.12	643.42	643.12	643.13	643.14	643.15
5	WT	639.16	639.16	639.15	639.15	639.15	639.13	639.13	639.13	639.12	639.11
	4.57	639.19	639.18	639.24	639.17	639.28	639.22	639.19	639.14	639.11	639.07
	c	639.17	639.20	639.28	639.32	639.28	639.21	639.17	639.14	639.10	639.07
	7.62	638.55	638.58	638.60	638.59	638.61	638.60	638.57	638.59	638.59	638.58
	13.72	639.17	639.14	639.18	639.22	639.20	639.14	639.14	639.13	639.15	639.17
	c	639.16	639.16	639.20	639.22	639.18	639.14	639.14	639.13	639.15	639.17
6	WT	637.22	637.30	637.28	637.52	637.35	637.30	637.28	-	-	-
	1.83	637.20	637.25	637.25	637.25	637.28	637.25	637.24	637.23	637.22	-
	4.27	637.03	637.11	637.07	637.11	637.09	637.05	637.03	637.04	637.04	637.08
	6.10	637.46	637.47	637.47	637.49	637.44	637.42	637.43	637.42	637.42	637.42
	c	637.45	637.47	637.47	637.49	637.42	637.42	637.43	637.41	637.42	637.43
	12.19	-	-	637.18	637.17	637.16	637.16	637.17	637.16	637.17	637.18
	c	-	-	-	-	-	-	-	-	-	-
	24.38	637.82	637.82	637.82	637.77	637.77	637.77	637.79	637.79	637.80	637.81
	c	637.82	637.85	637.79	637.76	637.77	637.79	637.78	637.78	637.80	637.83
7	WT	637.52	637.51	637.49	637.46	637.44	637.43	637.42	637.40	637.39	637.37
	3.66	637.44	637.44	637.45	637.44	637.25	636.98	636.86	636.76	636.67	636.62
	6.71	636.68	636.69	636.71	636.71	636.75	636.76	636.77	636.78	636.77	636.77
	c	636.69	636.78	636.82	636.87	636.90	636.91	636.92	636.91	636.90	636.86
	12.80	636.60	636.59	636.57	636.55	636.54	636.53	636.54	636.53	636.53	636.54
	c	636.39	636.37	636.37	636.39	636.39	636.42	636.47	636.51	636.59	636.68
	24.99	636.03	636.05	636.04	636.04	636.04	636.03	636.04	636.04	636.04	636.05
	c	636.06	636.05	636.04	636.03	636.03	636.03	636.03	636.04	636.04	636.04
8	WT	-	-	633.05	633.01	632.96	632.94	632.87	632.83	632.76	632.70
	5.18(1)	633.37	633.50	633.57	633.65	633.71	633.65	633.54	633.43	633.31	633.15
	(2)	633.03	633.22	633.31	633.38	633.47	633.50	633.48	633.45	633.40	633.29
	(3)	632.91	633.09	633.15	633.25	633.32	633.37	633.37	633.37	633.35	633.27
	8.23	632.68	632.79	632.87	632.95	633.04	633.15	633.24	633.31	633.37	633.41
	c	632.77	632.96	633.06	633.17	633.27	633.36	633.44	633.48	633.49	633.46
	14.33	633.03	633.05	633.04	633.01	633.02	633.03	633.03	633.01	633.01	633.02
9	Slough	632.55	632.62	632.50	632.47	632.57	632.48	632.53	-	632.51	-
	WT	632.77	632.77	632.78	632.80	632.80	632.79	632.77	632.77	632.76	-
	2.44	632.75	632.81	632.82	632.82	632.81	632.77	632.69	632.63	632.58	632.49
	c	632.79	632.83	632.83	632.82	632.79	632.73	632.63	632.60	632.54	632.42
	6.10	632.80	632.92	632.96	632.99	632.99	632.95	632.90	632.84	632.77	632.68
	c	632.88	632.98	633.00	633.00	632.98	632.92	632.85	632.81	632.74	632.56
	12.19	632.65	632.62	632.62	632.65	632.60	632.60	632.61	632.63	632.66	632.69
	c	632.54	632.53	632.53	632.55	632.56	632.60	632.65	632.70	632.74	632.81
	24.38	-	-	-	-	-	-	-	-	632.81	632.81

(Continued)

SITE AND LEVEL m. a.m.s.l.	PIEZ. DEPTH m	HYDRAULIC HEADS metres above mean sea level									
		Dec. 18/72	Dec 31/72	Jan 13/73	Jan 27/73	Feb 10/73	Feb 26/73	Mar 13/73	Mar 27/73	Apr 10/73	Apr 24/73
1	Slough	-	-	-	-	-	-	-	673.58	673.79	[illegible]
	WT	-	-	-	673.83	673.75	673.63	673.55	673.56	673.60	[illegible]
	3.05	674.04	673.97	673.76	673.61	673.45	673.26	673.20	673.22	673.00	[illegible]
	6.10	674.11	674.11	673.87	673.71	673.58	673.41	673.47	673.35	673.00	[illegible]
	12.19	672.62	672.51	672.40	-	672.23	672.42	672.31	[illegible]	[illegible]	[illegible]
2	WT	674.08	674.00	673.92	673.83	673.80	-	[illegible]	-	-	-
	4.27	674.00	673.94	673.87	-	-	673.47	673.42	-	[illegible]	[illegible]
	7.32	674.04	674.01	673.76	-	-	-	673.71	-	673.61	[illegible]
	c	674.07	674.02	674.00	673.95	673.78	673.56	673.47	673.46	673.61	[illegible]
	13.41	672.55	672.54	672.50	672.47	672.38	672.29	672.31	672.25	672.22	672.31
3	WT	675.39	675.38	675.38	675.37	675.34	675.32	675.32	675.31	675.29	675.27
	5.18	675.33	675.33	675.33	675.32	675.32	675.32	675.32	675.32	675.31	676.24
	8.23	673.37	673.32	673.41	~~673~~.22	673.28	673.18	673.27	673.19	673.10	[illegible]
	14.33	672.26	672.28	672.26	672.26	672.26	672.26	672.30	672.30	672.30	672.28
	c	672.26	672.28	672.26	672.26	672.26	672.26	672.30	672.30	672.30	672.28
4	WT	643.98	643.99	644.00	643.99	643.99	644.01	644.02	644.04	644.62	644.23
	6.71	644.77	644.75	644.79	644.70	644.74	644.69	644.74	644.86	645.36	645.15
	12.80	645.24	645.23	645.23	645.21	645.18	645.18	645.19	645.27	644.88	645.64
	24.99	643.14	643.16	643.17	643.17	643.19	643.20	643.22	643.23	643.28	643.24
	c	643.16	643.17	643.20	643.22	643.25	643.27	643.26	643.26	643.25	643.27
5	WT	639.14	639.10	-	-	-	-	-	-	-	-
	4.57	639.06	639.04	639.05	639.04	639.04	639.06	639.04	639.06	639.05	639.06
	c	639.05	639.05	639.05	639.03	639.05	639.06	639.04	639.06	639.07	639.06
	7.62	638.59	638.63	638.61	638.62	638.65	638.68	638.71	638.75	638.6[illegible]	638.63
	13.72	639.20	639.21	639.24	639.27	639.27	639.29	639.32	639.32	639.32	639.30
	c	639.20	639.21	639.27	639.30	639.29	639.33	639.36	639.32	639.30	639.29
6	WT	-	-	-	-	-	-	-	-	637.4[illegible]	637.46
	1.83	-	-	-	-	-	-	-	-	-	637.21
	4.27	637.11	637.17	637.09	637.18	637.19	637.16	637.20	637.20	637.13	637.16
	6.10	637.43	637.43	637.43	637.44	637.44	637.45	637.57	637.49	637.50	637.48
	c	637.43	637.42	637.43	637.41	[illegible]	637.47	637.49	637.52	637.50	637.46
	12.19	637.20	637.21	637.21	637.21	637.21	637.21	637.22	637.22	637.23	637.22
	c	-	637.25	637.25	637.25	637.25	637.25	637.25	637.25	637.25	637.24
	24.38	637.82	637.84	637.84	637.84	637.85	637.84	637.89	637.89	637.91	637.90
	c	637.83	637.85	637.84	637.84	637.85	637.84	637.90	637.89	637.91	637.90
7	WT	637.37	636.63	636.64	636.58	636.63	636.70	-	-	-	636.69
	3.66	636.64	636.69	636.69	6[illegible]68	636.70	636.71	636.83	636.85	636.83	636.81
	6.71	636.78	636.78	636.78	-	636.77	-	636.81	636.80	636.80	636.81
	c	636.85	636.77	636.76	636.75	636.74	636.73	636.73	636.72	636.72	636.71
	12.80	636.55	636.57	636.67	636.61	636.62	636.64	636.67	636.68	636.68	636.68
	c	636.72	636.79	636.84	636.89	636.89	636.87	636.84	636.80	636.75	636.68
	24.99	636.04	636.05	636.05	636.05	636.05	636.06	636.07	636.07	-	636.07
	c	636.05	636.04	636.05	636.06	636.07	636.08	636.14	636.14	636.14	636.14
8	WT	632.68	632.65	632.63	632.57	632.53	632.51	632.48	632.59	632.43	632.40
	5.18(1)	633.09	633.02	632.92	632.86	632.75	632.68	632.68	632.61	632.58	632.57
	(2)	633.24	633.17	633.08	633.00	632.86	632.78	632.78	632.73	632.68	632.65
	(3)	633.22	633.19	633.13	633.06	632.95	632.87	632.86	632.80	632.77	632.71
	8.23	633.43	633.43	633.41	633.37	633.24	633.17	633.17	633.09	633.01	632.93
	c	633.43	633.37	633.32	633.25	633.16	633.06	632.98	632.89	632.81	632.73
	14.33	633.02	633.02	633.01	633.03	632.99	632.99	633.04	633.04	633.05	633.05
9	Slough	-	-	-	-	-	-	-	632.70	632.83	632.75
	WT	-	-	-	-	-	-	-	-	-	632.65
	2.44	632.42	632.34	632.26	632.16	632.06	631.96	631.92	631.90	631.85	631.82
	c	632.22	632.27	632.16	632.09	631.98	631.90	631.84	631.80	631.80	631.80
	6.10	632.60	632.49	632.34	632.25	632.13	632.08	632.01	631.99	631.93	631.89
	c	632.47	632.34	632.24	632.15	632.07	632.00	631.91	631.88	631.86	632.02
	12.19	632.73	632.76	632.78	632.78	632.80	632.73	632.67	632.60	632.60	632.53
	c	632.86	632.84	632.83	632.78	632.74	632.6[illegible]	632.55	632.44	632.37	632.31
	24.38	632.81	632.83	632.84	632.85	632.86	632.88	632.90	632.91	632.93	632.94

(Continued)

SITE AND LEVEL m. a.m.s.l.	PIEZ. DEPTH m.	HYDRAULIC HEADS metres above mean sea level									
		May 8/73	May 22/73	Jun 5/73	Jun 19/73	Jul 3/73	Jul 17/73	Jul 31/73	Aug 17/73	Sep 1/73	[illegible] 15/73
1	Slough	674.77	674.69	674.58	674.72	674.73	674.72	674.74	674.93	674.93	[illegible]
	WT	673.89	674.06	674.13	674.18	674.26	674.28	674.30	674.32	674.35	674.35
	3.05	674.49	674.53	674.27	674.52	674.61	674.38	674.45	674.72	674.73	674.67
	6.10	674.59	674.51	674.38	674.66	674.40	674.46	674.53	674.85	674.80	674.80
	12.19	672.52	672.58	672.58	672.70	672.75	672.74	672.75	672.91	673.00	673.00
2	WT	674.28	674.40	674.31	674.57	674.54	674.41	674.42	674.77	674.71	674.67
	[illegible]	674.46	674.37	674.25	674.57	674.49	674.36	674.45	674.75	[illegible]	[illegible]
	[illegible]	673.82	673.97	674.04	674.08	[illegible]	674.27	674.29	674.37	674.48	[illegible]
	c	674.25	674.26	674.17	674.22	[illegible]	674.39	674.40	[illegible]	674.55	[illegible]
	13.41	672.40	672.51	672.55	672.67	672.71	672.72	672.74	672.87	672.98	[illegible]
3	WT	677.80	677.49	677.06	676.76	677.03	676.81	676.61	677.47	677.22	[illegible]
	5.18	676.52	676.49	676.34	676.28	676.33	676.34	676.30	676.39	676.42	676.35
	8.23	673.13	673.11	673.09	673.10	673.16	673.19	673.27	673.44	673.55	673.34
	14.33	672.28	672.32	672.32	672.33	672.38	672.40	672.42	672.42	[illegible]	[illegible]
	c	672.28	672.33	672.35	672.43	672.47	672.48	672.48	672.57	672.57	[illegible]
4	WT	644.46	644.62	644.69	644.66	644.74	644.77	644.71	644.85	[illegible]	[illegible]
	6.71	645.51	645.45	645.54	645.44	645.58	645.40	645.26	645.65	645.63	645.53
	12.80	645.75	645.75	645.66	645.66	645.86	645.80	645.71	645.91	646.00	645.99
	24.99	643.23	643.22	643.20	643.20	643.23	643.23	643.23	[illegible]	643.25	643.25
	c	643.21	643.19	643.18	643.20	643.23	643.22	643.22	[illegible]	643.26	643.25
5	WT	-	639.37	639.27	639.27	639.46	639.37	639.36	639.56	639.60	[illegible]
	4.57	639.06	639.07	639.07	639.07	639.13	639.17	639.17	639.18	639.24	639.29
	c	639.06	639.07	639.07	639.08	639.23	639.21	639.19	639.22	639.30	639.33
	7.62	638.71	638.72	638.61	638.59	638.74	638.57	638.54	638.67	638.80	638.70
	13.72	639.29	639.25	639.22	639.21	639.24	639.21	639.18	[illegible]9.20	639.21	639.16
	c	639.29	639.23	639.20	639.23	639.23	639.19	639.18	639.21	639.20	639.14
6	WT	637.46	637.43	637.22	637.28	[illegible]	637.22	637.29	637.51	637.55	637.48
	1.83	637.20	637.19	637.20	637.20	637.37	637.31	637.24	637.45	637.53	637.52
	4.27	637.20	637.18	637.03	637.17	637.18	637.10	637.13	637.28	637.32	637.28
	6.10	637.48	637.49	637.48	637.48	637.49	637.48	637.49	637.49	637.50	637.51
	c	637.49	637.49	637.48	637.48	637.46	637.48	637.49	637.49	637.50	637.51
	12.19	637.22	637.21	637.21	637.22	[illegible]	637.22	637.23	637.26	637.26	637.23
	c	637.21	637.20	637.18	637.19	637.23	637.22	637.26	637.29	637.25	637.21
	24.38	637.91	637.92	637.91	637.91	637.91	637.86	637.79	637.79	637.82	637.82
	c	637.91	637.92	637.89	637.91	637.89	637.81	637.76	637.81	637.82	637.83
7	WT	636.70	636.90	637.13	637.30	637.39	637.46	637.52	637.58	637.57	637.49
	3.66	636.99	637.05	637.20	637.37	637.47	637.54	637.61	637.67	637.67	637.58
	6.71	636.82	636.77	636.75	636.78	636.76	636.75	636.75	636.75	636.76	636.76
	c	636.70	636.69	636.69	636.69	636.72	636.70	636.71	636.75	636.83	636.85
	12.80	636.68	636.68	636.64	636.64	636.64	636.63	636.61	636.59	636.57	636.56
	c	636.64	636.59	636.56	636.51	636.40	636.45	636.42	636.37	636.16	636.63
	24.99	636.07	636.10	636.10	636.10	636.12	636.12	636.13	636.12	636.12	636.12
	c	636.09	636.10	636.11	636.12	636.14	636.14	636.13	636.12	636.11	636.41
8	WT	632.41	632.45	632.53	632.62	632.74	632.96	633.10	633.50	633.85	633.85
	5.19(1)	632.56	632.60	632.70	632.91	633.10	633.34	633.54	633.80	634.01	634.12
	(2)	632.61	632.61	632.63	632.73	632.84	632.98	633.15	633.40	633.59	633.74
	(3)	632.65	632.65	632.64	632.70	632.77	632.91	633.03	633.22	633.40	633.54
	8.23	632.83	632.76	632.68	632.68	632.66	632.66	632.67	632.72	632.82	632.92
	c	632.66	632.61	632.59	632.59	632.61	632.67	632.73	632.86	632.96	633.04
	14.33	633.05	633.05	633.04	633.16	633.16	633.16	633.16	633.15	633.14	633.14
9	Slough	632.73	632.63	632.42	632.77	632.81	632.66	632.66	632.81	632.76	632.73
	WT	632.64	632.52	632.48	632.48	632.48	632.51	632.55	632.60	632.66	-
	2.44	631.83	631.88	631.98	632.14	632.30	632.42	632.60	632.74	632.87	633.00
	c	631.86	631.96	632.10	632.27	632.45	632.62	632.76	632.92	633.06	633.00
	6.10	631.95	631.94	632.03	632.28	632.44	632.54	632.67	632.90	632.98	633.03
	c	632.07	632.15	632.22	632.45	632.51	632.63	632.87	633.07	633.07	633.02
	12.19	632.48	632.43	632.38	632.36	632.36	632.37	632.38	632.39	632.41	632.44
	c	632.28	632.27	632.28	632.31	632.36	632.41	632.43	632.45	632.49	632.55
	24.38	632.95	632.97	632.97	632.98	632.98	632.98	633.00	633.02	633.03	633.04

SITE AND LEVEL m. a.m.s.l.	PIEZ. DEPTH m.	HYDRAULIC HEADS metres above mean sea level
		Sep 25/73
1	Slough	-
	WT	-
	3.05	-
	6.10	-
	12.19	-
2	WT	-
	4.27	-
	7.32	-
	c	-
	13.41	-
3	WT	-
	5.18	-
	8.23	-
	14.33	-
	c	-
4	WT	-
	6.71	-
	12.80	-
	24.99	-
	c	-
5	WT	-
	4.57	-
	c	-
	7.62	-
	13.72	-
	c	-
6	WT	-
	1.83	-
	4.27	-
	6.10	-
	c	-
	12.19	-
	c	-
	24.38	-
	c	-
7	WT	-
	3.66	-
	6.71	-
	c	-
	12.80	-
	c	-
	24.99	-
	c	-
8	WT	633.88
	5.18(1)	634.12
	(2)	-
	(3)	-
	8.23	-
	c	-
	14.33	-
9	Slough	-
	WT	-
	2.44	632.88
	c	632.78
	6.10	632.86
	c	632.79
	12.19	-
	c	-
	24.38	-

Appendix 10. Hydraulic heads at supplementary study sites given by sloughs, and piezometers terminating at depths indicated (F=frozen).

SITE AND LEVEL	PIEZ. DEPTH	HYDRAULIC HEAD (metres above mean sea level) Jul [illegible]	Jul [illegible].71	Jul [illegible]	Jul 28.71	Aug [illegible].71	Aug 18.71	Aug [illegible].71	Sep [illegible].71	Sep [illegible].71	Oct [illegible].71	Oct [illegible].71	[illegible]
[illegible]	1.[illegible]				-	-	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]		[illegible]	648.[illegible]	648.17	648.1[illegible]	648.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]							Dry	Dry	Dry	Dry	[illegible]	[illegible]
	[illegible]												
	[illegible]							[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	Dry	Dry	Dry	Dry	Dry	Dry	[illegible]	[illegible]	[illegible]		
	[illegible]	[illegible]	[illegible]	[illegible]	6[illegible].8[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
	[illegible]												
[illegible]	1.[illegible]				[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible].71	[illegible]	[illegible]	[illegible]
	[illegible]				[illegible]	[illegible].71	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible].8	[illegible]

SITE AND LEVEL	PIEZ. DEPTH	HYDRAULIC HEAD (metres above mean sea level) Nov [illegible]	Dec [illegible]	Dec [illegible].71	Dec [illegible].71	Jan 19.72	Jan [illegible].72	Feb [illegible].72	Feb [illegible].72	Mar [illegible].72	Mar [illegible].72	Apr [illegible].72	Apr [illegible]
[illegible]	[illegible]	[illegible]	[illegible]	F	F	F	F	F	F	F	F	F	F
	[illegible]	[illegible]	[illegible]	F	F	F	F	F	F	F	F	F	F
[illegible]	Slough	Dry	Dry		-	-	-	-	-	-	-	-	-
	[illegible]				-		-	-	-	-	-	-	-
	[illegible]	[illegible]	[illegible]	[illegible]	647.16	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	647.07	[illegible]	[illegible]
[illegible]	Slough	Dry	Dry		-	-	-	-	-	-	-	-	-
	[illegible]	[illegible]	[illegible]	Dry	Dry	-	-	-	-	-	-	-	[illegible]
	[illegible]				-	-	-	-	-	-	-	-	-
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	-	-	-	-
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	-	[illegible]	[illegible]

SITE AND LEVEL	PIEZ. DEPTH (m)	HYDRAULIC HEADS (metres above mean sea level) May 16.72	May [illegible].72	Jun [illegible].72	Jun 20.72	Jul [illegible].72	Jul 18.72	Jul 26.72	Aug 15.72	Aug 27.72	Sep 12.72	Sep 26.72	Oct [illegible].72
[illegible]	1.5[illegible]	[illegible]	637.8[illegible]	637.[illegible]	637.92	637.87	637.8[illegible]	-	637.[illegible]	637.[illegible]	637.[illegible]	637.56	-
	[illegible]	[illegible]	[illegible]	[illegible]	638.0[illegible]	638.02	638.[illegible]	-	638.06	638.0[illegible]	638.[illegible]	638.05	-
[illegible]	Slough	[illegible]	[illegible]	638.[illegible]	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry
	2.1[illegible]		-	-	-	-	-	-	-	-	-	636.86	-
	[illegible].88	[illegible]	[illegible].37	637.17	637.17	637.16	637.16	637.15	637.11	637.11	637.1[illegible]	637.[illegible]	-
[illegible]	Slough	[illegible]	[illegible]	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry
	1.8[illegible]	[illegible]	[illegible]	635.[illegible]	635.[illegible]	635.65	635.[illegible]8	[illegible]	635.18	635.23	635.23	635.22	-
	[illegible].18	-	-	-	-	-	-	-	-	-	-	-	-
[illegible]	1.[illegible]	[illegible].81	[illegible].8[illegible]	[illegible].87	[illegible]	[illegible].98	[illegible].00	[illegible].05	[illegible].16	[illegible].17	[illegible].21	[illegible].26	-
	[illegible].88	[illegible]	[illegible]	[illegible].06	[illegible].10	[illegible].20	[illegible].47	[illegible].64	[illegible].69	[illegible].76	[illegible].87	[illegible].96	-

(Continued)

SITE AND LEVEL #	PIEZ. DEPTH (m)	Oct [illegible]/72	Nov 6/72	~~Nov~~ [illegible]	Dec [illegible]/72	Dec 18/72	Dec [illegible]/72	Jan [illegible]/73	Jan [illegible]/73	Feb 10/73	Feb 26/73	Mar 13/73	Mar [illegible]
		HYDRAULIC HEADS (metres above mean sea level)											
[illegible]	[illegible]	[illegible]	-	[illegible]	-	637.81	F	F	F	F	F	F	F
	[illegible]	638.[illegible]	-	638.02	-	638.04	F	F	F	F	F	F	F
[illegible]	[illegible]	Dry	Dry	Dry	-		-		-		-		-
	[illegible]	[illegible]	-	[illegible]	-	[illegible]	-	[illegible]	-	[illegible]	-	[illegible]	-
	[illegible]	[illegible]	-	[illegible]	-	[illegible]	-	[illegible]	-	[illegible]	-	[illegible]	-
[illegible]	[illegible]	Dry	Dry	Dry			-		-		-		-
	[illegible]	[illegible]		[illegible]		[illegible]	-		-		-		-
	[illegible]	[illegible]		F	-	F		F	-	F		-	
	[illegible]	[illegible]		[illegible]		[illegible]		[illegible]	-	[illegible]			

SITE AND LEVEL #	PIEZ. DEPTH (m)	A[illegible]	A[illegible]	May [illegible]	May [illegible]	Jun [illegible]	Jun 14/73	Jul [illegible]/73	Jul 17/73	Jul [illegible]/73	Aug 17/73	Sep [illegible]/73	Sep 14/73
		HYDRAULIC HEADS (metres above mean sea level)											
[illegible]	[illegible]	F	F		[illegible]	-	[illegible]	-	[illegible]	-	[illegible]	-	638.21
	[illegible]	F	F	[illegible]	[illegible]		[illegible]	-	[illegible]	-	[illegible]	-	638.37
[illegible]	[illegible]		[illegible]				[illegible]	-	[illegible]	-	638.61	-	-
	[illegible]		[illegible]	[illegible]	[illegible]		[illegible]	-	[illegible]	-	[illegible]	-	[illegible]
	[illegible]		[illegible]		[illegible]		[illegible]	-	[illegible]	-	637.31	-	[illegible]
[illegible]	[illegible]			-	[illegible]		[illegible]	-	[illegible]	-	[illegible]	-	-
	[illegible]	[illegible]		-	[illegible]	-	[illegible]	-	[illegible]	-	-	-	-
	[illegible]	[illegible]	-	-	[illegible]	-	[illegible]	-	[illegible]	-	-	-	-
	[illegible]	F	[illegible]	-	[illegible]	-	[illegible]	-	[illegible]	-	[illegible]	-	633.72
	[illegible]	[illegible]	[illegible]		[illegible]	-	[illegible]		[illegible]	-	633.78	-	[illegible]

Appendix 11. Moistures between 20 cm and 250 cm depth derived from neutron probe readings. Values missing are mainly at or below the water table.

SITE	DEPTH	MOISTURE percent by volume																							
	cm	Oct. 27,71	Nov [illegible],71	Dec 20,71	Jan [illegible] 72	Feb [illegible] 72	Mar [illegible] 72	Apr [illegible] 72	Apr 26,72	May 10,72	May [illegible] 72	Jun [illegible] 72	Jun 20,72	Jul [illegible] 72	Jul 18,72	Jul 26,72	Aug [illegible] 72	Aug [illegible] 72	Sep 12,72	Sept [illegible] 72	Oct [illegible]	Nov [illegible]	Dec [illegible]	Dec [illegible]	Jan [illegible]
1	20	10.7	[illegible]	16.3	17.0	[illegible]	[illegible]	18.5	-	-	-	-	-	[illegible]	-	-	[illegible]	-	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	30	27.9	10.1	[illegible]	17.1	18.6	18.5	19.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18.6	18.6	16.8
	50	23.6	26.2	12.7	12.6	12.6	[illegible]	12.4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	20.6
	100	-	-	15.7	[illegible]	58.7	48.5	[illegible]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	150	-	-	[illegible]	-	-	-	[illegible]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	20	20.0	[illegible]	[illegible]	24.9	26.2	25.8	26.6	29.9	29.1	27.8	18.5	[illegible]	22.7	[illegible]	[illegible]	25.8	18.8	[illegible]	[illegible]	[illegible]	[illegible]	25.8	25.7	24.8
	30	19.4	21.2	23.0	23.6	24.3	24.0	24.5	28.1	28.7	27.6	21.2	18.0	19.8	[illegible]	21.1	[illegible]	[illegible]	21.8	[illegible]	[illegible]	[illegible]	25.1	25.4	[illegible]
	50	20.3	21.4	21.7	24.2	25.1	25.3	25.7	26.4	25.9	25.3	24.0	22.8	21.8	22.8	21.8	25.7	[illegible]	[illegible]	[illegible]	[illegible]	27.1	27.6	[illegible]	27.9
	100	22.4	22.3	21.8	23.6	25.2	25.7	26.4	29.8	24.5	27.7	27.1	27.1	25.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	26.1	[illegible]	11.5	[illegible]
	150	22.8	18.8	20.3	24.8	12.0	12.4	11.5	[illegible]	12.8	-	12.1	30.8	[illegible]	[illegible]	[illegible]	[illegible]	28.6	27.7	[illegible]	[illegible]	27.8	[illegible]	25.1	[illegible]
	200	30.0	21.4	17.6	12.3	9.5	9.4	9.6	14.6	-	-	-	-	-	-	-	-	12.1	-	-	-	-	-	-	-
3	20	24.4	25.5	27.4	29.7	29.8	[illegible]	30.2	[illegible]	38.1	17.5	32.5	25.9	21.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	27.1	26.7
	30	21.5	20.3	24.2	21.6	25.6	[illegible]	26.3	41.2	12.7	12.4	28.4	23.8	21.5	20.5	[illegible]	[illegible]	18.7	[illegible]	[illegible]	[illegible]	[illegible]	18.6	[illegible]	[illegible]
	50	20.9	21.3	23.2	22.7	21.2	27.6	24.6	36.2	10.8	10.6	27.4	24.1	22.0	21.1	[illegible]	21.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	17.8
	100	27.2	27.2	29.0	31.5	12.7	31.8	14.5	[illegible]	19.7	11.3	12.8	12.0	11.1	[illegible]	[illegible]	30.1	[illegible]	[illegible]	[illegible]	[illegible]	28.5	[illegible]	[illegible]	30.5
	150	26.0	26.1	26.0	24.9	21.6	34.0	25.0	-	-	12.1	11.7	12.4	-	[illegible]	29.6	[illegible]	27.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	26.7	25.1
	200	23.5	23.1	21.8	24.3	[illegible]	21.5	24.7	-	-	-	-	-	-	[illegible]	29.5	28.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	24.4	25.2	[illegible]
	250	-	-	28.7	27.8	[illegible]	26.5	28.2	-	-	-	-	-	-	-	-	-	-	-	-	[illegible]	29.2	28.1	[illegible]	29.1
4	20	10.7	15.3	17.3	15.9	18.0	[illegible]	44.0	36.9	14.2	10.2	19.9	14.8	16.5	[illegible]	[illegible]	[illegible]	16.7	15.5	[illegible]	[illegible]	21.7	21.7	[illegible]	21.6
	30	9.2	10.6	11.9	10.6	10.3	14.9	63.6	12.4	29.4	24.8	19.8	14.0	11.1	12.1	[illegible]	22.8	14.8	[illegible]	[illegible]	[illegible]	[illegible]	11.9	[illegible]	14.8
	50	9.1	9.4	9.9	8.4	8.4	12.0	10.3	21.9	22.6	20.0	19.1	16.7	15.4	12.8	[illegible]	12.0	11.2	[illegible]	[illegible]	[illegible]	[illegible]	11.7	12.4	12.8
	100	16.4	16.4	16.9	16.6	17.7	22.3	21.8	24.1	21.5	21.2	24.3	21.4	22.2	[illegible]	[illegible]	[illegible]	20.1	[illegible]	[illegible]	[illegible]	19.6	19.5	18.8	19.6
	150	19.8	20.0	20.6	18.9	18.6	21.0	20.6	22.8	22.7	21.2	21.8	21.4	22.5	22.1	22.1	[illegible]	[illegible]	[illegible]	21.5	20.7	20.8	20.6	20.8	20.6
	200	22.3	22.5	22.7	21.2	21.3	[illegible]	[illegible]	25.2	-	-	-	-	[illegible]	25.1	25.1	[illegible]	24.7	[illegible]	[illegible]	[illegible]	[illegible]	25.3	[illegible]	25.1
	250	25.7	25.1	26.9	[illegible]	26.0	27.0	-	-	-	-	-	-	-	-	-	28.9	28.1	[illegible]	[illegible]	[illegible]	27.1	27.8	28.1	[illegible]
5	20	9.8	10.0	12.2	10.6	12.8	13.1	15.2	16.0	24.6	19.7	9.2	[illegible]	12.5	[illegible]	[illegible]	[illegible]	12.1	11.0	[illegible]	[illegible]	[illegible]	19.0	[illegible]	18.8
	30	10.0	10.6	12.6	11.8	13.3	14.3	11.9	21.9	21.7	20.3	14.2	[illegible]	12.7	12.1	[illegible]	22.5	15.7	10.6	[illegible]	15.2	[illegible]	16.5	16.1	16.7
	50	12.6	13.5	15.5	15.1	17.9	17.2	25.9	18.4	17.8	18.0	17.1	17.3	16.1	14.8	14.8	[illegible]	[illegible]	[illegible]	[illegible]	17.1	17.0	17.9	[illegible]	17.7
	100	20.0	19.1	30.0	19.5	19.1	21.5	-	-	18.0	18.0	19.1	18.9	18.5	18.1	17.9	20.6	19.7	[illegible]	[illegible]	19.2	19.5	19.7	19.6	19.5
	150	22.2	21.0	26.0	24.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	20	-	-	-	-	-	-	-	-	-	-	-	16.1	21.7	15.8	17.7	-	[illegible]	-	-	-	-	-	-	-
	30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	20	20.3	20.4	22.1	22.4	24.3	24.2	24.1	29.1	29.5	28.4	22.8	19.1	22.9	19.7	[illegible]	[illegible]	17.5	[illegible]	[illegible]	[illegible]	22.8	25.1	25.2	[illegible]
	30	24.0	23.2	22.1	22.5	23.1	24.3	24.5	24.5	25.8	25.5	24.9	22.1	22.5	21.6	21.9	22.9	19.6	21.1	[illegible]	[illegible]	21.5	[illegible]	23.8	23.1
	50	-	-	24.2	25.8	24.6	27.4	26.8	22.9	23.6	23.5	23.5	23.1	22.5	22.0	[illegible]	22.7	[illegible]	22.2	[illegible]	22.1	21.9	24.5	[illegible]	23.9
	100	-	-	-	-	-	-	-	-	-	21.2	22.2	22.6	21.7	[illegible]	21.9	22.1	[illegible]	21.1	21.8	21.5	21.0	[illegible]	21.5	21.5
8	20	8.4	10.0	11.5	10.3	10.6	12.3	13.0	11.8	29.9	25.8	14.5	10.1	11.2	10.1	10.8	21.1	10.6	10.5	9.7	15.5	16.7	17.0	17.0	17.1
	30	8.2	8.1	8.4	8.2	8.2	8.8	9.2	27.3	25.2	22.1	18.9	9.3	8.9	8.6	8.8	12.5	9.1	8.5	[illegible]	[illegible]	9.7	9.8	[illegible]	9.7
	50	9.9	9.6	10.8	11.0	10.5	10.6	12.0	30.7	28.8	26.9	21.7	16.0	14.3	12.6	11.7	12.2	12.2	11.0	10.8	11.1	10.8	11.0	12.0	11.0
	100	16.5	15.7	18.0	16.8	16.3	18.8	18.0	[illegible]	19.7	20.0	19.2	19.1	18.7	18.7	18.6	[illegible]	19.1	17.7	[illegible]	18.5	[illegible]	17.6	18.1	18.5
	150	21.3	21.4	21.4	20.6	21.5	24.8	24.7	26.1	23.4	23.0	21.0	22.7	23.4	[illegible]	[illegible]	22.9	[illegible]	22.8	[illegible]	[illegible]	22.8	22.6	22.3	[illegible]
	200	25.3	25.4	25.7	25.5	24.8	26.2	25.9	-	-	-	-	26.9	26.2	[illegible]	[illegible]	27.0	29.2	27.1	[illegible]	[illegible]	[illegible]	27.2	[illegible]	26.6
9	20	-	-	-	-	-	-	-	51.6	47.0	34.8	31.3	25.3	30.1	[illegible]	[illegible]	27.2	20.9	22.8	[illegible]	[illegible]	26.6	27.7	[illegible]	[illegible]
	30	-	-	-	-	-	-	-	-	-	43.2	-	16.9	-	-	-	-	-	-	-	-	-	[illegible]	[illegible]	16.3

(Continued)

MOISTURE percent by volume

SITE	DEPTH cm	Feb 26/73	Mar 27/73	Apr 10/73	Apr 24/73	May 8/73	May 22/73	Jun 5/73	Jun 19/73	Jul 3/73	Jul 17/73	Jul 31/73	Aug 17/73	Sep 1/73
1	20	37.6	19.7	-	-	-	25.9	21.1	24.8	21.2	20.5	21.3	-	-
	30	36.9	38.1	-	-	-	41.5	25.1	33.5	30.6	25.4	27.3	-	-
	50	28.0	30.8	-	-	-	-	18.4	50.2	50.2	-	51.8	-	-
	100	-	-	-	-	-	-	-	-	-	-	-	-	-
	150	-	-	-	-	-	-	-	-	-	-	-	-	-
2	20	25.2	26.2	30.0	27.6	27.9	23.5	18.8	28.8	28.1	21.9	26.0	27.4	27.4
	30	25.2	25.2	30.6	27.2	28.0	27.2	22.2	29.2	27.8	24.5	26.4	27.6	27.6
	50	26.9	27.6	34.1	26.6	26.8	27.1	24.9	29.1	27.8	27.1	27.8	28.9	28.2
	100	34.4	34.8	37.5	36.9	31.8	28.9	29.0	30.1	28.9	28.9	28.7	31.2	30.7
	150	32.6	33.8	31.2	33.0	32.8	30.2	29.3	-	-	30.2	29.9	-	-
	200	14.4	12.6	16.2	27.3	-	-	-	-	-	-	-	-	-
3	20	25.9	28.2	41.0	32.9	34.7	32.3	25.8	38.4	36.6	30.7	36.6	38.2	37.5
	30	19.0	19.4	33.5	24.7	26.5	25.7	24.0	33.2	31.0	28.2	30.5	31.6	31.9
	50	17.9	18.2	25.3	24.9	19.2	36.3	18.5	28.2	25.9	23.6	24.7	28.1	27.6
	100	29.3	30.8	30.5	30.3	29.9	29.0	[illegible]	29.9	29.8	28.5	30.2	31.2	31.3
	150	28.3	29.0	30.2	28.5	-	33.9	31.8	31.4	31.7	30.3	30.6	31.6	32.0
	200	24.4	25.0	24.8	24.0	-	-	-	-	-	-	-	-	-
	250	27.1	27.8	27.7	27.9	-	-	-	-	-	-	-	-	-
4	20	21.8	37.5	49.8	31.0	30.6	23.3	14.8	36.1	32.2	19.4	30.0	35.2	15.0
	30	14.7	30.9	45.4	24.1	24.3	19.8	13.1	32.0	26.7	16.4	20.9	29.8	29.0
	50	13.2	19.2	20.5	16.8	17.6	16.7	12.5	23.1	20.4	16.5	14.7	37.2	22.2
	100	22.0	23.2	21.4	20.2	20.2	22.0	21.0	21.3	22.2	21.7	21.2	22.1	23.4
	150	20.2	20.9	20.4	20.7	21.0	23.3	22.7	22.1	21.9	22.5	22.6	23.1	24.5
	200	25.1	25.4	24.0	25.0	25.3	-	-	-	-	-	-	-	-
	250	27.3	28.7	-	-	-	-	-	-	-	-	-	-	-
5	20	17.5	28.4	24.0	23.1	25.4	12.8	8.4	33.4	27.7	14.2	22.4	-	-
	30	15.9	19.5	20.9	49.4	22.1	17.0	11.8	36.7	30.0	22.4	23.5	-	-
	50	17.6	17.6	17.2	16.8	17.0	17.3	15.0	29.4	28.2	25.2	26.0	-	-
	100	19.4	19.5	19.3	17.8	17.7	17.9	18.1	23.6	24.1	23.9	24.6	-	-
	150	-	-	-	-	-	-	-	-	-	-	-	-	-
6	20	-	-	-	-	-	-	-	-	-	-	-	-	-
	30	-	-	-	-	-	-	-	-	-	-	-	-	-
7	20	24.3	32.8	25.0	24.7	28.2	23.9	18.3	30.8	27.4	20.4	21.0	30.8	-
	10	24.0	26.4	23.0	23.1	23.8	23.2	21.1	26.8	25.8	22.8	21.6	26.0	-
	50	25.0	24.2	23.0	21.8	21.8	21.8	21.4	27.6	24.8	24.4	24.6	24.7	-
	100	21.5	22.0	22.3	21.2	20.7	21.0	20.7	33.2	23.1	22.5	22.8	22.6	-
8	20	17.1	21.4	24.2	24.9	28.6	18.9	10.6	34.6	29.2	20.5	25.6	32.7	30.5
	30	10.1	10.7	14.8	17.0	21.9	16.3	10.3	29.1	24.2	18.4	18.7	27.2	24.7
	50	11.8	11.5	11.9	11.7	12.7	12.4	11.9	25.5	25.0	22.4	21.0	27.3	24.9
	100	19.1	18.4	19.0	17.6	17.6	17.1	17.1	17.1	16.7	16.0	16.5	16.8	17.4
	150	23.8	23.8	24.4	24.2	22.8	22.3	22.6	22.8	22.2	22.0	22.2	22.7	23.3
	200	26.6	-	26.3	25.7	-	-	-	-	26.4	25.4	26.6	27.3	-
9	20	28.9	28.0	31.3	30.2	30.3	24.7	18.9	34.4	32.6	25.3	28.3	32.8	32.2
	30	37.4	37.0	38.5	-	33.6	12.9	31.5	37.8	35.9	15.1	34.1	38.2	39.2

Appendix 12. Moisture at 10 cm depth between April and November derived from Neutron Probe readings.

DATE	SITES 1	2	3	4	5	6	7	8	9
1971									
Oct 27	31.7	21.2	20.7	13.3	7.2	-	17.6	12.1	-
Nov 23	32.7	21.2	20.8	13.4	7.3	-	17.7	12.2	-
1972									
May 10	-	24.1	37.4	23.4	27.1	-	27.9	30.8	47.4
May 23	-	23.6	36.2	18.8	18.9	-	24.9	26.4	39.8
Jun 6	-	11.6	28.6	9.6	4.7	-	11.4	10.4	38.1
Jun 20	-	11.9	22.2	6.5	4.2	-	9.7	7.8	21.6
Jul 3	-	21.2	26.7	14.4	17.3	-	23.8	14.7	30.0
Jul 18	25.6	18.1	24.5	8.2	6.2	-	13.1	8.9	21.2
Jul 26	23.7	23.5	24.9	13.7	12.0	-	20.3	12.7	26.8
Aug 15	24.2	25.8	32.2	21.1	25.6	-	22.2	23.1	23.1
Aug 27	21.4	21.3	24.6	9.2	7.0	-	9.3	8.5	14.1
Sep 12	23.2	17.1	19.5	9.6	7.8	-	12.6	13.4	23.3
Sep 26	31.3	23.4	32.2	31.8	24.2	-	24.6	21.3	26.6
Oct 10	23.3	19.5	30.6	27.0	17.9	-	18.3	17.5	22.7
Nov 6	26.6	23.0	29.8	27.0	23.7	-	20.8	25.3	27.7
1973									
Apr 10	-	24.4	43.0	53.0	25.4	-	22.5	28.5	34.1
Apr 24	-	24.2	36.3	34.9	25.8	-	23.9	28.4	33.8
May 5	-	23.2	36.2	36.7	27.3	-	27.9	31.6	33.4
May 22	-	16.7	35.3	23.2	17.5	-	18.4	18.4	20.9
Jun 6	-	10.4	22.3	5.4	13.0	-	10.4	7.8	14.2
Jun 19	-	24.4	47.7	25.9	39.3	-	33.6	37.7	39.7
Jul 3	-	23.3	45.8	24.9	27.9	-	25.5	34.8	40.1
Jul 17	-	16.3	34.0	13.7	7.1	-	12.1	20.7	22.9
Jul 31	-	21.1	47.4	25.7	23.5	-	24.6	29.6	27.7
Aug 17	-	21.2	50.8	27.4	-	-	32.1	38.2	36.8
Sep 9	-	23.0	51.1	25.3	-	-	-	36.8	33.9

Appendix 13. Matric moisture suctions obtained from tensiometers* (T), or from psychrometers where tensions exceeded 0.6 bars, compared with predictions from moisture (neutron probe) using pressure plate relationships. Bracketed psychrometer values are those calculated to take account of osmotic suctions in horizons with appreciable salinity. Missing observations are due to tensiometer and psychrometer failure, or flooding. Missing predictions are due to absence of either moisture tensions curves or neutron probe readings.

SITE	DEPTH cm	MATRIC SUCTIONS bars Oct 27 1971 Obs	 Oct 27 1971 Source	 Oct 27 1971 Pred	 May 23 1972 Obs	 May 23 1972 Source	 May 23 1972 Pred	 Jun 6 1972 Obs	 Jun 6 1972 Source	 Jun 6 1972 Pred	 Jun 20 1972 Obs	 Jun 20 1972 Source	 Jun 20 1972 Pred	 Jul 3 1972 Obs	 Jul 3 1972 Source	 Jul 3 1972 Pred
1	20	-	-	<0.1	-	-	-	-	-	-	-	-	-	-	-	-
	50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	20	-	-	>15	0.16	T	0.54	0.47	T	>15	4.4	P	>15	1.8	P	4.2
	50	1.6	P	6.0	0.22	T	0.59	0.12	T	1.2	2.0	P	1.9	5.0	P	3.0
	150	-	-	<0.05	0.019	T	-	0.025	T	<0.05	0.024	T	<0.05	0.024	T	<0.05
3	20	1.0	P	1.9	0.14	T	0.10	1.7	P	0.167	2.4	P	1.1	0.44	T	2.5
	50	-	-	1.7	0.15	T	0.11	0.36	T	0.23	0.27	T	0.52	0.36	T	1.1
	150	-	-	-	0.013	T	-	0.083	T	-	0.14	T	-	0.15	T	-
	250	-	-	-	-0.041	T	-	-0.027	T	-	-0.003	T	-	0.010	T	-
4	20	-	-	>15	0.18	T	0.10	4.8	P	3.3	7.0	P	>15	6.9	P	>15
	50	-	-	>15	0.25	T	0.49	0.31	T	0.69	0.46	T	2.1	0.30	T	4.3
	150	-	-	0.82	0.021	T	0.77	0.043	T	0.72	0.36	T	0.75	0.16	T	0.80
	250	-	-	0.54	-0.063	T	-	-0.070	T	-	-0.010	T	-	0.031	T	-
5	20	-	-	>15	-	-	6.4	(26)	P	>15	(29)	P	>15	(30)	P	>15
	50	-	-	>15	0.30	T	8.6	0.38	T	>15	0.35	T	>15	0.25	T	>15
	150	-	-	-	0.041	T	-	-0.067	T	-	0.026	T	-	0.041	T	-
6	20	-	-	-	0.017	T	-	0.044	T	-	-	-	1.5	-	-	0.23
	50	-	-	-	-0.011	T	-	0.14	T	-	0.10	T	-	0.049	T	-
7	20	10.5	P	>15	4.3	P	1.8	7.0	P	11.0	11.8	P	>15	14.7	P	12.6
	50	(4)	P	-	(4)	P	1.8	0.41	T	1.8	0.36	T	[illegible]	(21)	P	5.2
	150	-	-	-	0.075	T	-	0.20	T	-	0.42	T	-	0.23	T	-
	250	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	20	6.3	P	>15	12.6	P	0.12	10.2	P	4.3	10.8	P	>15	16.0	P	>15
	50	(8)	P	>15	(2)	P	0.23	(9)	P	0.38	(9)	P	>15	(12)	P	>15
	150	-	-	0.81	0.10	T	0.74	0.40	T	0.74	0.46	T	0.74	-	-	0.79
	250	-	-	-	0.059	T	-	0.19	T	-	0.49	T	-	0.17	T	-
9	20	-	-	-	0.036	T	<0.1	0.070	T	0.32	0.095	T	2.3	-	-	0.34
	50	-	-	-	0.019	T	-	0.061	T	-	0.072	T	-	-	-	-

* Tensiometer values are the geometric means of duplicate measurements. Psychrometer values were not replicated.

(Continued)

SITE	DEPTH cm	MATRIC SUCTIONS bars														
		Jul 18 1972			Jul 26 1972			Aug 15 1972			Aug 27 1972			Sept 12 1972		
		Obs	Source	Pred	Obs	Source	Pred	Obs	Source	Pred	Obs	Source	Pred	Obs	Source	Pred
1	20	0.021	T	-	-	-	-	0.010	T	0.1	0.017	T	-	0.026	T	0.30
	50	-0.013	T	-	0.037	T	-	-0.018	T	-	-0.005	T	-	-0.006	T	-
2	20	6.3	P	10.6	5.6	P	2.0	8.0	P	1.1	10.9	P	>15	17.8	P	>15
	50	7.4	P	1.9	6.5	P	1.3	6.5	P	0.63	13.9	P	2.1	10.8	P	2.4
	150	-	-	<0.05	0.029	T	<0.05	0.038	T	<0.05	0.042	T	<0.05	0.049	T	<0.05
3	20	0.15	T	3.2	0.34	T	0.17	0.16	T	0.23	1.3	P	1.5	0.11	T	>15
	50	-	-	1.6	-	-	1.6	-0.16	T	1.2	0.36	T	3.1	0.47	T	>15
	150	0.17	T	-	0.16	T	-	-	-	-	0.20	T	-	0.24	T	-
	250	0.087	T	-	0.090	T	-	0.11	T	-	0.12	T	-	0.102	T	-
4	20	12.5	P	>15	9.7	P	>15	1[illegible].6	P	0.10	11.3	P	>15	9.1	P	>15
	50	0.43	T	>15	0.49	T	>15	0.8	P	>15	2.2	P	>15	3.0	P	>15
	150	0.35	T	0.82	0.32	T	0.82	-	-	0.82	0.16	T	0.84	0.16	T	0.84
	250	0.063	T	-	0.054	T	-	0.040	T	0.16	0.046	T	0.23	0.058	T	0.44
5	20	(25)	P	>15	(30)	P	>15	(7)	P	1.2	(16)	P	>15	(15)	P	>15
	50	0.41	T	>15	0.26	T	>15	0.14	T	2.4	0.29	T	5.9	-	-	10.7
	150	0.026	T	-	-0.016	T	-	-0.007	T	-	-0.011	T	-	-0.009	T	-
6	20	0.088	T	1.7	0.095	T	0.89	0.018	T	-	0.10	T	2.7	0.098	T	-
	50	0.036	T	-	0.049	T	-	0.007	T	-	0.039	T	-	0.010	T	-
7	20	18.0	P	>15	19.8	P	>15	16.3	P	10.7	28.5	P	>15	29.0	P	>15
	50	(2)	P	6.2	(2)	P	5.6	(1)	P	4.9	0.35	T	5.6	(4)	P	5.8
	150	0.25	T	-	0.18	T	-	0.17	T	-	0.19	T	-	0.11	T	-
	250	-0.095	T	-	-0.10	T	-	-0.044	T	-	-0.077	T	-	-0.089	T	-
8	20	21.2	P	>15	21.8	P	>15	7.8	P	0.32	11.5	P	>15	25.1	P	>15
	50	(20)	P	>15	(8)	P	>15	(3)	P	>15	(4)	P	>15	(6)	P	>15
	150	0.30	T	0.81	0.31	T	0.79	0.26	T	0.75	0.29	T	0.79	0.28	T	0.76
	250	0.18	T	-	0.14	T	-	-	-	-	0.074	T	-	0.017	T	-
9	20	0.14	T	2.0	0.16	T	1.1	0.10	T	1.2	0.24	T	9.6	0.27	T	5.4
	50	0.067	T	-	0.098	T	-	0.078	T	-	0.14	T	-	0.15	T	-

(Continued)

SITE	DEPTH cm	MATRIC SUCTIONS, bars														
		Sep 26 1972			Oct 10 1972			Oct 24 1972			Apr 24 1973			May 8 1973		
		Obs	Source	Pred	Obs	Source	Pred	Obs	Source	Pred	Obs	Source	Pred	Obs	Source	Pred
1	20	0.043	T	<0.1	0.043	T	0.11	-	-	-	-	-	-	-	-	-
	50	-0.003	T	-	-0.022	T	-	-0.038	T	-	-	-	-	-	-	-
2	20	9.6	P	0.64	10.2	P	1.5	15.7	P	-	<1	P	0.58	-	-	0.53
	50	0.39	T	0.44	0.34	T	0.55	0.24	T	-	-	-	0.47	-	-	0.44
	150	0.059	T	<0.05	0.062	T	<0.05	0.057	T	-	-	-	<0.05	-	-	<0.05
3	20	0.13	T	1.3	0.15	T	0.98	0.33	T	-	<1	P	0.16	1.0	P	0.12
	50	0.15	T	5.8	0.31	T	7.6	0.18	T	-	<1	P	0.44	-	-	3.4
	150	0.15	T	-	0.26	T	-	0.35	T	-	-	-	-	-	-	-
	250	0.12	T	-	0.13	T	<0.05	0.17	T	-	-	-	0.07	-	-	-
4	20	9.9	P	1.6	2.7	P	1.3	9.2	P	-	<1	P	<0.1	1.2	P	<0.1
	50	-	-	>15	-	-	>15	-	-	-	-	-	2.0	-	-	1.4
	150	0.17	T	0.84	0.17	T	0.84	0.21	T	-	-	-	0.84	-	-	0.84
	250	0.034	T	0.18	0.050	T	0.31	0.063	T	-	-	-	-	-	-	-
5	20	(11)	P	>15	(7)	P	>15	(10)	P	-	(<1)	P	0.96	(<1)	P	0.40
	50	-	-	7.7	-	-	12.0	-	-	-	-	-	13.5	-	-	12.5
	150	0.008	T	-	0.011	T	-	0.038	T	-	-	-	-	-	-	-
6	20	0.036	T	-	0.094	T	-	0.048	T	-	-	-	-	-	-	-
	50	-0.031	T	-	0.065	T	-	0.006	T	-	-	-	-	-	-	-
7	20	30.7	P	6.5	21.1	P	10.7	25.3	P	-	11.9	P	6.9	7.7	P	1.9
	50	(3)	P	4.6	(1)	P	6.0	(1)	P	-	(<1)	P	6.6	(1)	P	6.6
	150	0.18	T	-	0.16	T	-	0.23	T	-	-	-	-	-	-	-
	250	-0.078	T	-	-0.051	T	-	-0.046	T	-	-	-	-	-	-	-
8	20	9.0	P	>15	-	-	2.6	14.0	P	-	-	-	0.13	-	-	<0.1
	50	(1)	P	>15	(3)	P	>15	-	-	-	(<1)	P	>15	(5)	P	>15
	150	0.28	T	0.45	0.12	T	0.73	0.24	T	-	-	-	0.60	-	-	0.76
	250	0.035	T	-	-0.13	T	-	-0.077	T	-	-	-	-	-	-	-
9	20	0.090	T	1.0	0.15	T	1.8	0.16	T	-	-	-	0.35	-	-	0.34
	50	0.13	T	-	0.10	T	-	0.14	T	-	-	-	-	-	-	-

(Continued)

SITE	DEPTH cm	MATRIC SUCTIONS bars														
		May 22 1973			Jun 5 1973			Jun 19 1973			Jul 3 1973			Jul 17 1973		
		Obs	Source	Pred	Obs	Source	Pred	Obs	Source	Pred	Obs	Source	Pred	Obs	Source	Pred
1	20	-	-	0.58	0.005	T	6.1	0.010	T	1.0	-0.017	T	2.2	0.046	T	8.3
	50	-	-	-	-0.025	T	<0.1	-0.050	T	<0.1	-0.013	T	<0.1	0.009	T	-
2	20	1	P	2.9	2.0	P	>15	<1	P	0.40	0.12	T	0.49	0.23	T	6.3
	50	-	-	0.41	-	-	0.84	<1	P	0.24	0.099	T	0.33	0.15	T	0.41
	150	-	-	<0.05	0.053	T	<0.05	0.000	T	-	0.035	T	-	0.064	T	<0.05
3	20	3.7	P	0.18	3.4	P	1.1	0.7	P	0.10	2.9	P	0.10	1.5	P	0.24
	50	2.3	P	0.10	1.9	P	4.6	0.044	T	0.20	0.050	T	0.33	0.048	T	0.65
	150	-	-	-	0.067	T	-	0.070	T	-	-0.044	T	-	0.049	T	-
	250	-	-	-	-0.031	T	-	0.030	T	-	-0.017	T	-	-0.015	T	-
4	20	0.5	P	0.64	6.5	P	>15	<1	P	<0.1	0.081	T	<0.1	4.9	P	4.4
	50	0.9	P	2.1	0.31	T	>15	0.21	T	0.18	0.6	P	0.42	0.19	T	2.4
	150	-	-	0.76	0.034	T	0.79	0.036	T	0.82	0.047	T	0.83	0.049	T	0.80
	250	-	-	-	-0.028	T	-	-0.004	T	-	-0.016	T	-	-0.019	T	-
5	20	(6)	P	>15	(30)	P	>15	(2)	P	<0.1	(2)	P	0.17	(6)	P	>15
	50	-	-	11.2	0.096	T	>15	0.063	T	0.14	0.072	T	0.22	0.083	T	0.62
	150	-	-	-	-0.004	T	-	-0.038	T	-	-0.050	T	-	-0.053	T	-
6	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	50	-	-	-	0.039	T	-	-0.034	T	-	-0.021	T	-	0.033	T	-
7	20	9.1	P	9.1	29.5	P	>15	0.11	T	0.65	4.1	P	2.6	14.9	P	>15
	50	(4)	P	6.6	(3)	P	7.6	(6)	P	1.0	(7)	P	2.5	(5)	P	2.8
	150	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	250	-	-	-	-0.080	T	-	-0.076	T	-	-0.074	T	-	-0.084	T	-
8	20	8.6	P	0.65	29.0	P	>15	<1	P	0.12	3.8	P	0.10	3.3	P	0.38
	50	(7)	P	>15	(1)	P	>15	0.052	T	0.34	0.000	T	0.39	0.005	T	0.93
	150	-	-	0.79	0.045	T	0.78	-0.011	T	0.76	-0.024	T	0.80	-	-	0.80
	250	-	-	-	0.021	T	-	0.026	T	-	0.036	T	-	0.060	T	-
9	20	-	-	2.9	0.078	T	>15	0.032	T	<0.1	0.063	T	0.12	0.085	T	2.3
	50	-	-	-	0.014	T	-	-0.002	T	-	0.021	T	-	0.049	T	-

(Continued)

SITE	DEPTH cm	MATRIC SUCTIONS bars								
		Jul 31 1973			Aug 17 1973			Sep 1 1973		
		Obs	Source	Pred	Obs	Source	Pred	Obs	Source	Pred
1	20	0.024	T	5.5	-	-	-	-	-	-
	50	-0.002	T	0.00	-	-	-	-	-	-
2	20	0.16	T	1.0	0.14	T	0.62	4.6	P	0.62
	50	0.032	T	0.32	0.033	T	0.45	-	-	0.30
	150	0.062	T	<0.1	0.001	T	-	-	-	-
3	20	3.3	P	0.10	2.1	P	0.10	1.6	P	0.10
	50	0.052	T	0.46	0.058	T	0.20	2.5	P	0.22
	150	0.052	T	-	0.036	T	-	-	-	-
	250	0.027	T	-	-0.030	T	-	-	-	-
4	20	1.3	P	<0.1	<1	P	<0.1	<1	P	<0.1
	50	0.14	T	6.5	0.11	T	0.35	1.1	P	0.23
	150	0.028	T	0.80	0.21	T	0.78	-	-	-
	250	-0.001	T	-	0.000	T	-	-	-	-
5	20	(10)	P	1.4	(<1)	P	-	[illegible]	P	-
	50	-	-	0.47	-	-	-	-	-	-
	150	-	-	-	-	-	-	-	-	-
6	20	-		-	-	-	-	-	-	-
	50	-0.027	T	-	-0.026	T	-	-	-	-
7	20	15.9	P	15	0.043	T	0.75	3.9	P	-
	50	(4)	P	2.6	0.07	T	2.6	(7)	P	-
	150	-	-	-	-	-	-	-	-	-
	250	-0.067	T	-	-0.071	T	-	-	-	-
8	20	<1	P	0.12	<1	P	0.10	<1	P	0.10
	50	0.26	T	1.6	0.17	T	0.21	(<1)	P	0.40
	150	0.027	T	0.80	-	-	0.77	-	-	-
	250	0.083	T	-	-0.071	T	-	-	-	-
9	20	0.082	T	0.76	0.049	T	0.11	-	-	0.15
	50	0.055	T	-	0.024	T	-	-	-	-

Appendix 14. Osmotic suctions (obs.) given by psychrometers at soil depths where matric suctions were by comparison small enough to be ignored, and osmotic suctions (calc.) calculated from neutron probe moisture and saturation extract salt contents assuming the salt content of the soil does not change.

DATE	OSMOTIC TENSIONS bars									
	Site 5 50 cm		Site 6 20 cm		Site 7 150 cm		Site 9 20 cm		Site 9 50 cm	
	obs.	calc.	obs.	calc.	obs.	calc.	obs.	calc.	obs.	calc.
1972										
May 23	-	9	-	-	2	-	13	-	13	-
Jun 6	14	9	3	-	3	-	12	9	12	-
Jun 20	13	10	4	3	9	-	12	10	10	-
Jul 3	15	10	4	3	6	-	7	9	12	-
Jul 18	11	11	8	3	5	-	10	10	15	-
Jul 26	11	11	9	3	7	-	9	10	12	-
Aug 15	3	7	10	-	4	-	9	10	10	-
Aug 27	2	8	10	4	4	-	13	13	16	-
Sep 12	3	9	11	-	10	-	14	11	13	-
Sep 26	1	8	2	-	10	-	11	9	2	-
Oct 10	4	9	7	-	10	-	-	10	12	-
1973										
Apr 24	6	9	-	-	-	-	12	8	-	-
May 8	4	9	-	-	-	-	12	9	-	-
May 22	7	9	-	-	9	-	8	11	-	-
Jun 6	10	10	-	-	10	-	13	14	-	-
Jun 19	6	5	-	-	4	-	7	8	-	-
Jul 3	6	6	-	-	13	-	17	8	-	-
Jul 17	7	6	-	-	10	-	14	11	-	-
Jul 31	7	6	-	-	9	-	12	10	-	-
Aug 17	6	-	-	-	7	-	6	8	-	-
Sep 1	3	-	-	-	-	-	8	8	-	-

Appendix 15. Thermocouple temperatures at different depths in the ground at the soil study sites. Missing values are due to delayed installation or in one instance to breakage of lead wires.

SITE	DEPTH cm	TEMPERATURE °C																			
		Oct 5/71	Oct 12/71	Oct 26/71	Nov 9/71	Nov 23/71	Dec 8/71	Dec 18/71	Dec 29/71	Jan 10/72	Jan 29/72	Feb 10/72	Feb 29/72	Mar 11/72	Mar 24/72	Apr 10/72	Apr 26/72	May 10/72	May 23/72	Jun 6/72	Jun 20/72
1	20	9.2	6.7	2.5	0.0	0.7	0.0	-5.3	-3.2	-3.8	-5.3	-3.2	-6.1	-6.8	-1.1	-1.6	0.5	8.2	14.4	19.3	16.7
	50	8.2	7.6	4.0	1.6	1.5	1.2	-1.3	-2.4	-2.8	-4.5	-3.6	-5.4	-5.3	-1.4	-1.8	-1.6	8.5	10.0	15.4	13.3
	150	9.4	8.9	7.2	5.1	4.9	4.6	4.1	1.6	0.9	-0.5	-0.5	-2.4	-2.8	-0.3	-0.5	-0.7	0.5	3.0	9.5	9.1
	300	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.0	2.5	4.4
2	20	10.3	6.6	1.6	-4.9	-1.4	-5.1	-10.1	-7.4	-7.9	-10.2	-7.7	-10.0	-8.8	-1.4	-2.1	4.4	8.4	13.8	21.0	18.1
	50	8.2	-7.5	3.1	-2.4	-0.6	-2.7	-7.2	-6.2	-6.7	-8.8	-7.2	-7.8	-8.9	-1.6	-2.4	1.0	5.9	9.2	15.3	13.1
	150	8.8	8.2	5.9	4.4	3.1	1.5	3.1	0.3	-0.9	-1.9	-2.0	-3.2	-3.6	-6.3	-1.9	-1.4	-1.6	2.3	5.9	8.2
	300	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.5	0.5	2.2	4.3
3	20	7.7	5.5	4.1	-3.6	-1.3	-4.6	-6.3	-3.5	-6.1	-7.1	-6.4	-6.3	-4.6	-1.3	-1.1	-0.6	4.1	9.5	18.0	15.1
	50	7.2	6.4	2.8	-0.3	0.0	-1.6	-3.7	-2.4	-4.3	-5.6	-5.0	-3.2	-1.8	-1.9	-1.6	-1.4	1.5	6.4	11.9	11.1
	150	8.3	7.6	5.4	4.4	3.3	3.1	1.3	1.9	-0.5	-1.1	-1.6	-1.1	-2.1	-0.4	-1.4	-1.1	-1.9	0.6	4.5	6.4
	300	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.1	0.5	1.6	3.1
4	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.1	9.5	13.7	11.7
	50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.0	7.6	10.7	9.7
	150	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.4	3.3	5.3	5.9
	300	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.4	1.5	3.0	3.2
5	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.2	9.5	17.5	13.9
	50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.5	7.6	12.1	11.4
	150	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.5	3.3	6.2	7.7
	300	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.7	1.4	2.7	4.5
6	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4.8	10.0	19.5	15.4
	50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.0	8.5	13.3	13.4
	150	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.0	2.5	8.1	10.2
	300	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.6	0.5	2.4	3.7
7	20	9.0	6.7	2.3	-3.0	-1.3	-5.7	-8.7	-6.5	-5.6	-7.1	-5.3	-6.8	-5.7	-2.4	-2.3	2.5	5.7	10.0	18.8	15.1
	50	9.1	8.1	3.7	-1.0	0.0	-5.5	-5.7	-5.6	-4.5	-5.8	-4.1	-5.6	-6.2	-3.3	-2.4	0.0	3.7	7.6	13.5	12.8
	150	10.2	9.0	5.8	3.9	2.2	1.1	1.0	-1.2	-0.3	-0.2	-0.7	-2.4	-3.4	-2.9	-2.1	-2.4	-2.1	2.0	6.4	8.3
	300	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-1.4	0.0	2.4	4.5
8	20	8.2	6.4	1.9	-4.9	-1.3	-8.1	-9.7	-9.8	-10.0	-10.1	-6.6	-9.5	-7.2	-2.3	-1.6	2.5	6.9	10.4	18.7	15.0
	50	8.8	7.5	3.7	-1.4	0.6	-3.7	-5.0	-6.7	-6.5	-7.5	-5.5	-6.9	-6.7	-2.9	-2.1	1.1	4.3	8.2	13.1	11.8
	150	9.5	8.3	5.9	4.1	1.8	2.0	2.0	-1.2	-0.2	-1.5	-1.0	-3.2	[illegible]	-2.3	-1.9	-0.6	-2.4	1.6	5.4	6.7
	300	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0	0.0	2.5	3.5
9	20	9.0	7.2	3.3	-2.3	-1.8	-3.5	-7.4	-7.2	-6.3	-6.8	-6.1	-6.8	-7.1	-2.4	-1.9	0.6	4.4	9.0	16.3	15.3
	50	8.8	8.0	3.4	-0.6	-0.9	-1.5	-4.6	-5.9	-5.7	-5.8	-5.2	-5.5	-7.7	-3.5	-2.4	-1.4	3.1	7.4	11.0	12.7
	150	9.5	8.9	6.2	4.7	2.8	3.1	-2.4	0.0	-0.8	-0.8	-1.4	-2.4	-3.7	-1.7	-1.9	-1.6	-1.9	0.7	4.1	7.0
	300	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.1	-0.2	1.0	1.0

(Continued)

SITE	DEPTH cm	Jul 3/72	Jul 18/72	Jul 26/72	Aug 15/72	Aug 27/72	Sep 12/72	Sep 26/72	Oct 10/72	TEMPERATURE °C Oct 24/72	Nov 6/72	Nov 21/72	Dec 9/72	Dec 18/72	Dec 31/72	Jan 13/73	Jan 27/73	Feb 10/73	Feb 26/73	Mar 13/73	Mar 27/73
1	20	13.6	14.7	16.5	16.7	20.6	9.5	0.6	0.8	0.2	-1.1	-0.6	-4.7	-4.9	-4.5	-5.4	-4.1	-6.1	-2.7	-2.0	-0.6
	50	13.4	13.3	12.6	15.6	17.9	9.0	3.6	4.0	1.3	-0.3	-0.3	-2.9	-2.9	-3.0	-4.2	-3.5	-3.7	-2.5	-1.9	-1.0
	150	9.9	10.0	10.8	11.6	12.5	10.9	9.0	7.5	4.5	3.3	3.1	1.9	0.9	0.7	0.6	0.7	1.0	0.3	0.2	0.2
	300	5.4	5.8	6.4	7.3	7.7	8.2	8.5	8.1	6.5	5.7	5.6	3.6	3.2	3.0	3.1	3.3	3.5	2.9	2.5	2.9
2	20	14.5	15.4	15.5	15.6	19.1	9.5	1.3	1.7	1.0	-0.9	-2.5	-8.6	-6.7	-6.8	-9.0	-6.1	-10.0	-5.3	-4.5	-1.6
	50	13.2	13.7	12.6	14.4	17.3	8.8	4.0	5.1	2.3	1.8	-0.2	-5.0	-5.3	-5.1	-7.3	-5.0	-7.1	-4.1	-3.8	-1.6
	150	8.7	9.4	9.2	10.3	12.1	9.8	9.0	7.8	5.1	4.5	3.6	3.0	2.2	0.0	-0.1	-0.7	-0.4	-0.6	-1.2	-0.5
	300	5.0	5.8	5.8	6.7	8.2	8.4	8.7	8.0	6.3	5.8	5.8	4.6	3.4	2.8	2.8	2.5	2.6	2.1	1.4	1.2
3	20	15.6	12.7	13.6	14.2	16.0	9.1	1.9	2.2	1.7	0.0	-0.8	-9.6	-7.2	-6.6	-7.5	-5.8	-7.7	-4.4	-3.2	-1.6
	50	11.6	11.7	11.1	13.0	15.8	8.4	4.8	5.0	2.3	1.5	1.0	-5.5	-5.5	-6.2	-5.5	-4.2	-5.4	-3.7	-2.7	-2.0
	150	7.5	7.7	7.4	9.0	10.4	8.5	8.3	7.3	5.0	4.7	4.0	3.0	2.4	0.6	0.6	-0.6	-0.8	-1.0	-0.5	-0.5
	300	3.9	4.4	4.4	5.6	6.9	7.5	7.7	7.2	6.4	6.2	5.9	4.2	3.2	2.8	2.8	2.5	2.3	2.2	1.8	1.4
4	20	12.1	15.4	13.3	14.7	15.9	9.1	1.5	3.7	1.2	-0.8	-3.7	-7.1	-6.1	-3.4	-6.6	-6.0	-7.4	-5.6	-2.5	0.0
	50	11.3	12.2	11.7	12.6	14.1	9.9	4.4	[illegible]	2.8	1.7	-0.3	-1.7	-2.9	-1.4	-3.9	-1.3	-5.5	-3.1	-2.5	-0.7
	150	6.9	8.3	8.0	8.2	9.5	9.2	8.0	[illegible]	5.0	4.5	3.3	3.3	2.6	2.0	0.5	1.2	0.6	0.8	0.5	-0.2
	300	4.6	5.8	5.3	5.6	6.4	7.2	8.1	7.7	6.3	5.8	4.9	4.7	4.4	4.0	2.8	2.4	2.4	1.8	1.0	2.0
5	20	15.0	14.1	13.1	16.1	16.4	9.0	1.1	2.8	1.5	-0.3	-3.4	-7.2	-7.1	-5.5	-8.2	-7.5	-9.7	-5.3	-3.8	-1.6
	50	12.5	13.5	12.3	13.7	16.0	10.5	4.4	6.1	2.8	1.2	0.2	-2.9	-4.6	-3.5	-6.7	-4.8	-6.8	-3.6	-3.5	-2.1
	150	9.2	10.1	9.5	10.5	11.6	11.1	9.3	8.4	5.0	4.4	3.6	2.3	0.7	0.2	-1.1	-1.4	-1.5	-1.6	-1.9	-1.7
	300	5.2	6.8	6.4	7.0	7.8	9.0	9.1	8.6	6.3	6.1	6.1	5.3	3.9	3.2	1.8	1.8	1.5	1.2	0.5	0.4
6	20	15.6	14.6	13.6	18.8	17.6	9.3	1.4	0.8	1.0	-1.5	-1.8	-3.8	-7.1	-4.3	-5.5	-4.5	-7.2	-3.7	-2.7	-0.8
	50	13.4	14.7	13.6	15.5	17.8	11.0	4.2	4.2	1.4	-0.3	-0.7	-1.4	-4.6	-2.8	-4.2	-3.2	-5.0	-2.9	-2.4	-1.1
	150	11.6	12.3	12.1	13.0	15.5	12.6	9.0	6.7	4.4	2.4	1.6	0.6	-1.4	-0.9	-1.1	-1.0	-1.2	-1.2	-1.0	-0.5
	300	5.5	6.2	6.7	7.5	9.1	9.2	9.7	8.8	7.6	6.7	5.8	4.3	3.5	3.2	3.0	2.8	3.0	2.5	2.7	2.2
7	20	14.4	13.7	13.2	17.6	17.8	9.0	1.9	2.8	1.8	-1.1	-4.0	-6.5	-7.5	-6.8	-9.2	-7.1	-9.8	-5.6	-4.1	-1.1
	50	12.5	13.5	12.6	15.2	17.4	10.5	4.5	5.6	2.8	0.3	-1.6	-3.8	-5.4	-4.9	-8.0	-5.1	-7.4	-4.1	-3.7	-2.3
	150	9.5	10.1	10.2	[illegible]	12.6	11.4	9.0	8.0	5.1	3.3	2.0	1.9	-0.5	-1.7	-1.9	-1.8	-2.1	-2.4	-2.0	-2.4
	300	5.2	6.3	6.3	[illegible]	8.1	9.0	8.9	8.1	6.3	5.3	4.4	4.6	2.8	1.8	1.5	1.4	0.7	0.6	0.0	-0.3
8	20	13.5	14.1	12.6	16.5	16.9	8.0	1.1	2.2	1.1	-1.4	-3.4	-13.9	-10.9	-8.6	-11.5	-8.7	-12.8	-6.8	-5.8	-1.1
	50	11.2	13.0	11.3	11.6	15.2	9.0	4.5	5.2	2.2	0.6	-0.7	-6.7	-7.2	-5.7	-8.5	-5.5	-7.5	-4.5	-4.1	-2.0
	150	7.1	8.3	8.2	9.8	10.1	8.8	7.9	6.8	4.8	3.6	2.8	1.1	0.1	-0.9	-1.4	-1.6	-0.8	-2.0	-2.1	-1.5
	300	4.0	5.1	5.2	6.6	6.6	6.9	7.0	6.7	5.6	5.2	4.2	3.6	3.2	2.3	1.9	1.5	1.8	1.1	0.3	0.6
9	20	14.4	15.1	13.3	[illegible]	[illegible]	9.1	1.8	2.5	1.2	-1.6	-2.9	-7.2	-6.8	-5.7	-8.0	-6.1	-8.4	-4.4	-4.0	-1.9
	50	12.5	14.5	13.0	15.2	16.5	9.5	4.3	4.8	2.2	-0.6	-1.5	-4.0	-5.0	-4.4	-6.9	-4.8	-6.7	-3.9	-3.5	-2.5
	150	8.2	9.6	9.5	11.1	12.6	10.2	8.6	7.2	5.2	3.1	2.3	0.9	0.5	0.1	-1.0	-0.9	-1.1	-1.3	-2.0	-1.4
	300	4.3	5.4	5.4	7.1	7.3	7.4	7.7	7.6	6.1	5.4	4.4	3.3	3.2	2.8	2.2	2.4	1.8	1.5	0.1	0.7

(Continued)

SITE	DEPTH cm	TEMPERATURE °C Apr 10/73	Apr 24/73	May 8/73	May 22/73	Jun 5/73	Jun 19/73	Jul 3/73	Jul 17/73	Jul 31/73	Aug 17/73	Sep 1/73	Sep 14/73
1	20	-0.6	1.1	5.4	11.4	12.1	16.1	18.1	15.8	21.2	16.3	13.7	9.0
	50	-0.8	-0.5	1.4	4.7	9.0	11.3	14.5	13.8	15.8	17.8	13.5	9.5
	150	0.1	0.2	-0.7	0.9	4.4	-	-	9.8	10.6	12.3	12.3	11.5
	300	2.0	2.0	1.1	1.5	2.0	3.4	4.0	4.7	5.3	6.9	7.8	8.2
2	20	2.3	3.3	7.6	13.2	14.7	14.8	19.0	16.4	20.1	17.4	12.5	7.5
	50	-0.8	2.0	4.5	8.3	11.6	11.3	15.4	14.9	15.8	16.4	12.2	8.5
	150	-0.8	-1.5	-1.5	1.9	5.1	6.6	9.7	-	11.4	12.5	11.9	10.1
	300	1.0	0.5	0.3	1.0	2.3	3.2	5.1	5.0	7.0	8.3	8.7	8.5
3	20	-0.5	0.2	5.7	9.8	11.0	12.5	14.5	13.9	16.1	14.7	9.8	5.5
	50	-0.6	-0.8	1.9	6.3	8.6	10.0	12.1	12.6	13.5	14.2	10.9	6.9
	150	-0.8	-1.0	-1.5	-0.7	3.6	5.3	7.1	8.1	9.0	10.0	9.5	8.8
	300	1.0	0.8	0.5	0.7	1.4	2.4	3.3	5.0	3.0	5.6	6.4	6.7
4	20	1.6	3.4	7.3	8.0	10.7	11.4	13.5	13.7	14.4	16.3	11.5	9.4
	50	-0.3	2.8	4.9	6.3	9.0	9.5	11.9	12.1	12.1	14.6	12.1	9.5
	150	0.2	1.6	1.9	2.8	5.0	5.4	7.2	8.3	-	-		-
	300	1.9	2.0	1.2	1.2	3.1	3.2	4.0	5.3	5.4	6.1		[illegible]
5	20	0.8	3.1	7.7	8.9	11.1	11.7	13.7	13.6	14.5	14.5	[illegible]	[illegible]
	50	-0.6	1.5	5.0	7.4	9.7	10.4	12.7	12.8	14.7	13.8	[illegible]	[illegible]
	150	-1.3	-1.2	-0.5	2.8	5.1	5.8	8.2	9.5	9.4	9.7	10.1	9.7
	300	0.3	0.2	0.3	1.0	1.8	3.1	4.3	5.8	6.1	6.1	7.4	7.1
6	20	1.2	2.9	14.1	10.9	13.3	13.5	15.7	15.8	17.4	-	-	9.7
	50	-0.7	0.0	6.9	7.5	11.6	11.8	14.4	15.6	16.3	17.7	13.8	12.5
	150	-0.8	-1.4	-0.9	1.6	7.5	8.9	11.4	12.5	13.7	15.1	13.2	12.8
	300	1.8	1.3	1.0	1.5	1.9	4.1	4.9	5.6	6.0	6.6	6.9	8.1
7	20	0.7	3.4	8.0	10.1	12.2	12.3	14.7	16.1	16.9	15.9	11.6	9.5
	50	-1.4	0.7	4.7	8.1	10.8	10.9	12.5	15.6	15.6	16.3	12.8	9.7
	150	-2.4	-2.1	-0.8	2.9	5.3	-	9.7	11.0	11.8	12.5	12.4	11.7
	300	-1.1	-1.0	-0.5	0.3	2.0	3.2	4.2	5.9	7.1	7.7	8.3	8.7
8	20	0.9	3.9	6.9	9.1	11.7	11.8	14.1	14.4	16.3	15.9	10.4	9.7
	50	-0.5	1.6	4.0	7.5	9.8	10.0	13.1	13.4	14.1	15.7	11.8	9.5
	150	-1.3	-1.3	-1.3	2.1	4.6	5.0	7.7	8.3	9.6	10.6	10.1	10.6
	300	0.2	0.2	-0.3	0.7	2.4	2.9	4.1	4.7	5.8	6.7	7.1	8.2
9	20	-1.1	2.2	6.1	9.6	10.9	11.8	15.1	15.[illegible]	16.9	15.5	11.3	10.4
	50	-1.8	-0.7	3.4	7.2	9.2	10.3	13.5	14.7	15.7	16.1	12.7	9.9
	150	-1.2	-1.5	-1.8	-0.4	3.2	5.1	7.8	8.9	10.4	11.7	11.7	11.2
	300	0.6	0.4	1.2	0.6	0.7	1.8	3.3	4.2	5.4	5.8	7.5	8.0

Appendix 16. Oxidation potentials determined on core samples in the field at the soil study sites.

SITE	HORIZON OR DEPTH	Eox	
		May 8/72	Sep 28/72
1	Ah	-0.12	-0.15
	Bmg1	-0.12	-0.17
	Bmg2	-0.08	-0.18
	BCg	-0.32	-0.18
	100 cm	-0.41	-0.18
	150 cm	-0.42	-0.18
	200 cm	-0.39	-0.15
	250 cm	-0.07	-0.12
	300 cm	-0.12	-
2	Ap	-0.45	-0.19
	Ae	-0.40	-0.24
	Btg	-0.47	-0.23
	BCg	-0.50	-0.21
	100 cm	-0.45	-0.21
	150 cm	-0.35	-0.14
	200 cm	-0.38	-0.14
	250 cm	-0.36	-0.14
3	Ap	-0.45	-0.20
	Ahe	-0.47	-0.20
	Bt	-0.45	-0.23
	BC	-0.46	-0.26
	100 cm	-0.45	-0.23
	150 cm	-0.42	-0.17
	200 cm	-0.41	-0.17
	250 cm	-0.46	-0.17
	300 cm	-0.47	-0.19
4	Ap	-0.31	-0.17
	Ah	-0.35	-0.17
	B	-0.36	-0.21
	Cca	-0.36	-0.17
	100 cm	-0.39	-0.17
	150 cm	-0.38	-0.17
	200 cm	-0.40	-0.17
	250 cm	-0.43	-0.17
	300 cm	-0.38	-
5	Ap	-0.32	-0.22
	Bntjk	-0.41	-0.21
	BCcasa	-0.40	-0.21
	50 cm	-0.41	-0.20
	100 cm	-0.43	-0.19
	150 cm	-0.47	-0.20
	200 cm	-0.30	-0.03
	250 cm	-0.30	-0.03
	300 cm	-0.31	-0.03
6	Ahk	-0.25	-0.17
	Bnsak	-0.31	-0.24
	Ccas	-0.35	-0.09
	Csk	-0.39	-0.14
	100 cm	-0.10	-0.13
	150 cm	-0.04	-0.13
	200 cm	-0.16	-0.04
	250 cm	-0.04	-
	300 cm	-0.04	-
7	Ah	-0.44	-0.24
	Ae	-0.45	-0.28
	Bnt1	-0.45	-0.27
	Bnt2	-0.38	-0.27
	Ccasa	-0.46	-0.29
	100 cm	-0.46	-0.29
	150 cm	-0.45	-0.29
	200 cm	-0.45	-0.04
	250 cm	-0.40	-0.04
	300 cm	-0.33	-
8	Ap	-0.44	-0.17
	AH	-0.48	-0.17
	Ae	-0.48	-0.17
	Bnt	-0.49	-0.16
	BCsa	-0.50	-0.16
	100 cm	-0.40	-0.16
	150 cm	-0.41	-0.16
	200 cm	-0.43	-0.20
	250 cm	-0.45	-
	300 cm	-0.41	-
9	Ahs	-0.35	-0.27
	Bnsa	-0.35	-0.19
	Bcsa	-0.35	-0.20
	Csak	-0.35	-0.20
	Ccas	-0.42	-0.20
	100 cm	-0.43	-0.20
	150 cm	-0.45	-0.06
	200 cm	-0.44	-
	250 cm	+0.33	-
	300 cm	+0.21	-