THE UNIVERSITY OF MANITOBA

DISTRIBUTION OF AIR-FILLED POROSITY ABOVE A WATER TABLE FOR TEXTURALLY DIFFERENT SOILS AND ITS APPLICATION IN SOIL DRAINAGE CLASSIFICATION.

by

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ABSTRACT

The purpose of this study was to evaluate the possibility of using air-filled porosity as a soil property in soil drainage classification.

The distribution of volumetric water content and air-filled porosity was determined, under field conditions, for ten relatively uniform soil profiles. The soils ranged in texture from sand to clay and all had high water tables.

In the laboratory, water content and air-filled porosity as a function of soil water tension were determined on undisturbed samples.

In the field, air-filled porosity generally increased as depth of water table increased. Similarly, in the laboratory, air-filled porosity increased as soil water tension increased. In both cases, the increases were greatest in the coarse texture soils.

In order to test the possibility of predicting air-filled porosity in the field on the basis of retention studies, conducted in the laboratory, linear regression analysis was conducted. The resulting equation was:

$$\text{Air-filled Porosity (Field)} = 3.046 + 0.9691 \times \text{Air-filled Porosity (Laboratory)} \quad (r^2=0.913,\ s=2.34).$$

This showed that air-filled porosity in the field could be predicted with reasonable accuracy from water retention studies conducted in the laboratory.

A tentative agronomical soil drainage classification using the value of 10 percent air-filled porosity as a limiting value of adequate soil drainage is proposed and the application for soils with a high water table is discussed.

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I INTRODUCTION

The importance of soil drainage as a soil characteristic and the direct relationship between drainage, soil capability, and other soil properties has long been recognized. In order to evaluate soil drainage quantitatively, different approaches have been used. Since each is designed to serve a specific need, the application of any one method is restricted.

Soil drainage is an important criterion in the Canadian Soil Classification System. Two aspects, namely, (1) actual moisture content in excess of field moisture capacity; and (2) the duration of the period during which such excess water is present in the plant root zone, are used in defining the soil drainage classes. In a field soil survey the above criteria are estimated by the soil surveyer and in conjunction with other indirect evidence of soil moisture status such as mottling, topography and vegetation, soils are classified into drainage classes.

The demand for information concerning soil drainage is growing. Agronomists, foresters, wildlife specialists, engineers, resource planners, and others are interested in more applicable and more meaningful measures of soil drainage. Some shortcomings of the soil drainage classification, as set out by the Canadian Soil Survey Committee, have recently been pointed out in the report of the Subcommittee On Soil Moisture Regimes of Canada Soil Survey Committee (1970). The principle ones are: (1) the definitions of soil drainage classes are vague; frequently soils with widely different moisture regimes are placed in the same drainage class; (2) field moisture capacity can not readily be estimated in the field and it is not a meaningful physical property for some soils; and (3) the applicability of drainage classification in its present stage of development is very restricted.

One possible way to make the information from soil drainage classification more useful to different users is to replace the criteria presently used by criteria which are more precisely defined and allow better applicability.

For the present study air-filled porosity was used to characterize soil drainage. Air-filled porosity (AFP) is the volume of air per unit bulk volume of soil. This soil property was selected because: (1) it is a single, precisely defined soil physical property; (2) it defines quantitatively soil aeration and also the degree of water saturation; and (3) the crop response to air-filled porosity has been studied and the relationship between air-filled porosity and rate of oxygen diffusion to plant roots has been established.

In South-Western Manitoba, where a large portion of the field study of this project was conducted, there is a large acreage of farming land with high water tables. The soils of the area have been surveyed in detail and water table measurements have been monitored at a large number of locations for several years. This project was initiated to determine if this information on water table depth-could be put to use in drainage classification of these soils.

The objectives of the project were: (1) to study distribution of air-filled porosity above water table for texturally different soil profiles in the field; (2) to test the possibility of predicting air-filled porosity in the field on the basis of water retention studies in the laboratory; and (3) to interpret the results of the project in terms of soil drainage classification.

II REVIEW OF LITERATURE

Definitions and Importance of Soil Drainage

"Soil drainage in a dynamic or active sense, refers to the rapidity and extent of removal of water from soil, in relation to additions, especially by surface runoff and by flow through the soil to underground spaces."...In the passive sense as a condition of the soil it refers to the frequency and duration of periods when the soil is free of saturation or partial saturation (U.S. Department of Agriculture, 1951, p. 165).

Agricultural drainage refers to the removal by artificial means of excess of water from the soil profile to enhance agricultural production, more specifically, the removal of excess gravitational water from the soil (Edminster and Schilfgaarde, 1955, p. 491). According to C. W. Rose (1966, pp. 171-172), "In agriculture, field drainage refers both to the steps taken to remove soil water present in quantity exceeding that which is desirable, and to the mechanism of this water removal."

In the Canadian soil classification system, soil drainage classes are defined in terms of (1) actual moisture in excess of field moisture capacity; and (2) the extent of the period during which such excess water is present in the plant root zone (Canada Soil Survey Committee, 1970, p. 215). In other words, soil drainage refers to the moisture status of a soil throughout the year. It is this definitien of soil drainage that is the concern of this thesis.

Soil drainage affects genesis of soils as it influences direction and rate of soil forming processes. The amount of water present in soil and its transport affects important soil physical and chemical properties: (1) temperature; (2) redox-potential; (3) transport of soil colloids, and soluble salts; and (4) rate of weathering. Therefore, information of soil drainage is of great interest to pedologists. The important characteristics of soils with inadequate drainage are associated with the process of gleying. Morphological features such as mottling and low chroma of soil matrix reflect soil moisture status and they are utilized in soil drainage classification. Mottling and colors of low chroma can be attributed mainly to the reduction of iron and manganese (Buckman and Brady, 1969, p. 340).

Besides the properties mentioned above, soil aeration, consistence, structure, kind and population of microorganisms, amount and location of soluble salts in soil profile are also influenced by soil drainage. These have a practical significance and they are of interest mainly to the agronomist.

Soil aeration, temperature and soil strength are the major areas of agronomist's interest in information on soil drainage. If soil drainage is inadequate, it means that aeration is inadequate with limitations on plant growth and other biological activities. Also, inadequately drained soils are characterized by high heat capacity. According to Kopecky (1935, cited by Wesseling and van Wijk, 1957, p. 503), the maximum difference in temperature between adequately and inadequately drained fields in the spring was found to be as large as 5° C. This difference usually permits earlier spring cultivation and may extend a growing season. Soil strength is also affected by soil drainage status. Inadequately drained, especially fine textured soils, do not provide sufficient support to perform cultivation.

Evaluation of Soil Drainage

Water permeability of soil, one component of soil drainage, has been studied intensively. Many different methods have been employed in order to evaluate it under the both field and laboratory conditions (Boersma, pp. 234-252, and Klute, pp. 210-233 and 253-261, 1965). This measure of soil drainage has certain limitations. For example, it is recognized that a soil may be relatively permeable to water and yet be poorly drained because it happens to be located in a discharge area or area with high water table. Despite such limitations, it is still a very useful parameter in assessing soil drainage for a large number of soils. This fact has been recognized by U.S. Department of Agriculture and a set of seven relative classes of soil permeability has been established (U.S. Department of Agriculture, 1951, p. 168). These permeability classes are then used in defining soil drainage classes

(U.S. Department of Agriculture, 1951, p. 170-172).

Depth of the water table is another component of soil drainage, being of interest to soil scientists, engineers and other potential users of information of soil drainage (McKeague, 1970, p. 10). The relationship between depth of water table and plant growth has been studied for different soils. Results obtained by a number of investigators are cited by Wesseling and van Wijk (1957, pp. 498-503). A more detailed discussion of this aspect occurs in a later section.

Another parameter of soil drainage is surface runoff, sometimes called external soil drainage. In the Soil Survey Manual, six classes of surface runoff are recognized on the basis of relative flow of water from the soil surface. Relative flow of water is determined by the characteristics of the soil profile, topography, and soil cover (U.S. Department of Agriculture, 1951, p. 166). Like water permeability, surface drainage is also used in defining soil drainage classes (U.S. Department of Agriculture, 1951, pp. 170-172).

The factors, soil water permeability, water table depth, and surface runoff combine to influence soil moisture status. Hence a measure of soil moisture status should give a more complete picture of drainage than a measure of any one of the factors affecting it. For this reason it is often used in soil drainage classification. For example, actual moisture content in excess of field moisture capacity is used as a measure of moisture status in the System of Soil Classification for Canada by the Canada Soil Survey Committee (1970, p. 215). On the other hand, in the United States Soil Survey Classification, soil moisture status is measured in terms of degree of saturation with water.

Van't Woudt and Hagan (1957, p. 514) stated: "It is well recognized that the problem of excessive moisture as it affects crop production is one which centers around deficient aeration." An attempt to use soil aeration in soil drainage classification has been made in Britain as cited by McKeague (1970, p. 12). They used the "index of aeration" which can be defined as the volume of water drained from saturated soil at 100 cm water tension.

Some other characteristics, that have been used to evaluate soil drainage, are: topography, soil morphology (color, degree of mottling), and vegetation. These have been employed, usually in routime soil survey, when exact measurements of soil drainage were not practical.

Criticism of Current Canadian System of Soil Drainage Classification

According to the System of Soil Classification for Canada: "The soil drainage classes are defined in terms of (1) actual moisture content in excess of field moisture capacity, and (2) the extent of the period during which such excess water is present in the plant-root zone (Canada Soil Survey Committee, 1970, p. 215).

The field moisture capacity (that is employed in the definition of soil moisture status) is not an easily definable state and it is difficult to estimate in the field (McKeague, 1970, p. 9). The other shortcoming in the use of field moisture capacity lies in the fact that it applies mainly to well drained soils and requires special interpretation if there is restricted drainage (Richards and Wadleigh, 1952, pp. 86-87). For example, field moisture capacity is not a very meaningful characteristic for some very fine textured soils of poor structure. Such soils are characterized by high a proportion of micropores. Therefore, these soils may not exceed field moisture capacity at any time of the year and yet remain nearly completely saturated with water.

The other shortcomings of the definition of soil drainage classes apply to the lack of adequate definition of: "The period during which such excess of water is present" and "plant root zone." Interpretations of these parameters may vary as large differences occur among plants in their sensitivity to excess water as well as in their rooting habits.

Critical Depth of Water Table for Plant Growth

Hooghoudt (1952) published results of experiments on tile drainage and subirrigation conducted on sandy soils of the Netherlands. He obtained maximum yields when the water table was maintained at the depth of 90 to 170 cm below soil surface for common arable crops (grains, potatoes, mangolds), and of 85 to 130 cm for grasslands (hay). The range in depth of optimum water table was due to differences in the thickness of the organic matter enriched surface layer (20-100 cm), in soil texture, and finally, in water and aeration requirements among different crops. Hooghoudt also established a field trial on heavy clay at Nieuw Beerta, the Netherlands, and maintained the water table at 40, 60, 90, 120 and 150 cm below the surface throughout the entire year. In the last two years of his experiment the water table was kept at 50 cm below the surface during period from October to February. In general, grains, peas, horsebeans, sugar beets, potatoes and other common arable crops showed yield increases with increasing depth of water table with the highest yields obtained when the water table was at the depth of 150 cm. The maximum yields in dry years were obtained for some crops at shallower water table levels (60-120 cm).

Roe (1936, cited by Wesseling and van Wijk, 1957, p. 501) carried out experiments in peat soils with various crops. He found maximum yields of arable crops at a water table depth of 90 to 100 cm. In the case of horticultural crops, the water table depth for maximum yields had been at 75 to 90 cm. The range in optimum water table depth was influenced by thickness of the peat layer. Harmer (1941, cited by Wesseling and van Wijk, 1957, p. 501) stated that the water table should be maintained at a depth of 75 to 90 cm for arable muck soils of Michigan or 60 to 75 for grasslands.

The critical depth of water table for some crops grown in soils of different textures, based on information presented by Damaska, et al. (1966) for conditions in Czechoslovakia is shown in Table I.

Several investigators observed that high water tables had detrimental effects on yields of crops during the vegetation period as well as during winter. Hooghoudt (1952) working with clay soils in the Netherlands, found that the surface horizons became very compact and sticky when the water table was kept for 5 years at the depth of 40 to 60 cm. He also concluded that the effect of high water tables in winter may be important for winter crops. In general, he observed that a water table at 50 cm during the winter had no effect on yields of crops, providing the level of the water table dropped to the 120 cm level after March.

Van der Molen (1953, cited by Wesseling and van Wijk, 1957, p. 498) conducted experiments in the new Zuiderzee polder of the Netherlands and found that most arable crops showed no injury with winter water tables at 20 cm below surface. The maximum allowable water table was, therefore, assumed to be 30 cm below the surface in that region. The Netherlands Service for Land and Water Use, on the other hand, assumed a maximum allowable water table of 40 cm below the soil surface for grassland and 50 cm for arable land for drainage calculations (Wesseling and van Wijk, 1957, p. 498).

The references cited from the literature in this section

TABLE I

CRITICAL DEPTH OF WATER TABLE AND ROOTING DEPTH FOR SOME COMMON CROPS

Crop	Maximum Rooting Depth (cm)	Depth of Penetration of Bulk of the Roots (cm)	Soil Textural Group*	Critical Depth of Water Table (cm)
Winter Wheat	120-140	30-50	M-MoF	200
Fall Rye	130-150	25-30	MoC-M	150
Barley	110-120	25	M-MoF	150-200
Corn	120-150	30-40	M-MoF	160-180
Sugar Beet	150	40-45	M-MoF	160-200
Potatoes	120	40-60	MoC-MoF	120-160
Rape	110	20	M-MoF	120
Flax	100	22	MoC-M	120-130
Alfalfa	>200	-	M-MoF	200
Clover	150-200	-	M-F	60

* MoC - Moderately coarse

M - Medium

MoF - Moderately fine

F - Fine

were meant to illustrate that the height of the water table is an important factor which influences soil drainage and consequently crop production. However, it can be seen that the critical depth of water table will depend on factors such as soil, climate, crop, and management practices.

Air-Filled Porosity as a Measure of Soil Drainage

Van't Woudt and Hagan stated: "It is well recognized that the problem of excessive moisture as it affects crop production is one which centers around deficient aeration" (1957, p. 514). For example, when the soil is saturated with water above a certain limit, gaseous exchange between atmosphere, soil and plant is inadequate. For most agricultural crops this lack of adequate gaseous exchange or adequate soil aeration results in reduced yields.

Soil aeration is defined as "the process by which air in the soil is replaced by air from the atmosphere. In a well-aerated soil, the soil air is very similar in composition to the atmosphere above the soil. Poorly aerated soils usually contain a much higher percentage of carbon dioxide and correspondingly lower percentage of oxygen than the atmosphere above the soil. The rate of aeration depends largely on the volume and continuity of pores within the soil" (Soil Science Society of America, 1971).

Aeration can be measured in both quantitative and qualitative terms. Measurement of the concentration of oxygen and carbon dioxide and the redox potential have been employed as qualitative measures of aeration status.

A commonly used quantitative measure of soil aeration is air-filled porosity (Grable, 1966). There is a close relationship between the portion of soil voids filled with air and the rate of oxygen diffusion within the soil. When soil is saturated with water there is very little diffusion of oxygen from the atmosphere to the soil air. In addition, the rate of oxygen diffusion to plant roots through water films is 10,000 times slower than through air (Grable, 1966). Therefore, a certain minimum amount of water free pores is required for adequate aeration. Taylor (1949) and Blake and Page (1948) have shown that for adequate diffusion of gases air-filled porosity of the soil should be in the neighbourhood of 10 percent. A discussion of the critical values of air-filled porosity is presented in the next section.

Other physical properties of the soil are also affected by the volume of air-filled porosity. For example, Russell (1952, p. 255) stated that "knowledge of the volume fraction occupied by the gaseous constituents is sufficient information to predict certain mechanical properties of soil." Among these, soil strength, thermal conductivity, and specific heat are of great practical significance.

Critical Values of Air-Filled Porosity for Plant Growth

Blake and Page (1948) conducted gaseous diffusion experiments "in situ" and came to the conclusion that diffusion of air in the clay soil cannot take place if porosity is less than 0.10 to 0.12. Vine et al. (1943, cited by Wesseling and van Wijk, 1957, p. 467) found that diffusion of gases in soils of Trinidad was negligible at an air content of 0.12. Taylor (1949) conducted laboratory experiments on diffusion of nitrogen in quartz sand, glass spheres, as well as in a mixture of quartz sand and glass spheres and found that diffusion ceased when air porosity was less than 10 percent. Thus it can be concluded that 10 percent of air-filled porosity is a limit to diffusion, even in a highly permeable material such as quartz sand.

Robinson (1964) found that 11 percent of air porosity was adequate for sugar cane grown in Hawaiian Low Humic Latosol. The experiments were conducted in lysimeters with water tables maintained at depth of 15, 30 and 45 cm below the surface. Willhite et al. (1965) obtained excellent yields of Timothy (*Phleum pratense*) grown in lysimeters at essentially zero air porosity when large quantities of nitrogen fertilizer were applied (400 pound per acre of nitrogen in urea form). The crop was grown with water tables maintained at 2.5, 15 and 46 cm as well as without the water table. The best yields were obtained with water table at depth of 46 cm below surface. Miller and Mazurak (1958) conducted experiments on growing sunflowers in lysimeters. As growing media they used various soil separates having various particle sizes. They found that the greatest rate of stem elongation occured at about 4 percent air porosity.

On the other hand, in experiments conducted in greenhouse, air porosities greater than 20 to 30 percent were needed for optimum establishment and growth of tomatoes in potted soils ranging in texture from sandy loam to clay loam (Flocker *et al*., 1959). Kopecky (cited by Wesseling and van Wijk, 1957, p. 472) suggested minimum air porosity for different crops. The values are given in the Table II.

TABLE II

MINIMUM AIR POROSITY AS REQUIRED BY DIFFERENT CROPS

Crop	Air Porosity, %
Grass	6-10
Wheat	10-15
Oats	10-15
Barley	15-20
Sugar Beet	15-20

In general, a review of the literature showed that there is no complete agreement on the required air-filled porosity for crop growth. This was adequately expressed by Grable (1966) when he stated: "No single value of porosity can be considered optimum or even minimum, for all situations."

Use of Air-Filled Porosity in Soil Drainage Classification

S. A. Wilde (1940) attempted to establish a simple drainage classification of gley forest soils that would satisfy the need of silvicultural practice as regards the choice of species, possibilities of natural regeneration, and technique of tree planting. The classification is based on depth of water table and upper limits of the water logged soil layer (gleyed horizon). The Alpha, Beta, and Gamma classification of gley soils, as set out by Wilde, appears to be comparable to the poorly, imperfectly and moderately well drained soils, respectively in the Canadian Soil Classification System.

Wilde states, "The air content...appears to be the single physical factor best expressing the nature and growth conditions of gley soils."

The distribution of air porosity in the profiles classified by Wilde as Alpha, Beta and Gamma gley soils is illustrated on Figure 1. From Figure 1 it is possible to read the distance from the soil surface to the point at which air porosity drops below 10 percent for each type of gley soil. These values are summarized and presented below:

Type of Gley Soil	Distance from the Soil Surface to the Point at Which Air Porosity Drops Below 10 Percent	
	in.	cm
Alpha	14	35.6
Beta	21	53.3
Gamma	49	124.5

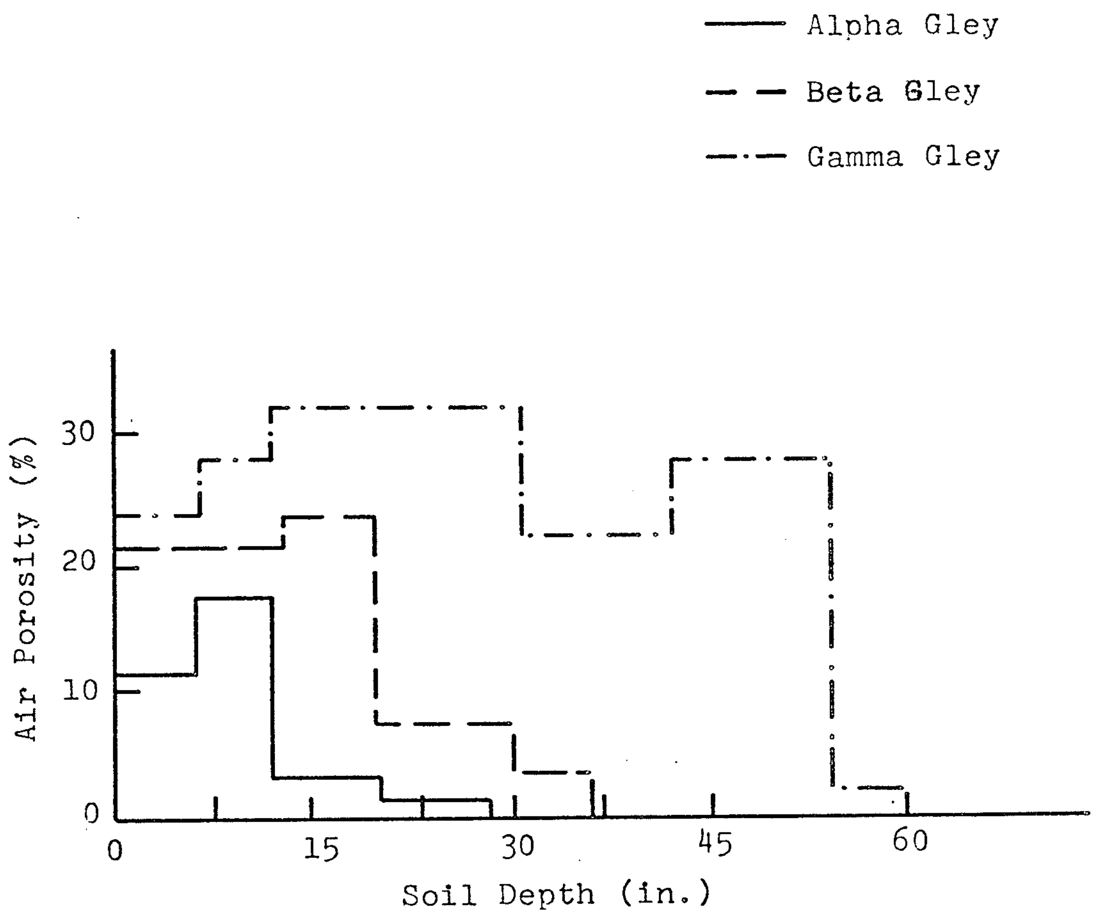

Figure 1. THE DISTRIBUTION OF AIR POROSITY WITHIN SOIL PROFILE FOR ALPHA, BETA, AND GAMMA GLEY SOILS (AFTER WILDE, 1940).

III. MATERIALS AND METHODS

Location and General Description of Soil Sites

Ten soil sites located near water table observation wells were selected for the study. An attempt was made to meet three basic conditions in their selection: (1) major textural groups should be represented; (2) the soil profiles of individual sites should be of uniform texture; and (3) water table should be within 2 m of the soil surface.

Seven of ten soil sites are located in South-Western Manitoba in the Souris and Whitewater Lake basins. The soils are developed on calcareous coarse to fine textured lacustrine parent materials.

The other three sites are located in South-Central Manitoba in the Red River basin. Two sites are developed on calcareous fine textured lacustrine and one on coarse textured deltaic parent material.

The soils were described and classified accordingly to the system developed by the Canada Soil Survey Committee. A summary of the locations and soil descriptions is given in Table III. Detailed soil descriptions appear in the Appendix.

Physical and Chemical Analyses of Soil

Before physical and chemical analyses were conducted soil samples were air-dried and sieved through a 2mm sieve.

TABLE III

LOCATION AND DESCRIPTION OF SOIL SAMPLING SITES

Site No.	Soil Series	Legal Description of Location	Textural Group	Subgroup	Water Well No.,* Location
1	Souris	N.W. Corner 29-4-24W	Coarse	Saline Gleyed Carbonated Rego Black	13-Souris Lake Basin
2	Long Plain	N.E. 1/4 22-8-5W		Gleyed Regosol	1-Elm Creek
3	Hartney	S.W. Corner 10-6-22W		Saline Gleyed Carbonated Rego Black	6-
4	Hartney	S.E. Corner 19-6-21W	Medium	Gleyed Rego Black	29-
5	Hartney	E.C. 33-6-22W		Saline Gleyed Carbonated Rego Black	30- Souris Lake Basin
6	Cameron	S.E. 1/4 26-6-21W		Gleyed Rego Black	1-
7	Cranmer	N.E. Corner 30-6-22W	Fine	Gleyed Carbonated Rego Black	5-
8	Pipestone	S.E. Corner 2-4-21W		Saline Gleyed Carbonated Rego Black	38-White Water Lake Basin
9	Neuhorst	N.E. Corner 4-3-5W		Gleyed Rego Black	5-Experimental Station, Morden
10	Osborne	River Lot 1, Parish of St. Norbert, 8 - 3E	Very Fine	Carbonated Rego Humic Gleysol	-Glenlea

*As used by the Manitoba Sóil Survey.

Particle Density. Particle density was determined by the pycnometer method as described by Blake (1965, pp. 371-373).

Particle Size Distribution. Particle size distribution was determined by pipette method as described by Kilmer and Alexander (1949).

Electrical Conductivity. Electrical conductivity was determined on a liquid extract obtained from water saturated soil paste as described by Richards (1954, p. 91).

Soil Reaction. Soil reaction was determined by measuring the pH of a suspension of soil in 0.01 M $CaCl_2$ solution (1:1 soil/$CaCl_2$) using glass and calomel electrodes.

Organic Matter. Organic matter was determined for surface and subsurface horizons. The chromic acid oxidation method as described by Atkinson, et al. (1958, p. 18-19) was used.

Field and Laboratory Procedures and Methods

At each site pits approximately 100 cm wide and 200 cm long were dug down to or near the water table. Every distinct horizon and subhorizon in each soil profile was sampled. Undisturbed soil samples were taken for water retention, bulk density, and water content determinations. Disturbed samples were taken for particle density, particle size distribution, electrical conductivity, pH, organic matter content, and carbonate content determinations.

<u>Bulk Density</u>. Bulk density was determined by taking undisturbed core samples. Aluminum cylinders 5.1 cm in diameter and in 4.3 cm deep with sharpened edge were used. Six replicates were taken for each horizon.

<u>Water Content</u>. Gravimetric water content was determined on the samples used for bulk density determination. Volumetric water content was calculated by multiplying gravimetric water content by bulk density determined for each horizon.

<u>Water Retention</u>. Aluminum cylinders of the same size as those used for bulk density determination were used for taking undisturbed samples for water retention studies. Rings were carefully rotated and pressed vertically into the soil until approximately 4/5 of the ring was filled. Samples were covered with a polyethylene film to retain moisture and carefully packed into plastic bags and sealed. Samples were stored at minus 26^{o} C. Shortly before retention studies were begun, the bottom soil surface in each ring was trimmed off in order to obtain good contact with the tension plate. A piece of cheese cloth was wrapped around the bottom of the cylinders to prevent loss of soil.

In general the water table at time of sampling (summer) was falling. In order to eliminate hysteresis effects, the drying curve was determined in the laboratory.

The samples were submerged in distilled water to determine water content at zero water tension. Then they were placed on the tension plate and water content in equilibrium with water tensions of 10, 20 and 40 cm was determined. For these determinations a tension plate was constructed in which sheets of blotting paper were used as the porous material. Approximately 60 samples were placed on the tension plate at a time. A metal weight was placed on top of the rings in order to improve contact between tension plates and soil samples. A plastic cover was used to eliminate evaporation from the samples.

The water content at 80 and 160 cm water tension was obtained by equilibrating the soil samples on ceramic porous plates.* The desired water tensions were obtained by using a source of vacuum which was regulated by water and mercury columns (Figure 2). Two columns of mercury were used with fixed height of 5 and 10 cm. Desired water tensions of 80 and 160 cm was obtained by selection of one of the mercury columns and adjustment of the height of column of water. When the desired water tension was 80 cm of water, columns of 5 cm of mercury and 12 cm of water were used; when desired water tension was 160 cm columns of 10 cm of mercury and 24 cm of water were used.

In order to improve contact between soil samples and tension plates a layer of medium textured soil (less than 2 mm) about 3 mm thick, was placed on the tension plates.

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*Obtained from Soil Moisture Equipment Co., Santa Barbara, California.

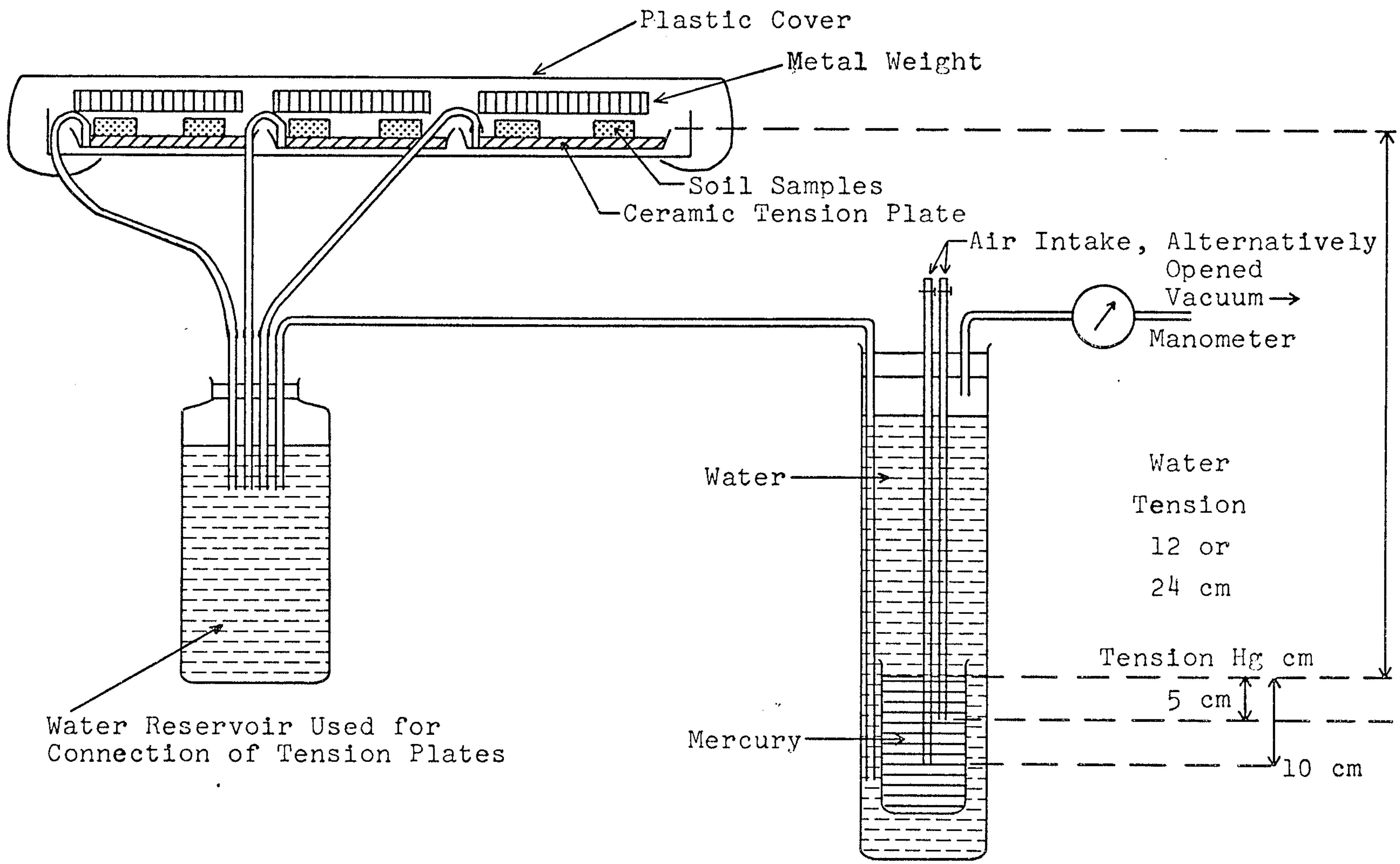

Figure 2. APPARATUS USED TO OBTAIN TENSIONS OF 80 AND 160 cm OF WATER.

A metal weight was placed on the top of the samples in order to improve contact between soil samples and tension plates. A plastic cover was used to eliminate evaporation from the soil samples.

The water content in soil samples of medium, fine and very fine textured soils at 80 and 160 cm water tension was determined after equilibrating samples on tension plates for 14 days. The water content in soil samples of coarse textured soils at these water tensions was determined after equilibrating them at these water tensions for 21 days. The calculated value was corrected for water content of the cheese cloth at each tension. The amount of this correction was determined by including two rings with cheese cloth at each tension.

After gravimetric and consequently volumetric water content for each sampled horizon and subhorizon was determined, retention curves were plotted in order to estimate water content for each sampled horizon and subhorizon at any water tension from 0 to 160 cm. Air-filled porosity was calculated as follows:

$$\text{Air-filled porosity} (\%) = \left[1 - \frac{\text{Bulk density}}{\text{Particle density}} - \text{Volumetric water content}\right] \times 100$$

<u>Statistical Analysis Conducted on Air-Filled Porosity Data Determined in the Field and in the Laboratory</u>

The possibility of prediction of water content and consequently air-filled porosity in the field from the values obtained from water retention studies was tested by linear regression analysis conducted on field and laboratory determinations.

In following discussion, it has to be assumed that a soil profile in the field is in equilibrium with water table. Under this condition a water content, say at 20 cm above the water table, has a tension of 20 cm of water exerted on it. Therefore, it should be possible to evaluate water content and consequently air-filled porosity in the field from the value, obtained from the retention curve, determined for the same soil horizon at 20 cm water tension.

Water content and air-filled porosity for each horizon, at the same tension as existed in the field, were estimated from the water retention curve for each individual horizon. Ideally, a plot of field vs predicted results should yield a straight line with a slope of unity passing through the origin. Linear regression analysis, using air-filled porosity observed in the field as the dependent variable, was used to determine the degree and nature of the relation between actual and predicted results. The resulting equation could be used to predict air-filled porosity in soils with a high water table on the basis of retention studies.

IV RESULTS AND DISCUSSION

Air-Filled Porosity Under Field Conditions

Air-filled porosity under field conditions is discussed from the point of view of: (1) its distribution within each textural group; (2) differences and similarities among the textural groups.

Distribution of Air-Filled Porosity in Soil Profiles for Each Textural Group. For the coarse textured soil profiles the highest values of air-filled porosity occurred in the surface soil horizons (Sites 1 and 2, Table IV). There was a gradual decrease in air-filled porosity as the distance to the water table decreased. Large variations in air-filled porosity occurred between the Souris and Long Plain series, particularly in the surface horizons (Figure 3). The lower air-filled porosity for the Souris soil can be attributed mainly to: (1) higher bulk density and finer soil texture (Tables IV and V).

For the medium textured soil profiles, the highest values of air-filled porosity occurred in the surface and subsurface horizons (Table IV). If one excludes the air-filled porosity values for the surface most horizons of Sites 3 and 5, then one can see also a gradual decrease in air-filled porosity with decreasing distance from the water table. At a distance of 1 metre and greater, above the water table, the value of air-filled porosity among the

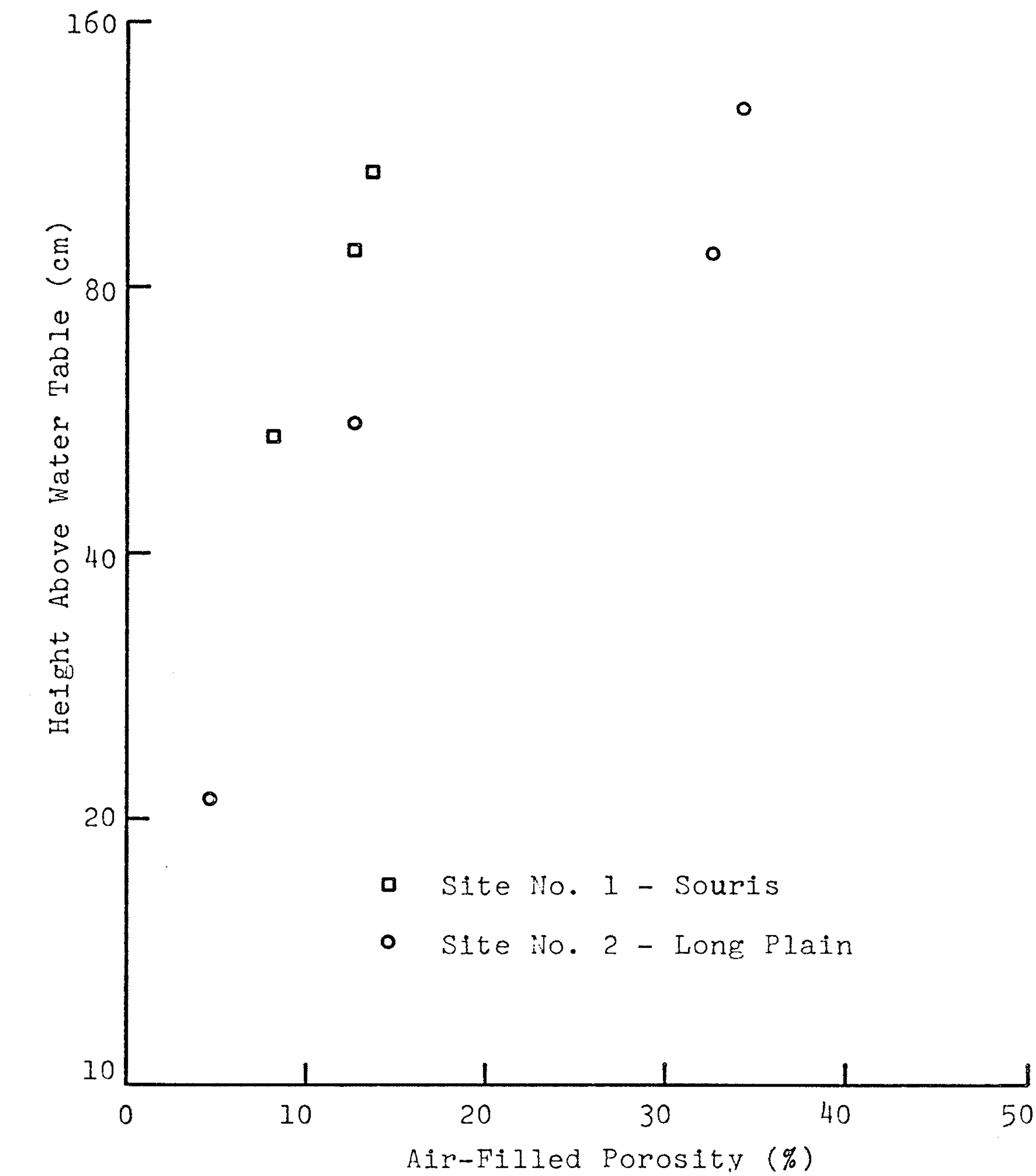

Figure 3. DISTRIBUTION OF AIR-FILLED POROSITY IN COARSE TEXTURED SOIL PROFILES AS DETERMINED IN THE FIELD.

TABLE IV

AIR-FILLED POROSITY DETERMINED IN THE FIELD
AND IN THE LABORATORY AND DIFFERENCE BETWEEN DETERMINATIONS

Textural Group	Soil Site No. / Soil Series	Tension cm H_2O	Particle Density gm cm^{-3}	Bulk Density gm cm^{-3}	Air-filled Porosity % Field	Air-filled Porosity % Laboratory	Air-filled Porosity % Difference Field-Lab.
COARSE	1 Souris	107	2.67	1.71	13.7	6.4	7.3
		87	2.68	1.73	12.7	7.3	5.4
		54	2.67	1.68	8.1	1.6	6.5
		0	2.67	1.62	5.5	2.0	3.5
	2 Long Plain	127	2.63	1.43	34.1	29.1	5.0
		87	2.65	1.52	32.9	24.9	8.0
		56	2.66	1.56	12.7	13.4	-0.7
		21	2.67	1.60	4.7	3.2	1.5
		0	2.67	1.57	3.4	3.7	0.3
MEDIUM	3 Hartney	180	2.62	1.58	3.9	-0.3	4.2
		155	2.65	1.49	3.3	0.6	3.9
		137	2.71	1.47	11.6	8.3	3.3
		120	2.63	1.49	10.5	9.3	1.2
		94	2.67	1.55	6.4	5.3	1.1
		51	2.70	1.56	1.4	0.3	1.1
		10	2.75	1.56	0.2	-1.1	1.3
	4 Hartney	80	2.56	1.08	23.8	20.9	2.9
		65	2.71	1.40	4.3	-1.3	5.6
		48	2.70	1.61	3.2	2.1	1.1
		18	2.68	1.52	4.8	2.9	1.9
		0	2.68	1.53	-0.3*	0.3	0.6
	5 Hartney	170	2.65	1.52	1.6	-1.6	3.2
		150	2.71	1.37	18.3	16.6	1.7
		125	2.74	1.42	19.6	17.6	2.0
		94	2.72	1.51	5.1	4.0	1.1
		64	2.71	1.51	3.7	3.0	0.7
		43	2.70	1.56	0.0	-4.3	4.3

*All negative values of air-filled porosity are taken to be zero.

TABLE IV (continued)

Textural Group	Soil Site No. / Soil Series	Tension cm H_2O	Particle Density gm cm^{-3}	Bulk Density gm cm^{-3}	Air-Filled Porosity % Field	Air-Filled Porosity % Laboratory	Air-Filled Porosity % Difference Field-Lab.
FINE	6 Cameron	142	2.53	1.36	0.4	-0.5*	-0.9
		114	2.70	1.43	8.2	7.1	1.1
		78	2.90	1.32	5.0	1.6	3.4
		28	2.73	1.41	3.7	0.7	3.0
		0	2.70	1.30	2.1	-4.3	6.4
	7 Neuhorst	71	2.58	1.33	4.0	0.5	3.5
		46	2.65	1.42	3.6	0.8	2.8
		33	2.68	1.49	1.9	-1.4	3.3
		15	2.83	1.41	4.4	-1.5	5.9
		0	2.63	1.53	3.3	-1.0	4.3
	8 Pipestone	122	2.57	1.04	7.8	6.4	1.4
		99	2.72	1.39	1.3	-0.5	1.8
		53	2.77	1.36	3.3	2.6	1.7
		15	2.81	1.42	8.9	4.7	4.2
		0	2.76	1.79	-1.0	-4.7	3.7
	9 Cranmer	119	2.54	1.48	1.8	-0.4	2.2
		89	2.74	1.50	2.0	4.8	-2.8
		48	2.75	1.49	3.8	2.5	1.3
		0	2.71	1.42	0.0	0.4	-0.4
VERY FINE	10 Osborne	82	2.67	1.26	-2.1	-6.4	4.3
		72	2.75	1.26	-1.3	-5.4	4.1
		56	2.74	1.30	-1.5	-8.2	5.7
		28	2.77	1.35	-0.9	-6.5	5.6
		0	2.77	1.34	-1.3	-8.3	7.0

*All negative values of air-filled porosity are taken to be zero.

TABLE V

DEPTH OF SAMPLING, PARTICLE SIZE DISTRIBUTION, ORGANIC MATTER CONTENT, AND DATE OF SAMPLING FOR SOILS USED

Textural Group	Soil Site No. / Date of Sampling	Depth of Sampling cm	Clay %	Silt %	Very Fine Sand %	Fine Sand %	Medium Sand %	Total Sand %	Organic Matter %
COARSE	1	38	10.7	4.9	25.6	45.0	12.1	84.4	2.6
		58	11.6	6.2	27.1	44.7	9.9	82.2	0.9
	14/10	91	8.6	3.9	36.0	45,9	5.3	87.5	-
	1970	145	13.1	6.9	25.3	46.4	8.1	80.0	-
	2	8	4.1	3.5	21.3	68.0	2.7	92.4	1.3
		48	2.2	1.0	29.2	64.0	2.8	96.8	0.3
	6/7	79	3.7	1.2	22.4	69.2	2.7	95.1	-
	1971	114	4.3	1.3	35.3	56.3	1.8	94.4	-
		135	3.6	1.4	25.6	67.5	1.0	95.0	-
MEDIUM	3	8	24.4	28.3	40.4	5.7	0.5	47.3	3.4
		33	22.1	29.4	41.8	4.0	0.9	48.5	1.6
		51	28.5	26.2	38.4	4.5	0.5	45.3	-
	27/8	68	21.0	27.9	45.9	3.6	0.3	51.5	-
	1970	94	12.0	27.2	47.7	5.9	0.2	60.8	-
		137	8.5	27.2	60.0	3.1	0.2	64.3	-
		178	19.0	73.6	--	--	--	7.4	-
	4	12	27.1	38.7	18.0	4.6	4.1	34.2	5.6
		27	38.7	43.3	10.6	3.9	2.6	18.0	-
	16/8	44	27.6	37.2	30.0	2.0	1.0	35.2	-
	1970	74	24.6	51.0	21.0	2.2	0.9	24.4	-
		92	16.0	71.4	--	--	--	12.6	-
	5	8	26.4	42.4	25.4	3.2	2.1	31.2	4.8
		28	41.0	35.5	19.1	2.0	2.0	23.5	2.2
		53	36.2	42.9	17.3	1.9	1.3	20.9	-
	24/8	84	21.7	75.6	--	--	--	2.7	-
	1970	114	12.3	76.7	--	--	--	11.0	-
		135	9.5	58.7	27.2	2.1	1.6	31.8	-

TABLE V (continued)

Textural Group	Soil Site No. / Date of Sampling	Depth of Sampling cm	Clay %	Silt %	Very Fine Sand %	Fine Sand %	Medium Sand %	Total Sand %	Organic Matter %
FINE	6	10	30.7	39.5	19.2	5.4	2.3	29.8	7.0
		38	48.9	33.4	--	--	--	17.7	-
	27/8	74	28.4	50.3	--	--	--	21.3	-
	1971	124	28.5	70.6	--	--	--	0.9	-
		152	26.1	70.2	--	--	--	3.7	-
	7	13	37.9	35.2	15.3	3.5	3.8	26.9	7.2
	28/8	38	49.8	34.5	--	--	--	15.7	3.2
	1971	51	48.5	39.8	--	--	--	11.7	-
		69	37.3	50.8	--	--	--	11.9	-
		84	25.5	18.7	38.1	9.5	4.6	55.8	-
	8	10	47.2	42.6	--	--	--	10.2	8.4
	25/8	33	46.9	45.9	--	--	--	7.2	2.0
	1971	79	53.5	42.6	--	--	--	3.9	0.9
		117	24.6	64.4	--	--	--	11.0	-
		132	24.7	36.7	10.7	10.9	8.5	38.6	-
	9	13	27.2	40.0	21.8	4.1	3.2	32.8	4.7
	15/10	43	49.5	44.1	--	--	--	6.4	-
	1970	84	29.1	68.0	--	--	--	2.9	-
		132	40.5	56.5	--	--	--	3.0	-
VERY FINE	10	10	77.4	18.8	--	--	--	3.8	3.3
	23/10	20	82.9	13.5	--	--	--	3.6	2.5
	1970	36	81.4	15.1	--	--	--	3.5	1.6
		64	79.5	17.4	--	--	--	3.1	-
		92	84.3	15.1	--	--	--	0.6	-

medium textured soils was smaller than that for the coarse textured soils (Figure 4).

The high value of air-filled porosity (23.8%) in the surface horizon of Site 4 was probably due to the lower bulk density (1.08 gm cm^{-3}) as compared to the surface horizons for the other two sites (Table IV). The low bulk density in this soil horizon may be attributed to cultivation performed just prior to sampling.

For the fine textured soils there was no clear indications of differences in air-filled porosity due to differences in distance from the water table. For Sites 6 and 9 the values for the surface horizons were found to be smaller than for subsurface horizons (Table IV). The variation of values of air-filled porosity within fine textured soil group was found to be still smaller than that for medium textured group (Figure 5).

For the very fine textured Osborne soil (Table IV), values of air-filled porosity for all horizons were found to be negative. The negative values may be attributed to experimental errors, therefore, for this study they will be taken to be zero.

<u>Differences and Similarities in the Distribution of Air-Filled Porosity Among the Textural Groups.</u> The highest values of air-filled porosity among the four textural groups occurred in the surface horizons of the coarse textured soils. The highest values for fine and very fine textured profiles were smaller than for the coarse and medium textured

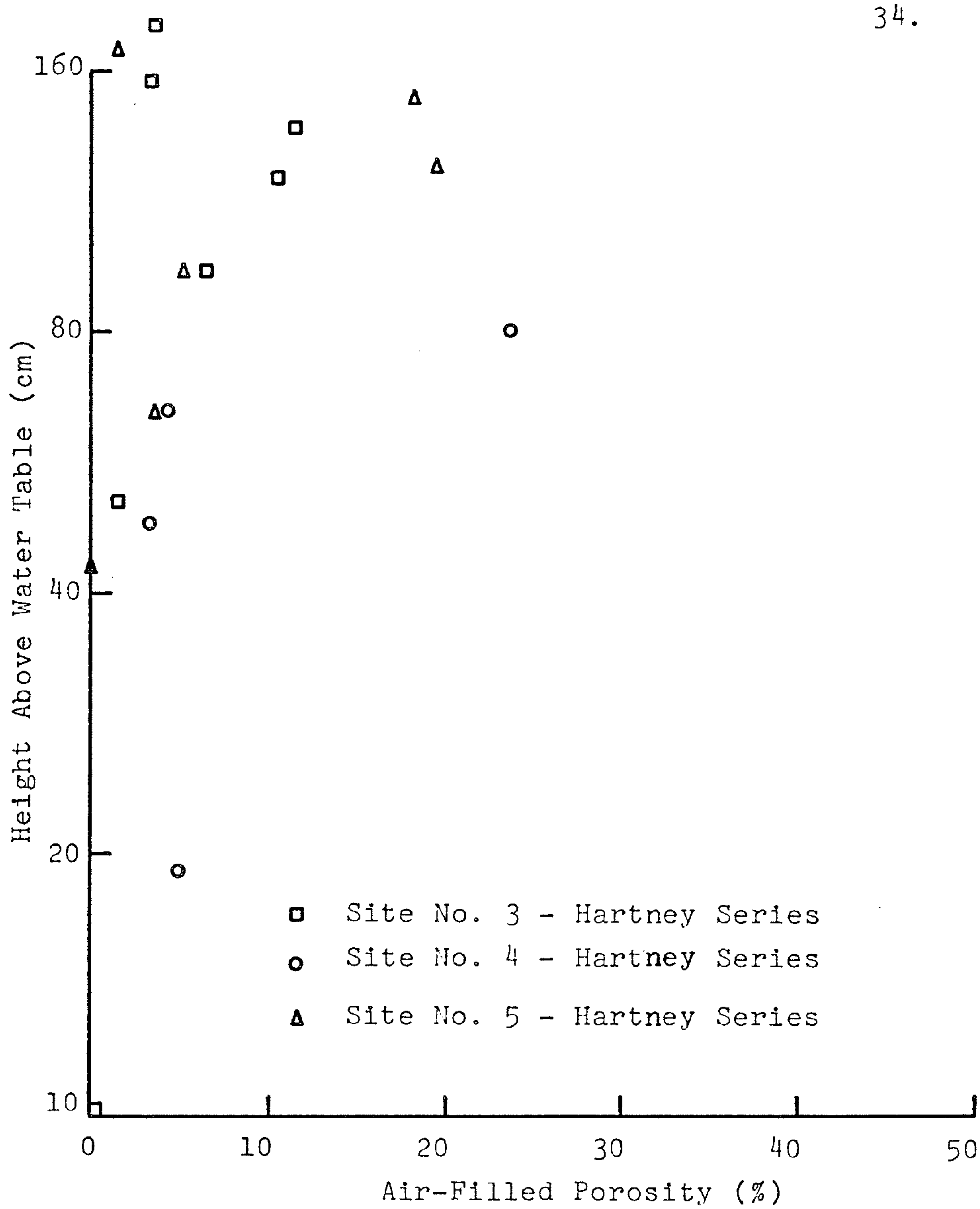

Figure 4. DISTRIBUTION OF AIR-FILLED POROSITY IN MEDIUM TEXTURED SOIL PROFILES AS DETERMINED IN THE FIELD.

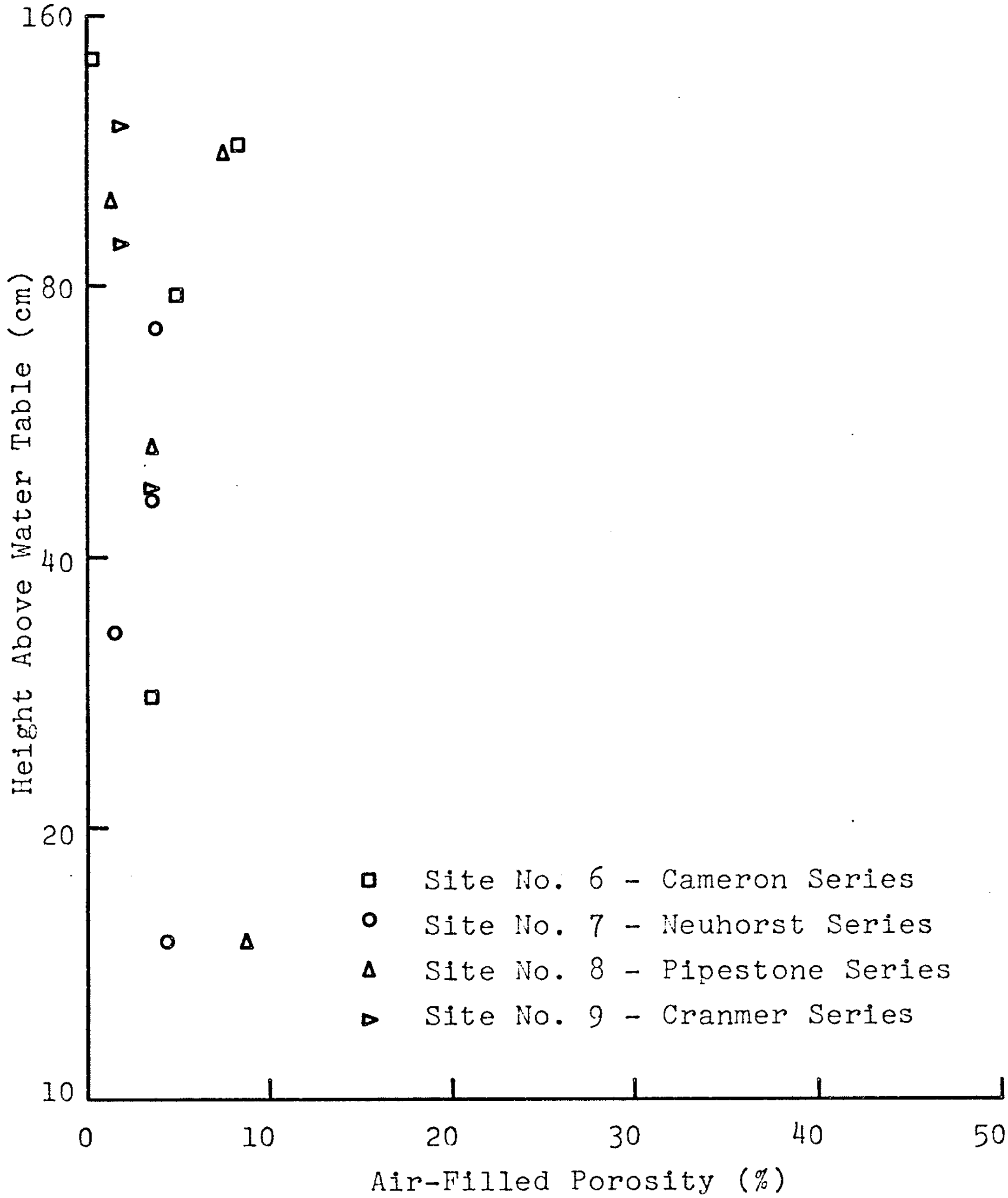

Figure 5. DISTRIBUTION OF AIR-FILLED POROSITY IN FINE TEXTURED SOIL PROFILE AS DETERMINED IN THE FIELD.

eral, the finer the soil texture, the smaller were the values of air-filled porosity when compared at the same distance above the water table (Table IV).

The values of air-filled porosity for coarse textured soil profiles gradually decreased with the decreasing distance to the water table. This was not observed for medium, fine and very fine textured soils (Table IV), with exception of Sites 4 and 8 where the highest value for air-filled porosity occurred in the surface horizon. In most cases, for both medium and fine textured soil profiles the highest air-filled porosity occurred below the surface horizon.

The smallest value of air-filled porosity, for all textural groups, occurred in soil horizons closest to the water table (Table IV). The higher values of air-filled porosity for some horizons close to water table may be attributed to experimental errors.

In general, the magnitude of the values of air-filled porosity was influenced mainly by: (1) distance of the soil horizon above a water table; (2) soil texture; and (3) bulk density (Table IV).

Air-Filled Porosity Under Laboratory Conditions

The volumetric water content estimated from the retention curve, and the bulk density values obtained from field data, were used to calculate air-filled porosity under laboratory conditions.

The relationship between volumetric water content, air-filled porosity and water tension is illustrated for the surface horizons of the coarse, medium and fine textured soils in Figures 6, 7, and 8.

Three points can be readily observed from the Figures: (1) the volumetric water content decreases and hence air-filled porosity increases gradually with increasing water tension; (2) the magnitude of change of air-filled porosity for equal changes in applied tension differed with soil texture. The increase is highest for coarse, smaller for medium and smallest for fine textured soil; and (3) in Figures 6 and 8 it may be seen that higher volumetric water contents were obtained at 20 cm than at tension of 10 cm. Such increases frequently occurred during the retention studies and probably may be attributed to changes of bulk density during retention studies.

The values of air-filled porosity based on laboratory data were smaller than those obtained from field data. However, the laboratory data of all soils showed a similar trend to those observed from field results.

Comparison of Air-Filled Porosities Obtained By Field and Laboratory Methods

The average difference between air-filled porosity determined in the field and in the laboratory was calculated to be 3.0 percent.

When the whole soil profile is taken into consideration, the smallest differences between field and laboratory values of air-filled porosity were found for medium tex-

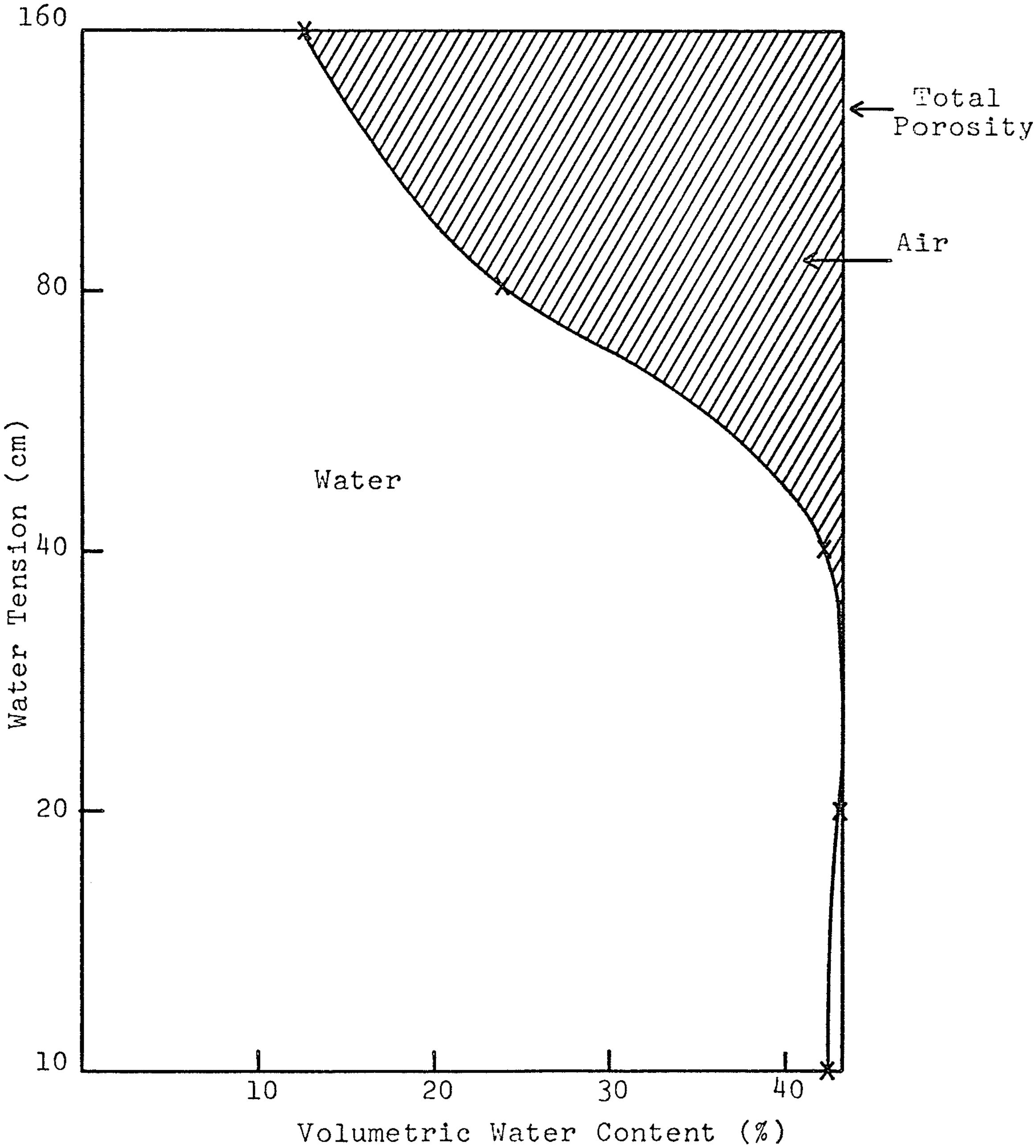

Figure 6. DISTRIBUTION OF WATER AND AIR IN COARSE TEXTURED SOIL AS DETERMINED FROM RETENTION STUDIES (SITE 2, SURFACE HORIZON).

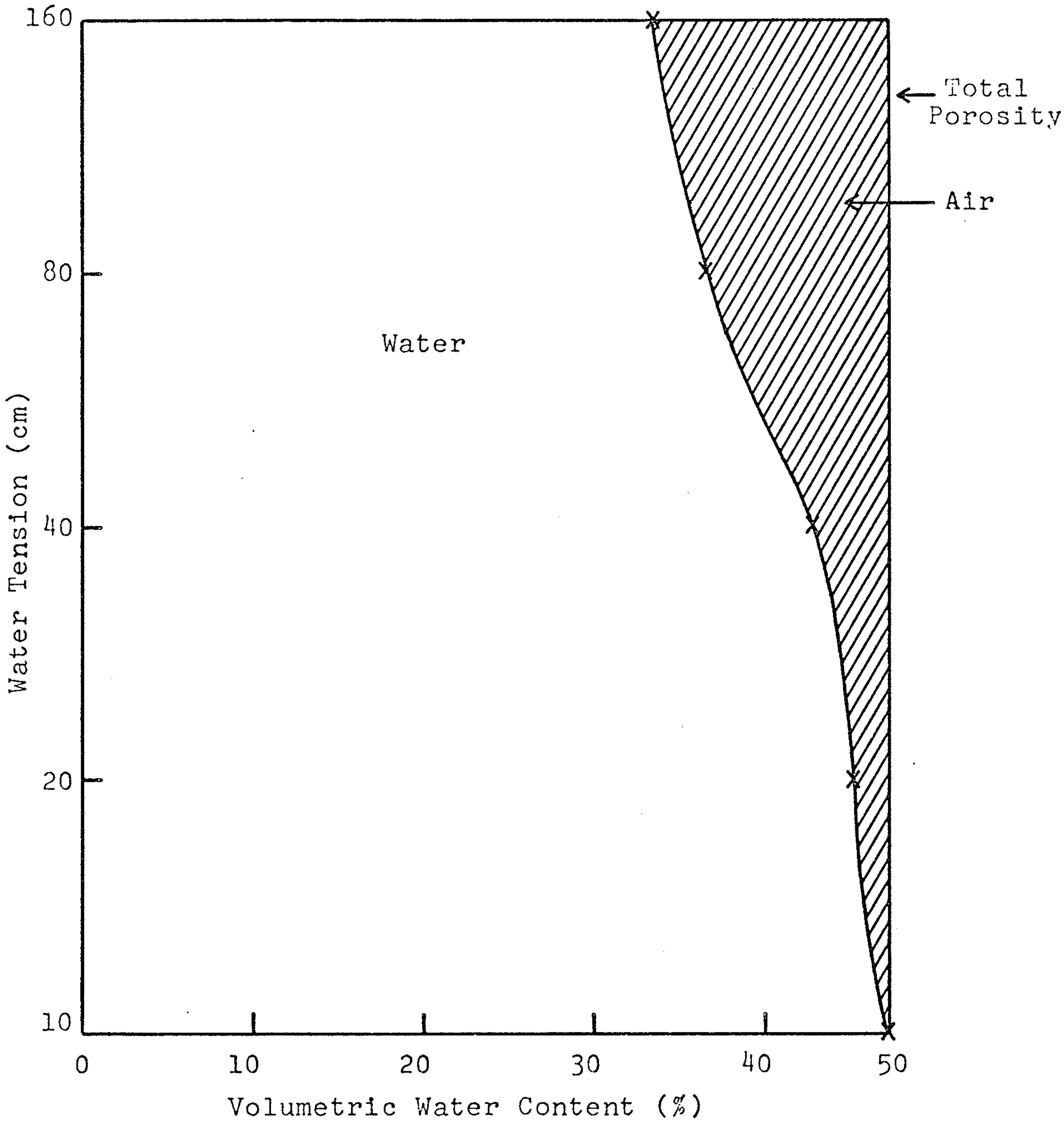

Figure 7. DISTRIBUTION OF WATER AND AIR IN MEDIUM TEXTURED SOIL AS DETERMINED FROM RETENTION STUDIES (SITE 4, SURFACE HORIZON).

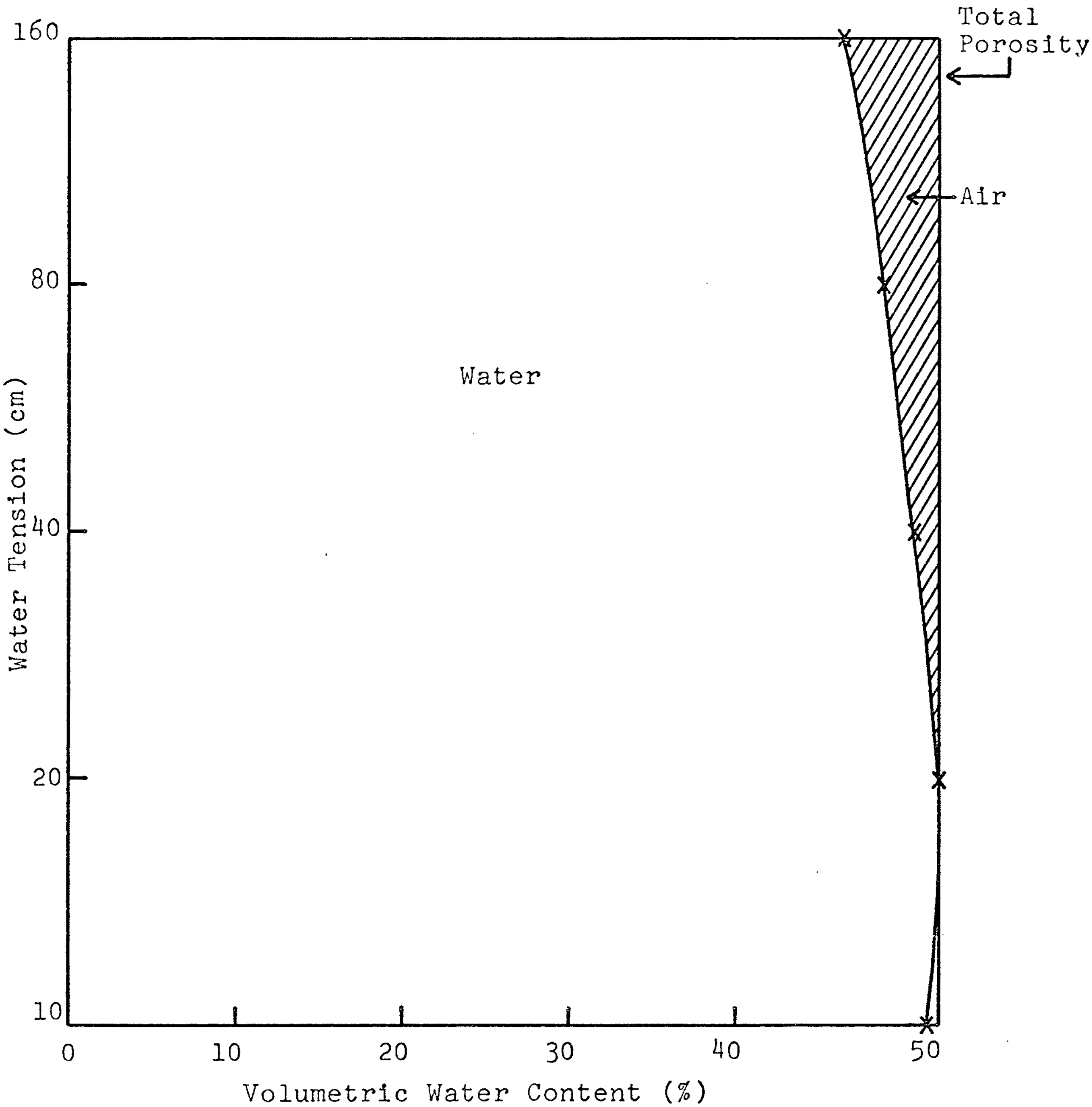

Figure 8. DISTRIBUTION OF WATER AND AIR IN FINE TEXTURED SOIL AS DETERMINED FROM RETENTION STUDIES (SITE 6, SURFACE HORIZON).

tured soils (Sites 3, 4, 5, Table IV). They ranged from 0.6 to 5.6 percent.

The differences between field and laboratory values for the coarse textured soils were found to be larger, particularly for surface and subsurface horizons. The largest difference, 8.0 percent, was found in the subsurface horizon of Long Plain soil (Table IV).

In fine and very fine textured soils, the differences between field and laboratory values were found to be larger than those in the medium textured group, particularly for horizons close to water table. The largest difference, 7.0 percent, was found close to the water table of the Osborne soil (Table IV).

Large differences found for surface horizons of coarse textured soils may be attributed to high rate of evapotranspiration and slow rate of water movement from the water table due to low hydraulic conductivity.

The major possible cause of discussed differences for fine and very fine textured soils may be attributed to the swelling of soil samples during retention studies. Swelling of soil samples during retention studies could take place as the overburden pressure, acting against swelling in undisturbed soil profile under field conditions was eliminated. The influence of swelling on values of air-filled porosity can be readily seen from the following relationship:

$$\text{Air-filled Porosity } \% = \left[1 - \frac{\text{Bulk Density}}{\text{Particle Density}} - \text{Volumetric Water Content} \right] \times 100$$

The values for bulk density determined under field conditions were used in calculating both the field and laboratory air-filled porosities. However, if swelling of soil sample took place during retention studies the actual bulk densities in the laboratory would be lower than those determined in the field and hence the total porosity would be higher than the calculated value.

Other possible reasons for the differences between values of air-filled porosity determined in the field and in the laboratory may be due to: (1) soil temperature; (2) soluble salts; and (3) fluctuation of water table under field conditions. Experimental errors, both in the field and laboratory, may also have contributed to the observed differences.

Prediction of Air-Filled Porosity in the Field on the Basis of Laboratory Results

A linear regression equation, showing the relationship between the air-filled porosity data obtained under field and laboratory conditions for all soils used in the study was determined to be:

$$\text{Air-filled Porosity (Field)} = 3.046 + 0.9691 \times \text{Air-filled Porosity (Laboratory)} \quad (r^2=0.913,\ s=2.34)$$

The correlation coefficient shows that 91.3 percent of the total variation of air-filled porosity in field can be explained by the relationship to air-filled porosity determined in the laboratory. The standard error of predicted value was calculated to be 2.34. An error of this magnitude is not excessive in predicting air-filled porosity under field conditions from laboratory data.

Proposed Tentative Agronomical Classification Based On Air-Filled Porosity

An attempt was made to employ air-filled porosity in establishing a soil drainage classification. The critical value of 10 percent of air-filled porosity was chosen for classification purposes. This value was frequently reported in literature to be the limit of adequate aeration for most soils. A close relationship between this value and growth limitations of some common crops has also been established.

The average depth to which the bulk of the roots penetrate, for some common crops, was given in Table II, p.16. On the average, the bulk of the roots are contained in the top 30 cm of soil. Therefore, it can be concluded that inadequate drainage within the distance of 30 cm will interfere with plant growth. As the distance from the soil surface to the point of inadequate aeration (drainage) increases, plant growth will be restricted to a lesser extent.

Using the above criteria, a soil in which inadequate aeration occurs within 30 cm of the soil surface, may be considered to be poorly drained. A soil in which inadequate aeration occurs within 50 to 70 cm of the soil surface may be considered to be moderately well drained soil. In this case, the bulk of the roots will be located in an adequately aerated zone. Finally, a soil at which adequate aeration occurs to a depth in excess of 70 cm may be classified as well drained. The above discussion may be summarized as follows:

Drainage Classes	Distance of Soil Surface at Which Air-Filled Porosity is Less Than 10 Percent (cm)
Poorly drained	Less than 30
Imperfectly drained	50
Moderately well drained	70
Well drained	More than 70

No attempt was made to set a time period during which there should be adequate aeration in order to obtain conditions for unrestricted plant growth. A review of literature revealed little information on this aspect. It is obvious however, that the time period is important and that it would be largely determined by factors such as: (1) climate, (2) crop, (3) soil; and (4) others. In setting a time limit one would probably have to consider the total time (complete vegetative period) as well as some critical time periods in which aeration would be most critical for plant growth.

From the air porosity data obtained under field conditions, the average distances from water table to the point above the water table where air-filled porosity was greater than 10 percent, were estimated from textural soil groups. The average distances for the coarse and medium textured soils were found to be 60 and 115 cm, respectively. In the fine and very fine textured soils air-filled porosity was found to be less than 10 percent in the entire soil profiles.

To construct the tentative soil drainage classification system for soil with a high water table (Table VI) the following information was used: (1) 10 percent air-filled porosity as the critical value required for adequate drainage; (2) the entire portion of the soil profile where air-filled porosity was less than 10 percent; and (3) average rooting depth of common crops.

TABLE VI

DEPTH OF THE WATER TABLE (cm) USED IN CLASSIFYING SOILS INTO SOIL DRAINAGE CLASSES

Textural	Drainage Classes			
Groups	Poorly Drained	Imperfectly Drained	Moderately Well Drained	Well Drained
Coarse	60-90	90-110	110-130	130
Medium	115-145	145-165	165-185	185
Fine	---	---	---	---
Very Fine	---	---	---	---

V SUMMARY AND CONCLUSIONS

1. For all textural groups with exception of very fine, air-filled porosity was distributed under both field and laboratory conditions as follows: the highest values occurred in surface or close to surface horizons, and the lowest in the horizons close to the water table. All values for very fine textured soil (Osborne Series), under both field and laboratory conditions, were determined to be zero.

2. Values of air-filled porosity predicted on the basis of retention studies conducted in the laboratory were on the average 3 percent smaller than values obtained under field conditions. The highest differences were determined for surface horizons of coarse textured soil profiles and close to water table horizons of fine textured soil profiles.

3. The variation values of air-filled porosity among soil profiles within each textural group under both, field and laboratory conditions was found to be largest for the coarse textured soil group, smaller for medium and smallest for the fine textured group. The variation was attributed mainly to differences in bulk density and to a lesser extent to differences in particle size distribution.

4. Linear regression conducted on air-filled porosity data showed a close relationship between air-filled porosity measured in the field and those predicted from water retention studies in the laboratory. The prediction equation was: air-filled porosity (field) = 3.046+0.9691 x air filled poro-

sity (laboratory) (r^2=0.913, s=2.34).

5. Value of 10 percent air-filled porosity was chosen as the critical limit for adequate aeration and employed in a proposed tentative agronomical soil drainage classification.

6. The distance from the water table to the point where the value of air-filled porosity, determined under field conditions was at least 10 percent, was on the average 58 cm for coarse textured soils, and 115 cm for medium textured soils. Air-filled porosity for fine and very fine textured soils was found to be less than 10 percent in the entire soil profiles.

7. A tentative agronomical drainage classification for coarse and medium textured soils, classified on the basis of water table depth was proposed:

Drainage Class	Water Table Depth from Soil Surface, cm	
	Coarse Textured Soil	Medium Textured Soil
Poorly drained	Less than 90	Less than 145
Imperfectly drained	90-110	145-165
Moderately well drained	110-130	165-185
Well drained	More than 130	More than 185

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VII APPENDIX

Site 1

Soil Series:	Souris.
Subgroup:	Saline Gleyed Carbonated Rego Black.
Location:	N.W. 29-4-24W.
Vegetation:	Grass (hay crop).
Parent Material:	Yellow, fine sandy, calcareous lacustrine.
Topography:	Level.
Drainage Class:	Imperfectly drained.
Water Table Depth:	145 cm (Well 13, Souris).

Horizon	Depth (cm)	Description
L-H	2-0	Black (10YR2/1, moist) moderately to well decomposed leaf mat.
Ahks	0-40	Black (10YR2/1, moist), very dark gray (10YR3/1, dry) fine sand; single grained; very friable; pH 9.0; effervescence strong; moderately saline; clear, irregular boundary.
ACkgs	40-53	Gray (10YR5/1, moist) loamy fine sand; single grained; very friable; pH 9.3; effervescence strong; few, medium, distinct yellowish brown mottles; (10YR5/6, moist) moderately saline; clear, irregular boundary.
Clkgs	53-81	Pale olive (5Y6/3, moist) loamy fine sand; single grained; slightly

Horizon	Depth (cm)	Description
		sticky, nonplastic; pH 9.1; effervescence strong; common, medium,, distinct yellowish brown mottles (10YR5/6, moist); moderately saline; gradual, smooth boundary.
C2kgs	53-142	Light olive gray (5Y6/2, moist) fine sand; single grained, slightly sticky, nonplastic; pH 8.9; effervescence strong; common, medium, distinct yellowish brown mottles (10YR5/6, moist); moderately saline; gradual, smooth boundary.
C3kgs	142+	Light olive gray (5Y6/2, moist) fine sand; single grained; slightly sticky, nonplastic; pH 8.9; effervescence strong; common, medium, distinct gray mottles (10YR6/1, moist); moderately saline.

Site 2

Soil Series: Long Plain.

Subgroup: Gleyed Orthic Regosol.

Location: N.C. 22-8-5W.

Vegetation: Grass (permanent pasture).

Topography: Level.

Drainage Class: Imperfectly drained.

Parent Material: Light brown, fine sandy, deltaic deposit.

Water Table Depth: 135 cm (Well 1, Elm Creek).

Horizon	Depth (cm)	Description
L-H	2-0	Black (10YR2/1, moist moderately to well decomposed leaf mat.
Ah	0-18	Gray (10YR4.5/1, moist), (10YR 5.5/1, dry) fine sand; weak, medium, granular; slightly sticky, nonplastic; pH 6.4; clear, irregular boundary.
C1g	18-51	Grayish brown (10YR5.5/2, moist) fine sand; single grained; nonsticky, nonplastic; pH 6.9; few, medium distinct yellowish red mottles (5Y5/6, moist); gradual, wavy boundary.
C2g	51-94	Grayish brown (10YR4.5/2, moist) fine sand; single grained; slightly sticky, nonplastic; pH 7.2; common, medium, distinct yellowish red mottles (5Y5/6, moist); diffusive boundary.
C3g	94-135	Grayish brown (10YR4.5/2, moist) fine sand; single grained; slightly sticky, nonplastic; pH 7.2; many, medium, distinct yellowish red mottles (5Y5/6, moist); diffusive boundary.

C4g	135+	Grayish brown (10YR5/2, moist), fine sand; single grained; slightly sticky, nonplastic; pH 7.2; many, medium, distinct olive yellow mottles (2.5Y6/6, moist).

Site 3

Soil Series: Hartney.

Subgroup: Saline Gleyed Carbonated Rego Black.

Location: S.W. 10-6-22W.

Vegetation: Alfalfa, willow trees within the distance of 5 m.

Parent Material: Yellow, medium textured, calcareous lacustrine.

Topography: Level.

Drainage Class: Imperfectly drained.

Water Table Depth: 188 cm (Well 6, Souris).

Horizon	Depth (cm)	Description
Apks	0-20	Black (10YR2.5/1, moist), gray (10YR5/1, dry) very fine sandy clay loam; amorphous; firm; pH 8.1; effervescence strong; weakly saline; abrupt, smooth boundary.
ACk	20-38	Dark gray (10YR4/1, moist) very fine sandy clay loam; amorphous; friable; pH 8.0; effervescence strong; clear, wavy boundary.

Horizon	Depth (cm)	Description
C1kg	38-53	Gray (10YR5/1, moist) very fine sandy clay loam; amorphous; very friable; pH 8.0; effervescence strong; few, fine, distinct, yellowish brown mottles (10YR5/8, moist); clear, wavy boundary.
C2kg	53-71	Gray (10YR5.5/1, moist) very fine sandy clay loam; amorphous; very friable; pH 8.0; effervescence strong; few, medium, distinct, yellowish brown mottles (10YR5/8, moist); clear, wavy boundary.
C3kg	71-86	Gray (10YR4/1, moist) very fine sandy loam; amorphous; friable; pH 8.0; effervescence strong; few, medium, distinct, yellowish brown mottles (10YR5/8, moist); clear, wavy boundary.
C4kg	86-107	Light olive gray (5Y6/2, moist) very fine sandy loam; friable; pH 7.9; effervescence strong; common, medium, distinct, yellowish brown (10YR 5/8, moist; gradual, wavy boundary.
C5kg	107-150	Olive gray (5Y5/2, moist) silty loam; amorphous; sticky, slightly plastic; pH 7.9; effervescence weak; many, medium, distinct, yellowish

Horizon	Depth (cm)	Description
		brown mottles (10YR5/8, moist); abrupt, smooth boundary.
C6kg	150-188	Olive gray (5Y5/2, moist) very fine sandy loam; amorphous; sticky, slightly plastic; pH 7.9; effervescence weak; distinct yellowish brown mottles (10YR5/8, moist).

Site 4

Soil Series:	Hartney.
Subgroup:	Gleyed Rego Black.
Location:	S.E. 19-6-21W.
Vegetation:	Freshly cultivated summer-fallow field.
Parent Material:	Yellow, medium textured, calcareous lacustrine.
Topography:	Level to very gentle slope.
Drainage Class:	Imperfectly drained.
Water Table Depth:	92 cm (Well 29, Souris).

Horizon	Depth (cm)	Description
Ap	0-15	Black (10YR2/1, moist), dark gray (10YR4.5/1, dry) loam; weak, medium, granular; friable; pH 8.2; effervescence strong; clear, smooth boundary.

Horizon	Depth (cm)	Description
ACk	15-25	Dark grayish brown (10YR3.5/2, moist) silty clay loam; amorphous; sticky, slightly plastic; pH 8.2; effervescence strong; abrupt, irregular boundary.
Cca	25-38	Grayish brown (10YR5/2, moist) silty clay loam; amorphous; sticky, slightly plastic; pH 8.2; effervescence very strong; gradual, smooth boundary.
C1kg	38-51	White (10YR8/1, dry) silty clay loam; amorphous; sticky, slightly plastic; pH 8.1; effervescence weak; common, medium, distinct yellow mottles (10YR8/6, dry); gradual, smooth boundary.
C2kg	51-91	White (10YR8/1, dry) loam; amor-pH 8.0; effervescence weak; many medium, distinct yellow mottles (10YR8/6, dry); gradual, smooth boundary.
C3kg	91-114	White (10YR8/1, dry) silt loam; amorphous; sticky, slightly plastic; pH 7.7; effervescence weak; many, medium, distinct yellow

Horizon	Depth (cm)	Description
		mottles (10YR8/6, dry); gradual, smooth boundary.
C4kg	114+	Pale brown (10YR6/3, dry); silt loam, amorphous; sticky, slightly plastic; pH 7.8; medium, distinct brownish yellow mottles (10YR 6/6, dry).

Site 5

Soil Series:	Hartney.
Subgroup:	Saline Gleyed Carbonated Rego Black.
Location:	E.C. 33-6-22W.
Vegetation:	Oats, very poor crop.
Parent Material:	Yellow, medium textured, calcareous lacustrine.
Topography:	Local depression.
Drainage Class:	Imperfectly drained.
Water Table Depth:	178 cm (Well 30, Souris).

Horizon	Depth (cm)	Description
Apks	0-18	Black (10YR2/1, moist), very dark gray (10YR3/1, dry) loam; strong, medium, prismatic; firm; moist; pH 7.8; effervescence weak; pseudomycelia of salts, moderately saline; abrupt, smooth boundary.

Horizon	Depth (cm)	Description
Ahks	18-28	Very dark gray (10YR3/1, moist) loam; weak, medium, subangular blocky; friable; pH 7.8; effervescence strong; pseudomycelia of salts, moderately saline; clear, smooth boundary.
ACkgs	28-38	Dark gray (10YR3.5/1, moist) clay; amorphous; very friable; pH 7.9; effervescence strong; pseudomycelia of salts and gypsum crystals, weakly saline; few, fine, distinct yellowish brown mottles (10YR5/8, moist); gradual, wavy boundary.
C1kgs	38-69	Light olive brown (2.5Y5.5/4, moist) silty clay loam; amorphous; very friable; pH 7.9; effervescence strong; pseudomycelia of salts and gypsum crystals, weakly saline; common, medium, distinct yellowish brown mottles (10YR5/8, moist); gradual, smooth boundary.
C2kgs	69-102	Light olive brown (2.4Y5/4, moist) silt loam; amorphous; sticky, plastic; pH 7.9; effervescence strong;

Horizon	Depth (cm)	Description
		pseudomycelia of salts; weakly saline; many, medium, distinct gray mottles (2.5Y6/0, moist); gradual, smooth boundary.
C3kgs	102-130	Light olive brown (2.5Y5/4, moist) silty loam; amorphous; sticky, slightly plastic; pH 7.8; effervescence strong; pseudomycelia of salts and gypsum crystals, weakly saline; many, medium, distinct gray mottles (2.5Y 6/0, moist); gradual, smooth boundary.
C4kgs	310+	Light olive brown (2.5Y5/4, moist) silty loam; amorphous; sticky, slightly plastic; pH 7.9; effervescence strong; pseudomycelia of salts and gypsum crystals, weakly saline; many, medium, distinct gray mottles (2.5Y6/0, moist).

Site 6

Soil Series: Cameron.

Subgroup: Gleyed Rego Black.

Location: S.E. 26-6-21W.

Vegetation: Freshly cultivated summer-fallow field.

Parent Material:		Yellow, moderately fine textured, calcareous lacustrine.
Topography:		Level to depressional.
Drainage Class:		Imperfectly drained.
Water Table Depth:		152 cm (Well 1, Souris).
Horizon	Depth (cm)	Description
Aps	0-20	Black (2.5Y2/0, moist), very dark gray (10YR3/1, dry) loam; weak, fine granular; pH 7.3; friable; pseudomycelia of salts; abrupt, smooth boundary.
ACks	20-28	Grayish brown (2.5Y5/2, moist) loam; amorphous; friable; pH 7.8; effervescence weak; pseudomycelia of salts; diffusive boundary.
Ccasg	28-41	Olive (5Y5/3, moist) clay; amorphous; very sticky, very plastic; pH 7.8; effervescence very strong; pseudomycelia of salts and crystals of gypsum; few, medium, distinct yellowish brown mottles (10YR5/8, moist); diffusive boundary.
Csakg	41-81	Olive (5Y5/3, moist) silty clay loam; amorphous; very sticky,

Horizon	Depth (cm)	Description
		plastic; pH 8.2; effervescence very strong; Pseudomycelia of salts and gypsum crystals, weakly saline; common, medium, distinct yellowish brown mottles (10YR 5/8, moist); diffusive boundary.
Clkgs	81-152	Light olive brown (2.5Y5/4, moist) silty clay loam; amorphous; very sticky, plastic; pH 8.0; effervescence strong; pseudomycelia of salts and gypsum crystals; many, medium, prominent yellowish brown mottles (10YR5/8, moist); diffusive boundary.
C2kgs	152+	Light olive brown (2.5Y5/4, moist) silty loam; amorphous; very sticky, plastic; pH 8.0; effervescence strong; pseudomycelia of salts and gypsum crystals; many, medium, prominent yellowish brown mottles (10YR5/8, moist).

Site 7

Soil Series: Neuhorst.

Subgroup: Gleyed Rego Black.

Location: N.E. 4-3-5W.

Vegetation:		Freshly cultivated summer-fallow field.
Parent Material:		Light brown, fine textured, calcareous lacustrine.
Topography:		Level.
Drainage Class:		Imperfectly drained.
Water Table Depth:		84 cm (Well 5, Morden).
Horizon	Depth (cm)	Description
Ah	0-20	Black (2.5Y2/0, moist), black (2Y2.5/0, dry) clay loam; weak, medium granular; friable; pH 6.1; irregular, abrupt boundary.
Ahg	20-48	Black (2.5Y2/0, moist) very dark grayish brown (2.5Y3/2, moist) clay; medium, angular blocky; very sticky, very plastic; pH 7.3; few, distinct, olive brown mottles (2.5Y4/4, moist); abrupt, irregular boundary.
Clkgs	48-66	Dark gray (2.5Y3.5/0, moist) silty clay; amorphous; very sticky, very plastic; pH 7.9; effervescence strong; large amount of gypsum crystals; common, medium, distinct light yellowish brown mottles (2.5Y6/4, moist) gradual, smooth

Horizon	Depth (cm)	Description
		boundary.
C2kgs	66-81	Grayish brown (2.5Y5/2, moist) silty clay; amorphous; very sticky, very plastic; pH 8.0; effervescence strong; large amount of gypsum crystals, weakly saline; common, medium, distinct light yellowish brown mottles (2.5Y6/4, moist); abrupt, smooth boundary.
C3kgs	81+	Grayish brown (2.5Y5/2, moist) very fine sandy clay loam; amorphous; sticky, plastic; pH 8.2; effervescence very strong; large amount of gypsum crystals, weakly saline; common, medium, distinct light yellowish brown mottles (2.5Y6/4, moist).

Site 8

Soil Series: Pipestone.

Subgroup; Saline Gleyed Carbonated Rego Black.

Location: S.E. 2-4-21W.

Vegetation: Barley.

Parent Material: Yellow brown, fine textured, calcareous lacustrine.

Topography:		Level.
Drainage Class:		Imperfectly drained.
Water Table Depth:		132 cm (Well 39, White Water Lake).
Horizon	Depth (cm)	Description
Apks	0-15	Black (10YR2/1, moist), very dark gray (10YR4/1, dry) silty clay; moderate, medium granular; friable; pH 8.3; effervescence slight; pseudomycelia of salts and carbonates, strongly saline; abrupt, smooth boundary.
Ahks	15-36	Very dark gray (10YR4/1, moist); silty clay; amorphous; very sticky, very plastic; pH 8.5; effervescence strong; pseudomycelia of salts and carbonates; gradual, smooth boundary.
ACkgs	36-102	Olive gray (tY5/2, moist) silty clay; amorphous; very sticky, very plastic; pH 8.3; efferescence strong; large amount of gypsum crystals; few, medium, distinct yellowish brown mottles (10YR 5/8, moist); diffusive boundary.
Clkgs	102-127	Pale olive (5Y6/3, moist) silty

Horizon	Depth (cm)	Description
		loam; amorphous; sticky, plastic; pH 8.4; effervescence strong; large amount of gypsum crystals; common, medium, distinct yellowish brown mottles (10YR5/8, moist); diffusive boundary.
C2kgs	127+	Olive (5Y5/4, moist) loam; amorphous; sticky, plastic; pH 8.3; effervescence strong; large amount of gypsum crystals; common, medium, distinct yellowish brown mottles (10YR5/8, moist).

Site 9

Soil Series: Cranmer.

Subgroup: Gleyed Carbonated Rego Black.

Location: N.W. 30-6-22W.

Vegetation: Wheat.

Parent Material: Yellow, fine textured, calcareous lacustrine.

Topography: Very gentle slope.

Drainage Class: Imperfectly drained.

Water Table Depth: 132 cm (Well 5, Souris).

Horizon	Depth (cm)	Description
Apk	0-20	Black (10YR2/1, moist), very

Horizon	Depth (cm)	Description
		dark gray (10YR3/1, dry) clay loam; weak, medium granular; sticky, plastic; pH 7.7 weak effervescence; abrupt, smooth boundary.
C1kg	20-64	Olive (5Y4/3, moist); silty clay loam; amorphous; very sticky, plastic; pH 7.7; effervescence strong; few, medium, distinct yellowish brown mottles (10YR 5/8, moist); gradual, smooth boundary.
C3kg	64-137	Brown gray (2.5Y4/2, moist) silty clay loam; amorphous; very sticky, plastic; pH 7.7; effervescence very strong; common, medium, distinct yellowish brown mottles (10YR5/8, moist); gradual, smooth boundary.
C4kg	137+	Dark grayish brown (2.5Y4/2, moist) silty clay; moderate, medium, subangular blocky; very sticky, plastic; pH 7.7; effervescence strong; many, med-

Horizon	Depth (cm)	Description
		ium distinct yellowish brown mottles (10YR5/8, moist).

Site 10

Soil Series: Osborne.

Subgroup: Carbonated Rego Humic Gleysol.

Location: River Lot 1, Parish of St. Norbert (Tp. 8, Rge. 3E).

Vegetation: Freshly cultivated after harvested barley.

Parent Material: Gray, very fine textured, calcareous lacustrine.

Water Table Depth: 92 cm (Glenlea).

Horizon	Depth (cm)	Description
Apgk	0-13	Black (10YR2/1, moist), very dark gray (10YR3/1, dry) clay; strong, medium granular; firm; pH 7.4; effervescence very weak; few, fine, distinct yellowish brown mottles (10YR5/6, moist); abrupt, smooth boundary.
ACkg	13-23	Very dark grayish brown (2.5Y 3/2, moist) clay; weak, medium angular blocky; very sticky, very plastic; pH 7.4; effervescence strong; common, medium,

Horizon	Depth (cm)	Description
		distinct yellowish brown mottles (10YR5/6, moist); clear, smooth boundary.
C1kg	23-48	Dark brown gray (2.5Y4/2, moist) clay; weak, medium subangular blocky; very sticky, very plastic; pH 7.7; effervescence strong; many, medium, distinct yellowish brown mottles (10YR5/6, moist); gradual, smooth boundary.
C2kg	48-76	Dark grayish brown (2.5Y4/2, moist) clay; weak, medium, subangular blocky; very sticky, very plastic; pH 7.7; effervescence strong; many, medium, distinct yellowish brown mottles (10YR5/6, moist); gradual, smooth boundary.
C3kg	76-122	Dark grayish brown (2.5Y4/2, moist) clay; amorphous; very sticky, very plastic; pH 7.7; effervescence strong; many, medium, distinct yellowish brown mottles (10YR5/6, moist).

TABLE 1A

PERCENTAGE OF VOLUMETRIC WATER CONTENT FOR SOURIS SERIES (SITE 1)

Horizon	Sample Depth cm	Total Porosity %	Water Tension, cm 0	10	20	40	80	160
Ahks	38	35.8	33.6	35.7	36.1	34.4	30.9	27.5
Clkgs	58	35.4	36.7	36.2	35.9	34.1	28.8	23.4
C2kgs	91	36.8	37.5	37.9	37.7	36.5	32.3	23.2
C3kgs	145	39.2	37.2	35.5	34.9	33.9	26.4	18.2

Water Table Depth: 145 cm.

TABLE 2A

PERCENTAGE OF VOLUMETRIC WATER CONTENT FOR LONG PLAIN SERIES (SITE 2)

Horizon	Sample Depth cm	Total Porosity %	Water Tension, cm 0	10	20	40	80	160
Ah	8	45.6	42.2	42.5	43.1	42.3	23.9	12.8
Clg	48	42.9	36.3	36.1	36.7	36.4	19.2	9.1
C2g	79	41.4	36.5	36.3	36.2	36.2	18.9	7.7
C3g	114	40.0	37.8	36.8	36.9	36.7	20.3	11.4
C4g	135	41.2	37.5	37.2	37.3	37.4	24.4	15.4

Water Table Depth: 135 cm.

TABLE 3A

PERCENTAGE OF VOLUMETRIC WATER CONTENT FOR HARTNEY SERIES (SITE 3)

Horizon	Sample Depth cm	Total Porosity %	Water Tension, cm 0	10	20	40	90	170
Apks	8	39.6	43.0	42.9	43.3	43.0	41.7	40.1
ACk	33	43.6	47.7	46.2	46.2	46.0	45.4	42.7
C1kg	51	45.7	47.3	45.6	45.3	43.5	40.3	36.0
C2kg	68	43.2	43.4	41.6	41.3	39.7	36.2	30.8
C4kg	94	42.0	42.5	41.2	41.1	40.1	37.2	28.6
C5kg	137	41.9	45.8	42.9	43.2	42.2	39.6	22.8
C6kg	178	43.1	49.4	44.2	44.1	44.1	41.2	39.9

Water Table Depth: 188 cm.

TABLE 4A

PERCENTAGE OF VOLUMETRIC WATER CONTENT FOR HARTNEY SERIES (SITE 4)

Horizon	Sample Depth cm	Total Porosity %	Water Tension, cm 0	10	20	40	80	160
Apk	12	57.7	48.4	47.1	45.3	43.0	36.8	33.4
Cca	27	48.1	51.6	51.9	51.6	51.10	48.6	46.7
C1kg	44	40.2	39.8	39.0	38.6	38.9	35.8	33.2
C2kg	74	43.2	40.5	41.5	40.1	39.1	35.4	33.0
C4kg	92	42.8	42.4	41.5	41.3	40.6	38.7	37.0

Water Table Depth: 92 cm.

TABLE 5A

PERCENTAGE OF VOLUMETRIC WATER CONTENT FOR HARTNEY SERIES (SITE 5)

Horizon	Sample Depth cm	Total Porosity %	Water Tension, cm					
			0	10	20	40	90	170
Apks	8	42.5	45.5	44.8	45.4	45.6	45.1	44.1
ACkgs	28	49.4	46.1	45.5	44.6	41.3	36.2	31.8
Clkgs	53	48.0	41.1	43.4	38.8	36.8	31.9	28.7
C3kgs	84	44.5	43.8	44.4	43.3	42.2	40.6	39.2
C3kgs	114	44.2	44.4	42.3	41.7	41.6	40.6	39.3
C4kgs	135	42.4	51.2	47.6	47.4	46.9	45.8	44.5

Water Table Depth: 178 cm.

TABLE 6A

PERCENTAGE OF VOLUMETRIC WATER CONTENT FOR CAMERON SERIES

(SITE 6)

Horizon	Sample Depth cm	Total Porosity %	Water Tension, cm					
			0	10	20	40	80	160
Aps	10	46.3	51.9	51.5	52.3	50.7	49.0	46.7
Ccags	38	47.1	43.8	43.8	45.0	42.4	40.7	38.6
Csakg	74	54.6	57.0	56.5	56.5	54.3	53.0	49.0
Clkgs	124	48.5	48.4	48.2	48.5	47.3	46.4	44.5
C2kgs	152	52.0	56.3	56.3	56.1	52.1	51.1	49.2

Water Table Depth: 152 cm.

TABLE 7A

PERCENTAGE OF VOLUMETRIC WATER CONTENT FOR NEUHORST SERIES (SITE 7)

Horizon	Sample Depth cm	Total Porosity %	Water Tension, cm					
			0	10	20	40	80	160
Ah	13	48.3	57.5	54.3	52.7	50.3	47.2	44.2
Ahg	38	46.5	46.1	46.1	46.5	46.0	44.4	42.7
Clkgs	51	44.4	45.5	45.6	46.2	45.9	44.6	42.9
C2kgs	69	49.2	51.5	50.8	50.3	47.7	44.1	40.6
C3kgs	84	46.0	47.0	46.8	46.1	44.4	40.4	36.6

Water Table Depth: 84 cm.

TABLE 8A

PERCENTAGE OF VOLUMETRIC WATER CONTENT FOR PIPESTONE SERIES (SITE 8)

Horizon	Sample Depth cm	Total Porosity %	Water Tension, cm					
			0	10	20	40	80	160
Apks	10	59.7	59.1	58.8	59.5	57.2	55.0	51.7
Ahks	33	48.8	50.9	51.1	52.3	50.8	49.5	47.2
ACks	79	50.8	52.6	50.5	50.8	49.3	48.2	46.2
Clkgs	117	49.5	47.7	45.2	44.5	43.0	42.4	40.4
C2kgs	132	35.2	39.9	38.7	38.7	37.7	37.0	35.9

Water TAble Depth: 132 cm.

TABLE 9A

PERCENTAGE OF VOLUMETRIC WATER CONTENT FOR CRANMER SERIES (SITE 9)

Horizon	Sample Depth cm	Total Porosity %	Water Tension, cm 0	10	20	40	80	160
Apk	13	41.8	43.2	44.7	45.1	44.5	43.0	41.7
C1kg	43	45.2	42.3	44.1	44.0	42.3	40.7	39.4
C2kg	84	45.6	45.1	46.1	45.6	43.3	41.9	40.5
C3kg	132	47.4	47.0	48.2	48.0	47.2	46.7	45.8

Water Table Depth: 132 cm.

TABLE 10A

PERCENTAGE OF VOLUMETRIC WATER CONTENT FOR OSBORNE SERIES (SITE 10)

Horizon	Sample Depth cm	Total Porosity %	Water Tension, cm 0	10	20	40	80	160
Apgk	10	52.8	63.1	62.6	62.0	59.2	59.4	57.0
ACgk	20	54.2	61.9	61.6	61.4	60.9	59.4	57.1
C1kg	36	52.5	62.6	61.8	61.6	61.1	59.7	56.9
C2kg	64	51.5	60.2	58.8	58.5	57.1	55.4	53.0
C3kg	92	51.5	59.8	59.2	58.9	57.7	56.1	54.3

Water Table Depth: 92 cm.