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Juhani Päivänen

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HYDRAULIC CONDUCTIVITY AND WATER RETENTION IN PEAT SOILS

JUHANI PÄIVÄNEN

SELOSTE:
TURPEEN VEDENLÄPÄISEVYYS JA VEDENPIDÄTYSKYKY

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PREFACE

The present investigation is a part of a larger study of the optimum water relationships of drained peat soils with regard to tree growth. The study was started in 1965 in the Department of Peatland Forestry, University of Helsinki. My role in the solution of the problems involved has been to assess the basic hydrologic properties of various peat soils. The results obtained from the partial studies concerning the hydraulic conductivity and water retention capacity of peat are presented in this paper.

Prof. LEO HEIKURAINEN, in his capacity as project leader, entrusted me with this part of the total project, and he closely followed the progress of my work. Acting Prof. KUSTAA SEPPÄLÄ, Dr. EERO PAAVILAINEN, Dr. PAAVO ELONEN and Mr. ERKKI AHTI, B.Sc. (Forestry), read the manuscript, making numerous suggestions for its improvement. Thanks to Dr. JUHANI SARASTO's positive attitude toward my work, I was able to carry out the field work required at the Forest Training Station of the University of Helsinki. Both in the field and in the laboratory I was assisted by many persons. Computing was planned in cooperation with Mr. JUKKA LAINE. Translation of the Finnish manuscript was done by Mr. KARL-JOHAN AHLSVED, B.Sc. (Forestry), and the English manuscript was checked by Mr. JOHN DEROME, B.Sc.

In the fall of 1970, I made a study tour to the U.S.A., supported by a grant from the W. K. Kellogg Foundation. Here I had an excellent opportunity to make myself acquainted with the methodology employed and the equipment used in the study of the physical properties of peat in a number of research organizations. With regard to the present work I wish to mention, in particular, Dr. DON BOELTER, U. S. Forest Service, North Central Forest Experiment Station, Northern Conifers Laboratory, Grand Rapids, Minn., for his valuable direction.

The National Research Council for Agriculture and Forestry and the Foundation for Research of National Resources in Finland made it economically possible to carry out this study. I wish to express my sincere thanks to all the persons and institutions mentioned, and to the Society of Forestry in Finland, which accepted the study for publication in its series.

Helsinki, March 1973

Juhani Päivänen

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To begin with, it is necessary to define the concepts used in the present paper to describe the water permeability and the water retention capacity of different peats as well as their structure.

In general, *permeability* is considered to be the property of a porous medium that indicates the ease with which gases, liquids, or other substances can pass through it (ANON. 1970, p. 12). In studies of the permeability of soil to water, we usually distinguish between two conceptually different categories of permeability, namely that of *saturated* and of *unsaturated soil*.

DARCY (1856, p. 576) was the first to present an equation for determining the rate of water movement in saturated soil:

$$Q = \frac{Ks}{e}(P + H + e - f), \quad (1)$$

in which
Q = the volume of water passing through a soil sample in unit time,
K = a coefficient describing the permeability of the soil to water,
s = the cross-sectional area of the soil sample,
e = the thickness of the soil sample,
P = the atmospheric pressure,
H = the height of the water layer on top of the soil sample,
f = the elasticity of the air.

The equation has also been presented in an abbreviated form by disregarding the influence of air elasticity and atmospheric pressure in studies of the water permeability of samples from different soils under similar conditions (cf., e.g., SILLANPÄÄ 1956, p. 10):

$$Q = \frac{Ks}{e}(H + e). \quad (2)$$

The formula can also be given a more general form:

$$v = K \cdot i, \quad (3)$$

in which
v = the rate of flow (unit volume/unit area/unit time) and

$$i = \frac{(H + e)}{e} = \text{the hydraulic gradient.}$$

The coefficient K used in Darcy's law has more recently been termed *hydraulic conductivity*, and it consequently indicates the flux of water per unit gradient of hydraulic potential (ANON. 1970, p. 19). K is equal to velocity and is usually expressed as cm/sec or cm/min.

112 Concepts pertaining to the water retention

1121 Soil-water energy relationships

Much attention has previously been given to the division of soil water into different categories on the basis of the forces influencing it. On a physical basis the soil water has thus been divided into free, capillary and hygroscopic water (e.g. BECKER-DILLINGEN 1939, p. 123; KRAMER 1949, p. 25; BUCKMAN and BRADY 1965, p. 172). Some suggestions for the classifying of soil water present still more detailed divisions, for example, water of crystallization, solid water (ice), water vapor, firmly bound water, loosely bound water and gravitational water (RODE 1959, pp. 424–431). Moreover, soil may contain chemically bound water in a great number of different organic compounds.

With regard to the availability of the water to higher plants, the following biological classification has been presented: superfluous, available and unavailable water (e.g. BUCKMAN and BRADY 1965, p. 173).

In order to make it possible to compare the water contents of different soils with each other, particularly from the viewpoint of the water consumption of the vegetation, the soil water relationships are described with the aid of soil-water energy relationships. The *total potential* of soil water can be divided into the *gravitational potential*, the *pressure potential* and the *osmotic potential* (e.g. HILLEL 1971, p. 52). The gravitational potential is independent of the chemical and pressure conditions of the soil water, and depends solely on the relative depth at which the soil layer under study is located. As the salt content of peat is usually very low, the influence of the osmotic pressure of soil water on the free energy may be considered negligible in the case of peat soils.

In determinations of the free energy of soil water, the zero point used is the free energy of pure, free water. The water in saturated soil is not under tension and moves under the influence of gravity. Below the ground water table the »submerge potential» (Rose 1966, p. 129), or the »hydrostatic potential» (Rawlins 1971, p. 8) is positive. If water is now removed, the pressure drops below the atmospheric pressure prevailing, and the tension with which the water is held increases. The more water is removed, the more difficult will it be to remove the remaining water, i.e., the free energy deficit increases. Thus, the tension with which water is held can be considered as being a negative pressure potential, or a *matric potential* (Anon. 1962, p. 2). This soil-water potential results from the capillary and adsorptive forces produced by the soil matrix. These forces attract and bind water in the soil and lower its potential energy below that of bulk water (Hillel 1971, p. 57). Some research workers also extend the concept matric potential to cover the forces caused by the electrostatic fields of soil particles (e.g. Gardner 1968, p. 111). The terms *matric potential*, *matric suction*, and *soil-water suction* have been used interchangeably in literature. The two last-mentioned terms have been mainly used to avoid the negative sign necessary to indicate a negative matric potential (Hillel 1971, p. 61).

The tension with which soil water is held is usually expressed as the force required to compensate for the suction of the soil. This force can be expressed, for example, in terms of pressure, which, being exerted on the soil water, increases its free energy to zero, or that of pure, free water.

The water tension increases so rapidly with decreasing soil-water content that graphical presentations of the phenomenon using coordinate systems with equal x and y scale divisions is impractical. For this reason, semi-logarithmic presentations have usually been used in studies concerning soil-water energy relationships. Schofield (1935, p. 39) was the first to use the term pF (in which p describes the logarithmic character of the concept and F stands for »free energy»), which is the logarithm of the height of the water column in centimeters corresponding to the free energy deficit. The following table shows the relationship between the height of the water column and the pF value. As the unit kp/cm² is commonly used to express pressure, it has been included in the table.

Height of the water column, cm	pF value	Pressure, kp/cm²
10	1	0.01
100	2	0.1
1000	3	1.0
10000	4	10.0

The concept *saturated soil* refers to the state of the soil at which the pores of the soil are completely filled with water. When excess water has been applied to soil or when rain water that has wetted the soil completely drains through the soil in a downward direction, a condition is gradually reached at which the downward movement essentially ceases. The soil is now said to have reached its *field capacity* (e.g. Veihmeyer and Hendrickson 1949, p. 75). The time required for the soil to reach field capacity under the conditions prevailing in the field has been assessed at 2—3 days. Concerning the matric suction of soil at field capacity definitions have been presented which differ very much from each other. Quite frequently 1/3 atm, or the weight of a water column with a height of 346 cm, has been used for field capacity. This corresponds to a pF value of 2.54 (e.g. Colman 1947, p. 280; Richard 1953, p. 27). Nevertheless, field experiments have resulted in considerably lower matric suction values: for example, 25—125 cm H_2O (Smith and Browning 1947, p. 21). According to Heinonen (1954, p. 11), the differences are due to the fact that determination of the matric suction at field capacity was carried out in the first-mentioned case in the laboratory on powdered and soaked soil samples using the centrifuge method. PEERLKAMP and BOEKEL (1960, p. 10) are of the opinion that the field capacity of soil is best defined as a well-chosen matric suction value, and not on the basis of determinations carried out in the field.

When the matric suction reaches a value of approximately pF 4.2, higher plants are no longer capable of absorbing water from the soil. The state now prevailing is called the *permanent wilting point.* There is a slight difference in the wilting point between different plant species due to differences in their osmotic suction (KOZLOWSKI 1965, p. 67).

The *ground water table* has usually been defined as the highest level at which free water occurs, or would occur if sufficiently large pores were present in the soil. At the ground water table the hydrostatic pressure of the soil water is zero, being positive below, and negative above it (RICHARD 1963, p. 247). As was established earlier, the imaginary negative values of this pressure equal the matric suction.

1122 The relationships between higher plants and soil water

The difference in the soil water content between field capacity and permanent wilting point is usually considered as being available to higher plants (e.g. KRAMER 1949, p. 39; ASLYNG 1952, p. 29; MARSHALL 1959 a, p. 2). As was stated earlier, field capacity as a pure concept is a vague indicator of the water content of soils. Therefore, several research workers have suggested that the range of soil water conditions in which water is available to higher plants be expressed directly on the pF scale, for example, pF 2.0—4.2 (HOLSTENER-JØRGENSEN 1958, p. 114). Narrower ranges, too, have been suggested, for example, pF 3.0—4.1 (WOODRUFF 1940, p. 41).

However, these limit values cannot be applied in the case of peat soils because in such soils the water table is located close to the ground surface. At equilibrium the vertical distance between the soil layer under observation and the water table expresses directly the matric suction in terms of the height of the water column (RICHARDS 1941 b). If, for example, the distance between the soil layer under observation and the water table is 30 cm, the corresponding matric suction is pF 1.47. If, in turn, the distance mentioned is 50 cm, the corresponding value of the matric suction is pF 1.70 (see e.g. AHTI 1972). Consequently, the matric suction corresponding to the upper limit of available water would be considerably lower in the case of soils with high water tables such as peat soils, than has been presented for mineral soils. This matter will be dealt with further on in this study.

The maximum quantity of water which can be stored by the soil in an available form with regard to higher plants is called the *available-water capacity* (HEINONEN 1954, p. 76).

Some research workers are of the opinion that plants can use water for growth and assimilation in a similar way at all water content values between field capacity and the permanent wilting point (VEIHMEYER and HENDRICKSON 1949, p. 89). Nevertheless, several studies have shown that vegetative growth becomes slower when the water content of the soil decreases below field capacity (e.g. HEINONEN 1954, p. 14). This is explained by the increasing matric suction as the soil dries, and consequently, a larger quantity of energy is required to remove a certain amount of water from the soil. Moreover, soil drying slows down the movement of the water film surrounding the soil particles, and this means that the movement of water towards the root hairs is restricted (MARSHALL 1959 a, pp. 55—56). It has been established that the yields of certain cultivated plants decrease with increasing matric suction (e.g. WADLEIGH and AYERS 1945, TAYLOR 1952, GALVIN 1965). On the basis of this phenomenon we may speak about *decreasingly available water* (HEINONEN 1954, p. 76).

No optimum curves of the kind presented for the interrelationships between the growth of cultivated plants and the soil-water tension of the substrate (HEINONEN 1954, p. 15) have been worked out for forest trees. It is clear, however, that, particularly in the case of undrained peatlands, excessive water in the substrate checks root growth

(Paavilainen 1967) and microbical activity (Lähde 1966) and may lead to unfavorable biochemical phenomena. It has been established, for example, that the growth of trees is better, the more efficiently drained is the substrate in which they grow (Lukkala 1929). This can be observed in the proximity of ditches. One of the most important tasks of draining is therefore to adjust the water content of the soil at a level which ensures sufficient aeration of the soil (Romell 1922, p. 233). Field experiments have also shown that the possibility of overdrainage exists if fertilizer is applied in conjunction with extremely efficient drainage (Huikari and Paarlahti 1967, p. 105).

113 Concepts pertaining to the structure of peat

In order to enable examination of the interrelationships between the fundamental hydrological properties and the structure of peat, the basic concepts used in the study of peat structure must be defined.

The *peat classification* system used in the present study is based on macroscopic determination of the relative occurrence of various peat constituents in peat samples (cf. Heikurainen and Huikari 1952, Heikurainen 1964). When necessary, a microscope was used to determine the peat type for samples in an advanced stage of decomposition. The peats were divided into three groups based on the dominant peats constituent as follows: Sphagnum peats (S peats), sedge peats (C peats) and woody peats (L peats).

In addition to the peat type, the stage of decomposition of the peat affects its structure. Methods used to determine the degree of decomposition of peat have been dealt with previously (Päivänen 1969), and only the most important ones will be reviewed here.

For this study the classification of peats according to their stage of decomposition was carried out using the scale presented by von Post (1922). According to this method, the *degree of humification* of peat is determined by means of ocular study of peat samples. A fresh peat sample is pressed in the hand, and the degree of humification is estimated on the basis of the color of the water which runs out from the sample, the quantity of amorphous peat mass and the elasticity of the peat remaining in the hand. von Post's scale includes ten classes of humification: H 1 refers to fully undecomposed plant material and H 10 to fully decomposed peat.

As peat decomposes it also becomes denser; its *bulk density* increases. In the present study the bulk density of peat was determined from the oven-dry weight (105° C) of a core of undisturbed and saturated peat. This method has been described previously by Päivänen (1968, p. 4), Boelter (1969, p. 607) and Anon. (1970, p. 3).

According to the literature concerning peat, the *humification percentage* (Pjavtshenko 1958) and the fiber content (Farnham and Finney 1965) of peat have also been frequently used to indicate the stage of decomposition.

12 Hydraulic conductivity and water retention capacity of peat according to previous knowledge

On the basis of information which is available from the literature, several general features can be presented on the hydraulic conductivity of peat. Many research workers have established that the hydraulic conductivity decreases rapidly with increasing degree of humification (Malmström 1923, p. 113; Sarasto 1963, p. 34; Baden and Eggelsmann 1963, p. 240; Päivänen 1968). There is a positive correlation between the hydraulic conductivity of peat and its fiber content and a negative correlation between the hydraulic conductivity and the bulk density (Boelter 1969, p. 608). A general observation has been made that the hydraulic conductivity of peat decreases with increasing depth from the ground surface (Wechmann 1943; Huikari 1959; Meshechok 1969, p. 239). Peats which contain remnants of wood are characterized by a relatively high hydraulic conductivity (Huikari 1959; Illner 1962, p. 24). The hydraulic conductivity of peat may be so poor that peat can even be used in dam construction (Tveiten 1956). Peat in bottomless lysimeters can make them almost watertight (Bay 1966).

Interpretation and application of the observations that have been presented on the hydraulic conductivity of peat is somewhat difficult because of the great variety of the methods that have been used. Some studies have been carried out in the laboratory, and others, in the field. The previous information which is available comes mainly from agricultural research. A serious drawback is the fact that information on the kind of the peat is rarely presented in connection with hydraulic conductivity values (see e.g. MacFarlane 1969, pp. 82—84). Moreover, peatlands occur on the earth in regions with different climates, and consequently, data on the hydraulic conductivity of peat which has been obtained in Florida, for example (Colley 1950, Harrison and Weaver 1958, Weaver and Speir 1960, Stewart *et al.* 1963), cannot be applied to Finnish conditions.

In Finland, information on the hydraulic conductivity of peat has been presented by Huikari (1959), Eggelsmann and Mäkelä (1964), Sarasto (1963), and Päivänen (1968). The large amount of data collected by Huikari is based on field measurements, but the results of his studies have been presented as relative values only. The results of Sarasto's and Päivänen's studies are from laboratory determinations, while those presented by Eggelsmann and Mäkelä are from cultivated fields. As there is the possibility that the methods used in the laboratory give higher hydraulic conductivity values than those used in the field (cf. Boelter 1965), we do not know at present the real magnitude of the hydraulic conductivity of the peat substrate in our drained peatlands.

The information which is available on the water retention capacity of peat is even more scanty than that concerning the hydraulic conductivity. Generally speaking, the data which has been presented is based on determinations carried out on a few samples only. Moreover, in many instances, the interrelationships between the water content of the soil and the matric suction have not been assessed over the whole range of variations in the water content (Feustel and Byers 1936, Stewart *et al.* 1963, Patric and Stephens 1968, Sturges 1968). The only studies in which the changes in the water retention capacity have been examined in relation to the increase in decomposition are the preliminary study of the present work (Päivänen 1968) and Boelter's study of a slightly later origin (1969).

When the present study was started, no investigational results were available on the water desorption characteristics of Finnish peat soils. Even Heinonen's (1954) thorough study of the water relationships of the tilled layer of agricultural soils leaves ordinary peat soils beyond examination. Some data on the water desorption characteristics of garden peat was available from a paper presented by Puustjärvi (1963). More recently, both Paavilainen (1967) and Paavilainen and Virrankoski (1967) touched on the determination of matric suction in their studies.

13 Aims of the study

Generally speaking, it can be stated that the most important hydrologic properties of the soil are the hydraulic conductivity and the water retention capacity (L'vovich 1966, p. 1020). In the Department of Peatland Forestry, University of Helsinki, a study of the optimum water relationships of peat soils which have been drained for forestry purposes is being carried out (Heikurainen 1967, p. 265). This study can be divided into three parts: *a*) determination of the optimum water content of the rhizosphere, *b*) determination of the drainage depth required to adjust the average soil water content to the desired level and *c*) determination of the combinations of ditch spacing and ditch depth which would lead to the desired drainage depth.

The hydraulic conductivity studies carried out in the present connection are a part of the study program under point *c* above. van Schilfgaarde (1957, p. 83), for example, has tried to express by means of an equation the dependence of the required ditch spacing on such factors as the distance between the ground water table and the impermeable layer, the hydraulic conductivity and the average precipitation. Other models for the solution of problems involving ditch spacing have also been presented. A common feature of them all is that the hydraulic conductivity of the soil in question is presupposed to be known or determinable

(Walker 1952, Sabo 1963, Klyavinsh 1963, van Beers 1965, Kostjakov (cf. Ferda 1968). It is also useful to know the hydraulic conductivity when estimating the magnitude and occurrence of fluctuations in the runoff from certain watersheds (Bay and Klawitter 1963, p. 176).

Consequently, the hydraulic conductivity values of peat are required for many purposes. However, as mentioned in the preceding section, no absolute values are presently available from *in situ* measurements of the hydraulic conductivity of virgin or drained Finnish peat soils.

The water retention studies carried out in conjunction with the present work belong under point *a* in the abovementioned division of the larger study project concerning the optimum water relationships of peat soils. It seems possible that the relationships between tree growth and the water content of the substrate, just as in the case of cultivated plants, could be shown by means of an optimum curve. The theoretical model concerning optimum water relationships of peat soils presented by Heikurainen *et al.* (1964, pp. 16–17) was based on this assumption. So far, it has not been established at what matric suction the growth of trees reaches an optimum level. This problem can probably only be solved by means of field or pot experiments. Investigations into the optimum water content of the substrate must be related, in any case, to corresponding matric suction values. Only in this way can different soils be compared with each other with regard to the availability of water to the plant cover. Knowledge of the water retention capacity of soils is of importance also in studies concerning the water balance of peatland watersheds and in estimations of the quantity of water which can be removed through drainage (L'vovich 1966, p. 1019; Bay 1967, p. 413).

The goal of the present study is to obtain information on the hydraulic conductivity and water retention of peat. Each of the two items has required its own methods of study and a separate study material. For this reason the results, too, will be presented in separate sections.

The aims of the part of the study dealing with the hydraulic conductivity of peat were

— to collect, using the most suitable method on the basis of the literature, a set of data which could be used as a basis for assessing the magnitude of the hydraulic conductivity of various peat soils,

— to determine which properties of the various peats best explain their hydraulic conductivity,

— to find out, by means of comparison with previous data, whether the laboratory and the field methods used give similar hydraulic conductivity values.

The aims of the part of the study dealing with the water retention capacity of peat were

— to assess the water desorption characteristics of various peats,

— to find a characteristic describing peat structure, which would give the best possible explanation for water retention capacity,

— to estimate, on the basis of the results thus obtained, the quantities of water, superfluous, available and unavailable to the plant cover as well as the quantity of water that can be removed from various peat soils through drainage.

2 HYDRAULIC CONDUCTIVITY

21 Methods used for determination of the hydraulic conductivity of soil

211 Field methods

The earliest methods used in determinations of the hydraulic conductivity have probably been based on infiltration experiments (cf., e.g., BERKMANN 1913, p. 5; KOPECKY 1914, p. 178), but the methods based on infiltration and filtration have since been criticized. SCHENDEL (1962, p. 101), for example, states that the rate of filtration is highly dependent on the water content of the soil ($r = 0.946$). He even uses the rate of filtration as a characteristic in his estimations concerning the water content of soils. Against this background it does not seem reasonable that the rate of filtration should be used as a characteristic in determinations of the hydraulic conductivity of peat soils, as it is influenced by the water content of the peat. Different values would be obtained even in the same study area if there were variations in the distance between the ground water table and the bottom of the infiltration cylinder. According to HUIKARI (1959, p. 17), however, the infiltration method can be used if the water table is located below the peat layers under study. In his studies, the infiltration method gave almost the same relative conductivity values as those obtained by the percolation method in the laboratory. According to the experience gained by JÄRVINEN (1962, p. 20), the former method is not very adaptable in drained peatlands, mainly because it requires a very large number of measurements to eliminate dispersion, and because the method cannot be used during and immediately after rainstorms. In summary, it can be stated that the infiltration rate of water into the soil depends to quite an extent on the water content of the soil and that, even if under certain conditions it describes rather well the relative conductivity of the soil, these two terms — the infiltration rate of water and the hydraulic conductivity — have different meanings (cf., e.g., RICHARDS 1952, p. 87). In the preliminary experiments carried out in 1965 by the present author, the method used by HUIKARI (1959) and JÄRVINEN (1962) was shown to be unusable, and consequently, determinations of the hydraulic conductivity by the infiltration method were discontinued.

The infiltration method is thus not very adaptable for use in studies concerning the hydraulic conductivity of peat. On the other hand, it is possible to assess through infiltration and percolation experiments the quantities of percolation water and the rate of percolation as has been done, for example, by JOFFE (1932) and TROEDSSON (1955) in the case of mineral soils. The fact that the ground water table is located near the ground surface in peat soils limits the usability of this method in peatlands. Furthermore, the changes taking place in the soil-water content during the experiments must be taken into consideration in one way or another in order to make it possible to obtain true percolation rate values.

The above-related infiltration and percolation experiments are used to assess the vertical movement of water in unsaturated soils. It ought to be mentioned in this connection that attempts have been made to determine the hydraulic conductivity of soil in the laboratory by observing the water flow from a pressure membrane extractor (e.g. YOUNGS 1964, RICHARDS 1965).

The infiltration method can also be used for measurements of the hydraulic conductivity of soil layers located below the ground water table, as presented, for example, by KHAFAGI (1944, pp. 42, 65). The rate of movement of ground water can be studied by adding dyeing agents, salts (WENZEL 1942) or radioactive substance to the water. These methods, however, are laborious and inaccurate.

The hydraulic conductivity of soil layers located below the ground water table can be determined using either the auger hole or the piezometer methods. The auger hole method was first described by DISERENS (1934), and it has been further developed by several research workers (e.g. KIRKHAM 1945, VAN BAVEL and KIRKHAM 1948, KIRKHAM and VAN BAVEL 1948, JOHNSON *et al.* 1952). In this method, a hole is bored in the soil down to a certain depth below the ground water table. When equilibrium has been reached with the surrounding ground water, some of the water in the hole is removed. The rate at which the water rises in the hole is measured and then converted by means of suitable formulae into the hydraulic conductivity of the soil. Simplified forms of the formulae have also been derived (e.g. ERKIN (cf. KHAFAGI 1944, p. 35), VAN BEERS 1958). KIRKHAM (1965) carried out a theoretical study on the principles of the method and established that the formula and nomograms presented by VAN BEERS (1958) give almost perfect results.

According to LUTHIN and KIRKHAM (1949), the drawbacks of the auger hole method are as follows: 1) The hydraulic conductivity obtained by this method represents some sort of average value for the whole distance between the ground water table and the bottom of each ground water hole. 2) The variation in the hydraulic conductivity over the whole soil profile cannot be established. 3) The method is limited to shallow depths below the ground water table. FREVERT and KIRKHAM (1948) mention the following advantages of the method: 1) The soil is disturbed as little as possible. 2) The measurement of the hydraulic conductivity takes place at the true temperature of the soil and the soil water. 3) The method minimizes the influence of the unhomogeneity of the soil as the range of influence of the hole is large. VAN BAVEL and KIRKHAM (1948) point out that the liquid which is used for the measurements is soil water proper, and not tap water, which might bring about unknown side effects.

In Finland, HUIKARI (1959) has used the auger hole method in determinations of the hydraulic conductivity of peat soils. The results from his studies, however, have been presented only in the form of relative values.

In the piezometer method, a tube is driven vertically into the soil. The tube is emptied, and a cavity several inches in depth is made in the soil under the lower end of the tube. Water can enter the tube only through the walls and the bottom of this cavity (LUTHIN and KIRKHAM 1949, REEVE and JENSEN 1949). The method, just like the auger hole method, is based on the rate at which water rises in the tube after the water table in it has been lowered. The piezometer method will be dealt with in more detail later, in conjunction with the presentation of the method employed in this study.

The tube method, which can be considered to be a modification of the piezometer method, is based on the use of tubes with a relatively large diameter (e.g. 8 in.), no cavity being made under the lower end. Consequently, water can enter the tube only through an area corresponding to that of the cross-sectional area of the tube. It is considered that the auger hole and piezometer methods indicate the horizontal conductivity of soil, whereas the tube method can be used to determine the vertical hydraulic conductivity (e.g. REEVE and KIRKHAM 1951).

212 Laboratory methods

In determinations of the hydraulic conductivity in the laboratory, various percolation methods have been used (cf. MITSCHERLICH 1920, GOODE and CHRISTIANSEN 1945, LÅG and EINEVOLL 1954, HARTGE 1961, SCHLICHTING and BLUME 1966, ANON. 1967).

HASUND (1910, p. 40) was probably the first to apply the percolation method in determinations of the hydraulic conductivity of peat. MALMSTRÖM (1923, 1928, 1939) developed a permeameter specifically designed for the study of peat samples. In this method, however, any open spaces remaining between the peat sample and the wall of the permeameter must be filled up with plaster in order to prevent free movement of water along the wall (MALMSTRÖM 1923, pp. 110—111). SARASTO (1961, pp. 24—25) modified MALMSTRÖM's permeameter in such a way that the water which penetrates the peat sample is collected into two funnels, one placed inside the other, and only the water that comes from the inner funnel is used for the determinations.

The top area of the inner funnel equals the effective sample area of 12.5 × 12.5 cm. The boundary-flow water is removed through the outer funnel. A method, which in a similar way eliminates leakage at the soil-permeameter wall interface by measuring the conductivity of the central parts of the sample only, has been used by McNeal and Reeve (1964, pp. 713–714). On the other hand, some other studies have indicated that the leakage along the interface between the sample and the wall of the vessel is negligible (Collins and Schaffer 1967, p. 381).

The only error which Malmström (1923, p. 114) observed with his apparatus was that the quantity of water penetrating the sample decreased continuously as a function of time. He considered the error small, however, and to eliminate it he restricted the measurement period to less than 24 hours. The measurements were usually performed only during the first hour of percolation. The studies carried out by Sarasto (1961, p. 21), however, proved that the decrease in the water flow is not continuous, but that the flow becomes constant 1–4 days after the experiment has been started. The phenomenon can be understood to mean that this time is required for the peat colloids to become swollen to their full extent and for the peat to become saturated with water. The same phenomenon has been observed by several other research workers, and in most cases the measurements on the quantity of water that has penetrated the samples were not started until the rate of flow had become practically constant (e.g. Smith 1949, p. 556; Steinbrenner 1951, p. 380; Segeberg 1952, p. 347; Låg and Einevoll 1954, p. 527; Hanrahan 1954, pp. 110–111).

The hydraulic conductivity is also influenced by the changes occurring in the viscosity of water as a function of temperature. In comparisons concerning hydraulic conductivity values, these have to be converted to correspond to the same temperature using certain viscosity coefficients (Malmström 1923, p. 114; Gustafsson 1940, p. 430; Sillanpää 1956, p. 42; Järnefelt 1958, p. 26; Huikari 1959, p. 9; Sarasto 1961, p. 24; Flannery and Kirkham 1964, p. 238).

22 Methods of study

221 Determination of the hydraulic conductivity of peat

As stated in the foregoing, when planning the field measurements to be carried out in the present study there were two possible methods for assessing the horizontal hydraulic conductivity of peat soils, namely, the auger hole and the piezometer methods. The latter was decided on in this connection in order to make it possible to assess, by means of a series of simultaneous measurements, the horizontal hydraulic conductivity at various depths in the peat profiles under study. This would not have been possible if the auger hole method had been used. The auger hole method is, furthermore, a laborious method because it may take a very long time before the water table rises to a certain level in the ground water holes. The holes have to be kept under continuous observation for hours, and sometimes even for days (cf. Huikari 1959).

The following method was used: an aluminum tube with an inner diameter of 1 1/4 in. was driven vertically into the peat soil so that the lower end of the tube was located at the same level as the upper limit of the peat layer to be studied. The peat which filled the tube was removed with an auger, the diameter of which was only 1.5 mm less than the inner diameter of the tube. A cavity with a length of ten centimeter was then made with the auger under the lower end of the tube. As the peat layer studied in each instance was ten centimeter thick, the mid point of the cavity was situated in the middle of the peat layer under observation. With a pump, specifically constructed for this purpose, the water entering the tube and the cavity was then removed several times so as to remove any peat mud remaining in the hole. Water was removed from the cleaned hole with the pump, and the rate of rising of the water entering the tube was then recorded. The rate of rising of the water was converted into hydraulic conductivity values by means of the following formula (Frevert and Kirkham 1948, p. 434; Reeve and Kirkham 1951, p. 583):

$$K = \frac{2.30\,\pi r^2}{A\,(t_2 - t_1)} \log \frac{h_1}{h_2}, \qquad (4)$$

in which

K = hydraulic conductivity, cm/sec
r = radius of the piezometer, cm
A = geometric function, cm
h_1 = distance from ground water table to water level in the piezometer at the time t_1, cm
h_2 = distance from ground water table to water level in the piezometer at the time t_2, cm
$t_2 - t_1$ = time interval over which the water level rise was measured, sec.

The function A used in equation (4) has been evaluated by means of an electric analogue of the ground water problem (see LUTHIN and KIRKHAM 1949, p. 352). According to the figure presented by LUTHIN and KIRKHAM (1949, p. 353), the function A is 13.5 in., or 34.5 cm, for the piezometers used in this study.

As the distance between the ground water table and the water table in the tube (h_1 and h_2) is difficult to measure in the field, the upper edge of the piezometer was used as a reference point in all the measurements. A hole was made in the soil near the piezometer tube, which was large enough to make the ground water table visible. The values required for the formula were obtained by subtraction as follows (cf., e.g., BOERSMA 1965, p. 229):

$$h_1 = L_1 - E \text{ and}$$
$$h_2 = L_2 - E,$$

in which

E = distance from the top of the piezometer to the ground water table
L_1 and L_2 = distance from the top of the piezometer to the water level in the piezometer at the time t_1 and t_2 respectively.

It must be considered an advantage of the method that the ground water table is continuously observed during the period of measurement. If the ground water table outside the piezometer drops when water is removed from the tube, the interface between the piezometer wall and the surrounding peat is evidently not sufficiently tight, and so the piezometer has to be moved to another place. In places with soft peat, it is sometimes necessary to construct a platform of wood above the ground in order to avoid changes in the level of the ground water table caused by the weight of the observer.

Time determinations were made using a stop watch. The distances from the top end of the piezometer tube to the ground water table and to the water table in the piezometer were measured at an accuracy of one millimeter using a stiff aluminum measuring rod. As it was difficult to see the water table in the narrow tubes, the end of the measuring rod was covered with blue chalk and lowered slightly below the water table in the piezometer. When the rod was removed, the correct distance between the upper end of the piezometer tube and the water table could be determined by deducting the length of the wetted part of the rod, which was clearly discernible as a result of the chalk, from the value recorded at the top of the tube. Attempts were made to decrease any possible inaccuracies in the determination of the water level in the piezometer tubes by extending the period of observation so that the water in the tube would have time to rise at least three centimeter. The period of observation was ended at the time when the water table had risen 2/3 of the distance between the lowered water table and the level of the ground water table ($h_2 \geqq 1/3\ h_1$).

As it is of the greatest importance that the shape and size of the cavity are what they are supposed to be (e.g. BOERSMA 1965, p. 233), checks were made in the case of some sample plots. A pit was dug close to the piezometer tube, the water which collected in it was removed and the cavity was uncovered by means of a sharp knife. The cavity was found to keep its shape rather well, undecomposed Sphagnum peat being the only exception. In sample plots where the soil consisted of undecomposed Sphagnum peat, the piezometer tube was equipped with an extension made out of stiff, densely perforated plastic tube. According to LUTHIN and KIRKHAM (1949, p. 357), the use of such an extention makes it possible to use the same value of the function A as in the case of open cavities.

At each observation depth, the temperature of the water was determined at an accuracy of 1 °C using two replications. The means thus obtained were used for determination of the viscosity coefficient of the water.

For each separate recording at each

observation depth the hydraulic conductivity value was calculated using equation (4). The hydraulic conductivity values thus obtained were adjusted to correspond to a temperature of 15 °C using the viscosity coefficients presented by SILLANPÄÄ (1956, p. 42) and by FLANNERY and KIRKHAM (1964, p. 238). After inserting, in equation (4), the constants which depend on the size of the piezometer tube and the cavity, as well as the viscosity coefficient, the equation takes the following form:

$$K = \frac{\mu\, 0.537}{t} \log \frac{h_1}{h_2}, \qquad (5)$$

in which μ = viscosity coefficient ($\mu = 1.0$ when $T = 15$ °C).

222 Measurements and observations carried out in order to describe peat structure

On the basis of data obtained from the literature and from the results of the preliminary study (PÄIVÄNEN 1968), it was concluded that it is meaningless to present data on the hydraulic conductivity of peat if the influence of the structure of the peat has not been taken into consideration.

In the present study the structure of the peats studied was described by means of the peat type, the stage of decomposition and the bulk density. The methods used in determining the peat type and the stage of decomposition were described in section 113. For determination of the bulk density of the peats, undisturbed peat samples were taken in four replications from each sample plot and each depth of observation covered by the study. The volume of each sample was 348 cm³, and they were dried at 105° C in the laboratory. The bulk density was calculated from the dry weight and the fresh volume of the samples. As the samples were taken from peat layers below the ground water table, their volume may be considered as corresponding to that of saturated peat.

23 Material of the study

231 Collection of the material

The material of the present study was collected in the period May-July 1971 from sample plots located in the surroundings of the Forest Training Station, University of Helsinki (61° 50'N; 24° 20'E). The sample plots had all been set up in peatland areas which had been drained for forestry purposes, most of them having also been used for collection of data for the study of the optimum soil water relationships with regard to tree growth.

The method of measurement used presupposes that the ground water table is located near the soil surface. For this reason measurements were started in early spring, disregarding places, however, where soil frost still remained. Measurements were carried out in 18 sample plots. When the ground water table was close enough to the soil surface (0–8 cm), measurements on the hydraulic conductivity were carried out at five depth layers as follows: 10–20, 20–30, 30–40, 40–50 and 50–60 cm. In the case of each soil depth studied, the rate of rising of the water was determined in four piezometer tubes and each tube was used for four measurements in the same place. Each depth was consequently represented by 16 determinations. For the topmost layer, measurements could not be carried out in each sample plot, because the ground water table was either located too far from the soil surface or because the soil was still frozen at this depth during the period when the ground water table was sufficiently near the surface of the soil.

Of the observation points 28 were located in Sphagnum peat, 23 in sedge peat and 29 in woody peat. Thus, the total number of observations concerning the rate of rising of water in the piezometer tubes was 1280. Measurements on the hydraulic conductivity using four piezometers in each of five depth layers in the above-related manner required two man-days. This means that the time consumption in peatlands is almost twice that required for measurements in loam soil (cf. LUTHIN and KIRKHAM 1949, p. 351). The time consumption required per sample plot is of course related to the rate of rising of the water in the piezometers, i.e., to the hydraulic conductivity of the soil, and also, to the difficulties involved with driving the tubes into and removing them from the soil.

Table 1. Examples of the average hydraulic conductivity at various soil depths and the confidence interval of the values at the 95 % level.

Sample plot and peat type	Depth of observation, cm	Hydraulic conductivity, 10-6 cm/sec	Confidence interval, %
Sample plot 12,	25	3055 ± 573	± 18.8
S peat	35	649 ± 160	± 24.7
	45	576 ± 117	± 20.3
Sample plot 9,	25	1480 ± 473	± 32.0
C peat	35	173 ± 46	± 26.6
	45	1751 ± 153	± 8.7
Sample plot 26,	25	3317 ± 1009	± 30.4
L peat	35	3028 ± 1212	± 30.0
	45	1417 ± 264	± 18.6

232 Examination of the dispersion

The hydraulic conductivity values obtained by means of the piezometer tubes from different depths in the sample plots were examined using analysis of variance. The differences between individual piezometers were usually statistically significant. The dispersion is mainly due to local variation within the same peat layer because the variance between individual piezometers was considerably larger than the residual, which included the dispersion between the replications, i.e., the measurements from the same tube. Table 1 shows the mean values and their confidence interval for sixteen hydraulic conductivity determinations (four measurements in each of four piezometers) in the case of randomly selected sample plots which are representative of S, C and L peat.

The table shows that the dispersion may be rather large within the same peat layer, the confidence interval at the 95 % level being even as large as ± 40 % of the mean. According to LUTHIN and KIRKHAM (1949, p. 355) a confidence interval even of this magnitude is satisfactory; this is especially true when these figures are compared with those obtained from hydraulic conductivity measurements using other methods. According to VAN BEERS (1958, p. 28), the hydraulic conductivity values obtained by the auger hole method show a variation covering tens of per cent even in cases where measurements have been performed in adjacent places in the same soil profile. Simultaneously, however, he emphasizes the fact that the differences obtained between various soil types are much larger, at times even thousandfold. HOVE (1969, p. 40) mentions ± 30 % as the confidence interval for hydraulic conductivity values obtained by the auger hole method.

The following examinations are based on the arithmetic means of sixteen hydraulic conductivity values for each depth of observation.

233 Material of the preliminary study

The present work includes a comparison (section 252) between hydraulic conductivity values obtained using the piezometer method and those obtained in the laboratory in conjunction with the preliminary study (PÄIVÄNEN 1968). The preliminary study was carried out using an apparatus developed from the permeameter used by SARASTO (1961, 1963) and MALMSTRÖM (1923). Determinations were performed on a total of 262 samples. The samples were saturated, and the water pressure exerted on their surface was kept constant during the period of measurement. The temperature of the water used was recorded. The quantities of water percolating through the samples per unit time was converted into hydraulic conductivity values using Darcy's law (see, e.g., HILLEL 1971, pp. 87–88).

Table 2. Correlation matrices for the dependence of hydraulic conductivity (y) on the independent variables used in the study by peat types.

		x_1	x_2	x_3
S peat				
Bulk density	x_1			
Degree of humification	x_2	.973***1)		
Sampling depth	x_3	.385*	.511*	
Hydraulic conductivity	log y	−.714***	−.797***	−.688***
C peat				
Bulk density	x_1			
Degree of humification	x_2	.978***		
Sampling depth	x_3	−.384*	−.322	
Hydraulic conductivity	log y	−.359	−.429*	−.492*
L peat				
Bulk density	x_1			
Degree of humification	x_2	.891***		
Sampling depth	x_3	−.105	−.030	
Hydraulic conductivity	log y	−.115	−.256	−.745***
Entire material				
Bulk density	x_1			
Degree of humification	x_2	.949***		
Sampling depth	x_3	.058	.173	
Hydraulic conductivity	log y	−.409***	−.496***	−.583***

1) * significant at the 5 % level
** significant at the 1 % level
*** significant at the 0.1 % level

24 Results of the hydraulic conductivity studies

241 Independent variables used

One of the aims of the present study was to find a property of peat which would be easy to determine or estimate and at the same time would in the best possible way explain the hydraulic conductivity. For this reason the bulk density, the degree of humification and the sampling depth were used by peat type as independent variables. After graphical examination of the problem and after a few experiments had been carried out to find a suitable function to explain the hydraulic conductivity, the following, semilogarithmic linear function was chosen:

$$\log y = a + b\, x_{1 \ldots 3} \quad (6)$$

in which
log y = $\log_{10}$ from the hydraulic conductivity value,
x_1 = bulk density, g/cm^3,
x_2 = degree of humification according to von Post (1922),
x_3 = sampling depth, cm.

Table 2 shows the correlation matrices by peat type between the logarithmic hydraulic conductivity and the independent variables used in the regression analyses. The table also shows the statistical significance of the correlations based on the F-test.

In the following connection the possibilities of using the single independent variables are examined by peat type. Later on, the possibilities of increasing the coefficient of determination by increasing the number of variables will be dealt with.

It is meaningless to study the hydraulic conductivity without relating it to the quality and structure of the peat under study. For this reason the magnitude of the hydraulic conductivity of different peats will be dealt with later in this study. In the present connection it ought to be mentioned, however, that the lowest hydraulic conductivity values recorded were of the magnitude 0.000 002 cm/sec. Accordingly, the hydraulic conductivity is expressed in this study in terms of 10^{-6} cm/sec; this means that the coefficients included are always integers.

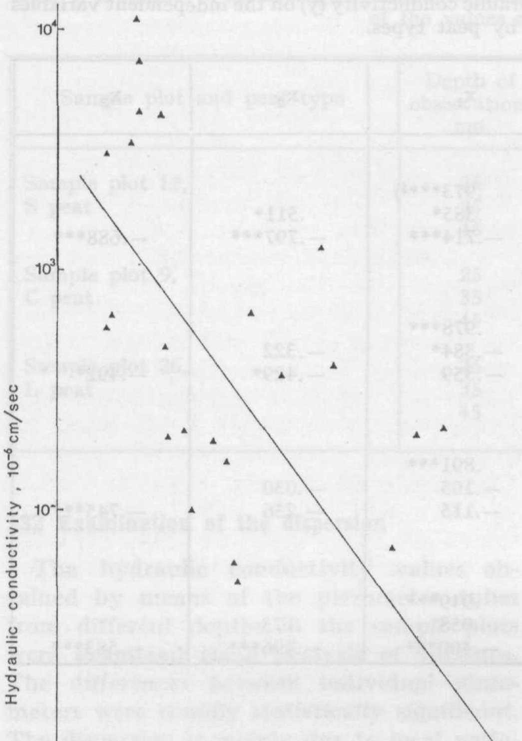

Fig. 1. Effect of bulk density on the hydraulic conductivity of Sphagnum peat.

242 Effect of the bulk density

A typical feature of the decomposition of peat is that the plant remnants decrease in size as the decomposition process advances. Small remnants fill the empty space between larger ones, and consequently, the quantity of solid material per unit volume increases, i.e., the bulk density of the peat increases. On the other hand, we know that the ash content of peats at an advanced stage of decomposition is usually higher than that of less decomposed peats (Holmen 1964, p. 142; Irwin 1968, p. 220). The influence of the ash content was not eliminated in this study, however, although probably only the density of the peat, which is reflected by its bulk density, is of importance for the hydraulic conductivity. Determinations of the ash contents, which were partly performed on material from the sample plots of this study, indicated that the ash contents were rather low (see Tables 8—10); consequently, the importance of the ash content is small.

As can be seen from Table 2, there is a strong negative correlation between the hydraulic conductivity (y) and the bulk density (x_1) in the case of Sphagnum peats. The linear regression equation and the coefficient of determination were as follows:

$$\log y = -2.026 - 15.224\, x_1;\ r^2 = .51$$

Fig. 1 shows the cluster of values originally recorded in addition to the line obtained by analytic leveling. As the hydraulic conductivity decreases very rapidly with increasing bulk density, semilogarithmic leveling seems to be well suited for the handling of the data.

In the case of sedge and woody peats, bulk density showed to have no significant effect on the hydraulic conductivity. When the corresponding correlation was calculated for the entire material, the regression took the following shape:

$$\log y = -2.232 - 8.690\, x_1;\ r^2 = .17$$

The coefficient of determination of the regression remained consequently at a rather low level.

The hydraulic conductivity values obtained for both sedge and woody peat showed the largest dispersion in the case of the sampling depth of 15 cm. As the material of the present study was collected from drained peatlands, the peat of the topmost soil layer had frequently reached a more advanced stage of decomposition than that of deeper soil layers. In the case of sedge peats, for example, it could be observed that there is a significant negative correlation between bulk density and sampling depth. On the other hand, the topmost peat layer frequently contains non-capillary pores which have been formed after the decay of wood remnants, and through which water can move fast. Wind-induced movements of tree roots in the relatively soft peat soils may produce horizontal, non-capillary pores in the rhizosphere. The interrelationships between the hydraulic conductivity and the sampling depth will be dealt with in more detail in section 244.

In order that the influence of bulk density on the hydraulic conductivity could be studied side by side for several peat types, the data was also handled so as to disregard the hydraulic conductivity values obtained for the sampling depths above the 25 cm layer. The following regressions were statistically significant (see also Fig. 2):

Peat type	Equation	r^2	F
S peat	$\log y = -2.321 - 13.220\, x_1$	.45	18.24***
C peat	$\log y = -1.924 - 10.702\, x_1$	.37	10.38**
Entire material	$\log y = -2.217 - 9.800\, x_1$	.22	19.54***

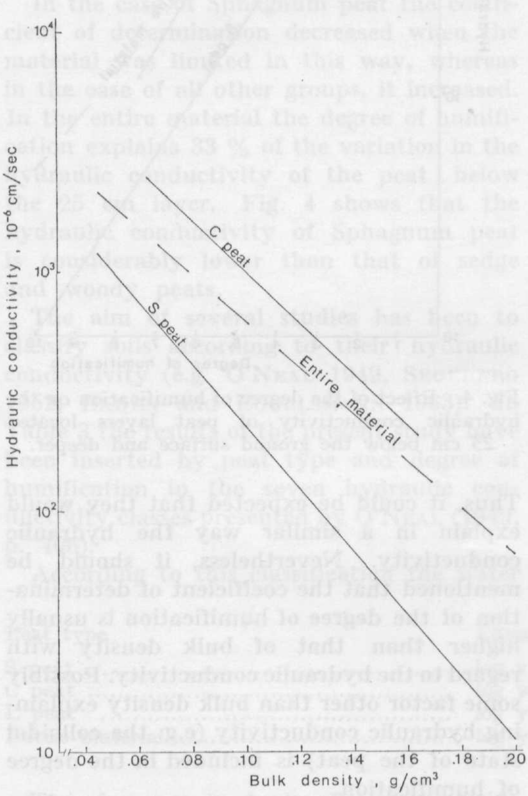

Fig. 2. Effect of bulk density on the hydraulic conductivity of peat layers located 25 cm below the ground surface and deeper.

It can be seen that, in the case of Sphagnum peat, disregarding the hydraulic conductivity values obtained for the topmost sampling depth (15 cm layer) decreased the coefficient of determination. In the case of sedge peat, the regression was significant, and in the case of the entire material, the coefficient of determination showed a slight increase. Even when treated in this way woody peat showed no significant correlation between the hydraulic conductivity and bulk density.

Fig. 2 shows that at equal bulk density the hydraulic conductivity of sedge peat exceeds that of Sphagnum peat. The linear regression presented by BOELTER (1969, p. 608) between the logarithmic hydraulic conductivity and the bulk density of peat is very similar to the corresponding regression for Sphagnum peat obtained in the present study. There is nothing mentioned in BOELTER's study, however, about the plant species composition of the peat layers in which his hydraulic conductivity determinations were made. In the case of clay soils, bulk density has not been found to explain hydraulic conductivity in the way which was established for peat soils (cf., e.g., HERMSMEIER 1966, p. 6).

243 Effect of the degree of humification

Between the hydraulic conductivity (y) and the degree of humification (x_2) of peat, the following significant regression equations were obtained:

Peat type	Equation	r^2	F
S peat	$\log y = -2.310 - 0.278\, x_2$	.63	45.13***
C peat	$\log y = -2.283 - 0.145\, x_2$	.18	4.73*
Entire material	$\log y = -2.315 - 0.174\, x_2$	.25	25.44***

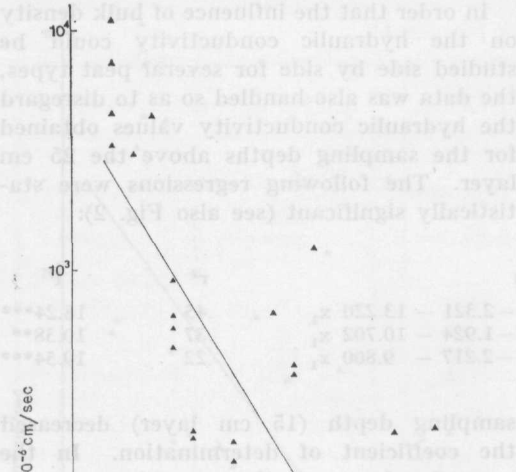

Fig. 3. Effect of the degree of humification on the hydraulic conductivity of Sphagnum peat.

Just as in the case of bulk density, the coefficient of determination of the degree of humification with regard to hydraulic conductivity was rather good for Sphagnum peat (see also Fig. 3). As can be seen from Table 1 and as we know from previous studies (e.g. PÄIVÄNEN 1969), there is a clear correlation between the bulk density and the degree of humification of peat.

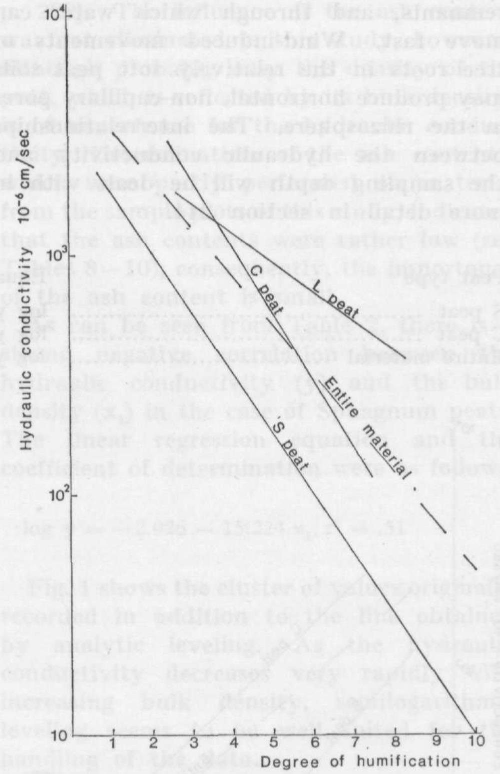

Fig. 4. Effect of the degree of humification on the hydraulic conductivity of peat layers located 25 cm below the ground surface and deeper.

Thus, it could be expected that they would explain in a similar way the hydraulic conductivity. Nevertheless, it should be mentioned that the coefficient of determination of the degree of humification is usually higher than that of bulk density with regard to the hydraulic conductivity. Possibly some factor other than bulk density explaining hydraulic conductivity (e.g. the colloidal state of the peat) is included in the degree of humification.

In order to be able to compare different peat types with each other, regression equations were calculated from material from which the hydraulic conductivity values obtained from peat above the 25 cm layer had been excluded (see Fig. 4):

Peat type	Equation	r^2	F
S peat	$\log y = -2.471 - 0.253\ x_2$	.55	27.01***
C peat	$\log y = -1.850 - 0.278\ x_2$	.52	19.51***
L peat	$\log y = -2.399 - 0.124\ x_2$	.15	4.28*
Entire material	$\log y = -2.261 - 0.205\ x_2$	.33	33.10***

Table 3. Degree of humification of various peats in the hydraulic conductivity classes presented by O'Neal (1949).

Hydraulic conductivity		Degree of humification		
Class	10^{-6} cm/sec	S peat	C peat	L peat
Very rapid	>7200	1	. .	. .
Rapid	3600—6900	1	. .	. .
Moderately rapid	1800—3300	1	1—3	. .
Moderate	633—1500	2—3	3—5	3—6
Moderately slow	133—550	3—5	5—7	6—9
Slow	33—133	5—8	7—9	. .
Very slow	6—26	8—10	. .	. .

In the case of Sphagnum peat the coefficient of determination decreased when the material was limited in this way, whereas in the case of all other groups, it increased. In the entire material the degree of humification explains 33 % of the variation in the hydraulic conductivity of the peat below the 25 cm layer. Fig. 4 shows that the hydraulic conductivity of Sphagnum peat is considerably lower than that of sedge and woody peats.

The aim of several studies has been to classify soils according to their hydraulic conductivity (e.g. O'Neal 1949, Segeberg 1952, Baden and Eggelsmann 1963). In Table 3 the results of the present study have been inserted by peat type and degree of humification in the seven hydraulic conductivity classes presented by O'Neal (1949, p. 406).

According to this classification the water conductivity is »moderately rapid» or greater only in the case of undecomposed peats. Comparison of the degree of humification of different peat types belonging to the same hydraulic conductivity class shows that the degree of humification increases when moving from Sphagnum peat to sedge peat and woody peat (see for example the class »moderately slow»). It also appears extremely logical that Sphagnum peat in an advanced stage of decomposition would be put into the hydraulic conductivity class »very slow».

244 Effect of the sampling depth

The following regression equations were established for the correlation between the hydraulic conductivity (y) of peat and the sampling depth (x_3):

Peat type	Equation	r^2	F
S peat	$\log y = -1.806 - 0.048\ x_3$	.47	23.31***
C peat	$\log y = -2.209 - 0.019\ x_3$	.24	6.71*
L peat	$\log y = -1.706 - 0.034\ x_3$	.55	33.62***
Entire material	$\log y = -1.915 - 0.034\ x_3$	.34	40.18***

The decrease in hydraulic conductivity with increasing soil depth seems to be greatest in the case of Sphagnum peat, and smallest in the case of sedge peat (see Fig. 5). In the case of the latter peat type, however, the coefficient of determination is only 24 %, and the regression almost significant. At similar sampling depths, the hydraulic conductivity is always lower for Sphagnum peat than for the other peat types studied. Fig. 6 illustrates the variation in the hydraulic conductivity of Sphagnum peat at various sampling depths. On average, the hydraulic conductivity at a depth of 55 cm is 4.5 % of that recorded for the 15 cm layer; in the case of Sphagnum peat, however, the corresponding figure is only 1 % (Fig. 5). The decrease in the relative hydraulic conductivity with increasing soil depth which was recorded by Huikari (1959) using the auger hole method was of similar magnitude. Boelter (1965) has also observed that the hydraulic conductivity rapidly decreases with increasing

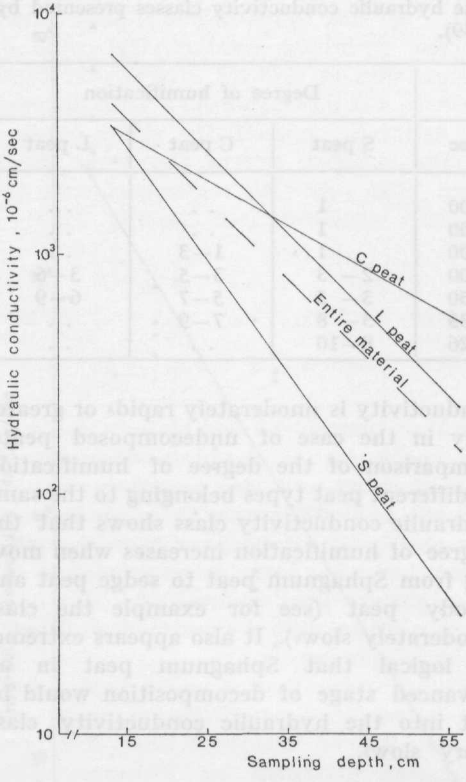

Fig. 5. Effect of the sampling depth on the hydraulic conductivity of various peats.

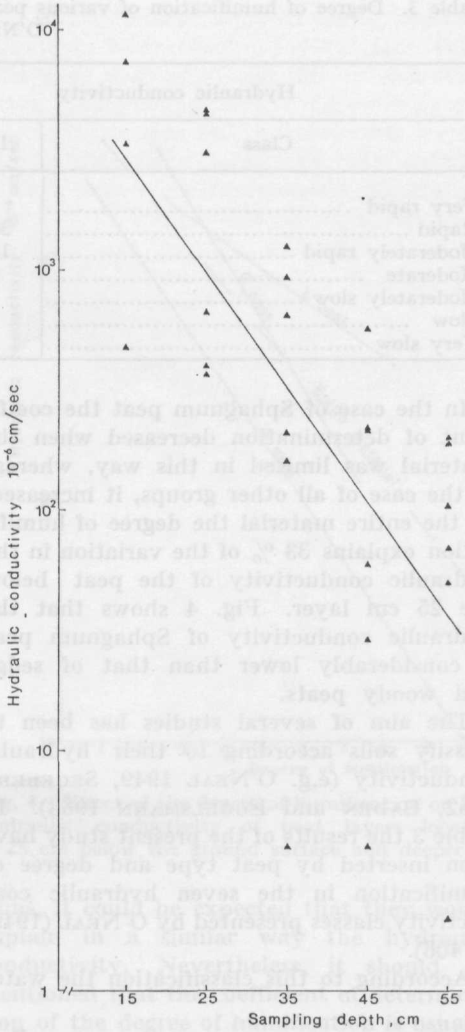

Fig. 6. Effect of the sampling depth on the hydraulic conductivity of Sphagnum peat.

depth in peat soils. The studies performed by MESHECHOK (1969) using the auger hole method produced results which showed that the decrease in hydraulic conductivity with increasing depth of the ground water table would slope slightly more gently.

The lower hydraulic conductivity of deeper peat layers in comparison with that of superficial peat is probably due to several factors. The capacity of humus colloids to retain water and to arrest water movement is generally known. The quantity of humus colloids increases with the advance of decomposition (PUUSTJÄRVI 1956, p. 434) and with increasing peat depth (YEFIMOV and VASIL'KOVA 1971, p. 318). Even in the case of laboratory experiments, accumulation of colloidal particles has led to a decrease in the hydraulic conductivity in the lower part of samples (TVEITEN 1956, p. 5). Moreover, drying of some organic colloids leads to structural changes which are irreversible (PUUSTJÄRVI 1955, p. 269). In the case of the piezometer method used in the present study, the hydraulic conductivity was always recorded for peat layers located below the ground water table. For most of the year, however, superficial peat layers are located above the ground water table, and during this period the swelling capacity of the humus colloids occurring in these layers and their capacity to arrest water movement may be decreased. The possible wind-induced movement of tree roots and the formation of non-capillary pores through the decaying of roots were already mentioned as causes for improved water movement (cf. Hintikka 1972). The low hydraulic conductivity of deep peat layers might also be explained by the the pressure exerted on them by saturated peat layers lying on top of them (cf. Hove 1969, p. 2). It has been established through experiments performed in the laboratory that pressure which is exerted on the surface of the samples being studied decreases their hydraulic conductivity (Hanrahan 1954, p. 110; Sarasto 1961, p. 25).

245 Joint effect of two independent variables

For practical use, the best solution would be to find an independent variable which alone could describe (predict) the hydraulic conductivity of various peats. Nevertheless, it was found in the foregoing connection that the coefficient of determination remains at a rather low level when only one variable is used. For this reason, the logarithmic form of hydraulic conductivity as a linear function of two independent variables was tested with the study data. The bulk density (x_1) and the degree of humification (x_2) were both used in turn as independent variables side by side with the sampling depth (x_3):

$$\log y = a + b\, x_{1 \text{ or } 2} + c\, x_3 \qquad (7)$$

As bulk density and degree of humification correlate closely with each other (see Table 2), their simultaneous use for explanation of hydraulic conductivity could lead to difficulties in the interpretation of the results.

In virgin peatlands, the degree of humification of the peat usually increases with increasing soil depth. In the case of peatlands which have been drained for forestry, however, this is not necessarily the situation. Due to drainage, the decomposition process is speeded up in the topmost peat layer. According to the results of the present study, there is a slight positive correlation in the case of Sphagnum peat between the bulk density and the sampling depth, and between the degree of humification and the sampling depth. In the case of sedge peat, the corresponding correlations are negative, whereas in the case of woody peat, no correlation could be observed between these variables. This is due to the fact that the data was collected from peatlands that had been drained, and in which, consequently, the vertical distribution of peats representative of different degrees of humification has been disturbed. Therefore the bulk density and the degree of humification can be alternatively used side by side with the sampling depth to explain hydraulic conductivity.

The results obtained from the calculations are presented by peat type in Table 4. The table also shows the statistical significance of the regression coefficients of the variables as obtained from the t-test. In general, inclusion of a second variable improved the coefficient of determination. The only exception was recorded for woody peat, where the use of bulk density as an independent variable side by side with the sampling depth did not significantly improve the coefficient of determination of the function. The function model which included two independent variables explained 70 % of the variation in the hydraulic conductivity in

Table 4. Dependence of the hydraulic conductivity (y) of peat on the sampling depth (x_3) in combination with the bulk density (x_1) or the degree of humification (x_2).

Peat type	Function	R^2	t-test	
			Significance of b	Significance of c
S peat	$\log y = -1.195 - 11.246x_1 - 0.034x_3$	.71	−4.52***	−4.15***
S peat	$\log y = -1.649 - 0.210x_2 - 0.026x_3$	.74	−5.08***	−3.21**
C peat	$\log y = -0.810 - 10.232x_1 - 0.028x_3$	.59	−4.17***	−4.79***
C peat	$\log y = -0.960 - 0.222x_2 - 0.027x_3$	.63	−4.54***	−4.87***
L peat	$\log y = -1.132 - 0.096x_2 - 0.034x_3$	.63	−2.35*	−6.33***
Entire material	$\log y = -1.097 - 7.994x_1 - 0.032x_3$	.48	−4.58***	−6.82***
Entire material	$\log y = -1.363 - 0.143x_2 - 0.030x_3$	.50	−4.98***	−6.27***

the case of Sphagnum peat, about 60 % in the case of each of sedge and woody peats, but only about 50 % of the variation in the case of entire material. The low numerical value of the last-mentioned figure depends of course on differences in the hydraulic conductivity between the peat types. It seems that the peat types should always be dealt with separately.

25 Comparison with results obtained from previous studies

251 Comparison with hydraulic conductivity values obtained by the use of field methods

As was already mentioned, the interrelationships between bulk density and hydraulic conductivity of Sphagnum peat are very similar to those which BOELTER (1969, p. 608) established for the conditions prevailing in Minnesota. The method employed in the present study is also the same as that which was introduced by BOELTER for use in peat studies. However, BOELTER's study does not reveal the plant species composition of the peat profiles studied. STURGES (1968), in his studies of extremely dense herbaceous peat (bulk density 0.216) with the piezometer method, obtained still smaller hydraulic conductivity values (2—3 $\times 10^{-7}$) than those recorded in the present study for peats at an advanced stage of decomposition.

The hydraulic conductivity and bulk density values (750—970 $\times 10^{-6}$ cm/sec and 0.065 g/cm^3 respectively) obtained with the auger hole method by EGGELSMANN and MÄKELÄ (1964) in an undrained and a poorly drained *Sphagnum fuscum* bog, were in conformity with the results of the present study concerning undecomposed Sphagnum peat (cf. Fig. 1)..

BADEN and EGGELSMANN (1963) have carried out field studies on the hydraulic conductivity for different peat types and degrees of humification. Their data was collected using the auger hole method. Table 5 gives a comparison between the hydraulic conductivity values of Sphagnum and sedge peats by degree of humification which were obtained at depths from 25 to 55 cm in the present study and the corresponding averages presented by BADEN and EGGELSMANN (1963, p. 240) for »Sphagnumtorfe» and »Braunmoos-» and »Braunmoos-Seggentorfe».

It can be seen from the table that the hydraulic conductivity values presented are of similar magnitude in both of these studies. In the data presented by BADEN and EGGELSMANN, the influence of the increase in the degree of humification on the decrease in the hydraulic conductivity is not as strong as in the present study. This may be due to differences in the methods of determination. It should be kept in mind, however, that determination of the degree of humification according to the method presented by VON POST (1922) includes a

Table 5. Comparison between the results of the present study and the values presented by BADEN and EGGELSMANN (1963). Hydraulic conductivity, 10^{-6} cm/sec.

Degree of humification (v. POST 1922)	Sphagnum peats		Sedge peats	
	Present material	BADEN and EGGELSMANN	Present material	BADEN and EGGELSMANN
1	2200	. .	. .	. .
2	1050	1660	. .	. .
3	600	500	2100	1620
4	330	330	1100	640
5	180	100	580	330
6	100	80	300	200
7	58	70	150	170
8	34	60	85	140
9	18	60	. .	100
10	10	60	. .	100

Table 6. Conversion of the average times of rising of the water table recorded with the auger hole method by Huikari (1959, pp. 10—11) into hydraulic conductivity values corresponding to a temperature of 15 °C.

Distance between ground water table and ground surface, cm	Average rising time, min.	Hydraulic conductivity, 10^{-6} cm/sec
0—10	5	1680
10—20	17	535
20—30	105	95
30—40	210	50
40—	390	30

certain degree of subjectivity. The auger hole method gives a hydraulic conductivity value which is the average for the whole length of the ground water well which is below the ground water table, and this means that it is difficult to distinguish between the influence of different peat layers and of the degree of humification (cf. also Illner 1962).

In Finland, Huikari (1959) has carried out hydraulic conductivity determinations on peats using the auger hole method. Nevertheless, the results obtained were not converted into hydraulic conductivity values, but were presented in terms of average times of rising of the water and as relative hydraulic conductivity values. In order to make the results presented by Huikari (1959, pp. 10—11, Table 2) comparable with the data of the present study, the times of rising of the water were converted into hydraulic conductivity values using the formula presented by van Beers (1958, p. 21). As Huikari has adjusted the times of rising of the water to correspond to a temperature of 7 °C, the hydraulic conductivity values obtained through conversion had still to be adjusted to correspond to 15 °C, at which temperature the results of the present study were standardized. Table 6 shows the original figures and the results of the conversion performed.

As the auger hole method gives the average hydraulic conductivity for the length of the part of the ground water well located below the water table (Luthin and Kirkham 1949, Reeve and Kirkham 1951), the depth of the ground water table from the soil surface cannot be considered as corresponding to the sampling depth. If we assume that the weighted point of the re-entering of water into the ground water well is located 15 cm under the original level of the water table, the broken line presented in Fig. 7 indicates the effect of the sampling depth on the hydraulic conductivity of peat according to the data presented by Huikari. It can be observed that there is an agreement between the broken line and that representing

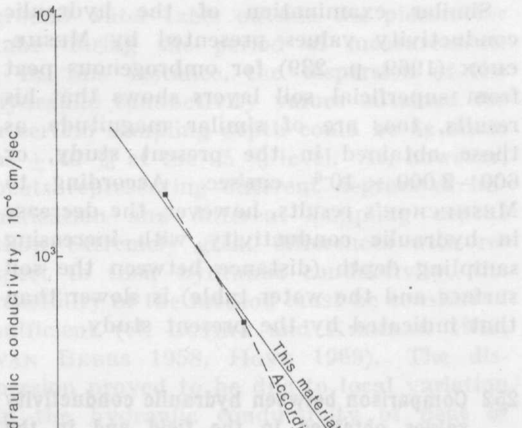

Fig. 7. Effect of the sampling depth on the hydraulic conductivity of Sphagnum peats according to the present material and according to Huikari (1959, pp. 10—11, Table 2).

Table 7. Comparison between average hydraulic conductivities (10^{-6} cm/sec) of Sphagnum peat by degree of humification at a temperature of 15 °C obtained in the laboratory (Päivänen 1968) and in the field.

Degree of humification	Laboratory samples a	Piezometer method b	a/b
1	8000	2200	3.6
2	3666	1050	3.5
3	1833	600	3.1
4	1166	330	3.5
5	833	180	4.6
6	666	100	6.7
7	500	58	8.6
8	400	34	11.8
9	333	18	18.5
10	250	10	25.0

the dependence between the sampling depth and the hydraulic conductivity in the case of Sphagnum-dominated peats reported in the present study. The data collected by Huikari comes mainly from pine swamps and open bogs, which also consist mainly of Sphagnum-dominated peats.

Similar examination of the hydraulic conductivity values presented by Meshechok (1969, p. 239) for ombrogenous peat from superficial soil layers shows that his results, too, are of similar magnitude as those obtained in the present study, or $600-3\,000 \times 10^{-6}$ cm/sec. According to Meshechok's results, however, the decrease in hydraulic conductivity with increasing sampling depth (distance between the soil surface and the water table) is slower than that indicated by the present study.

252 Comparison between hydraulic conductivity values obtained in the field and in the laboratory

As was mentioned in section 233, the present study series was preceded by laboratory experiments on the hydraulic conductivity, in which permeameters were used for the determinations (Päivänen 1968). Table 7 shows, by degree of humification, the horizontal hydraulic conductivity values obtained for Sphagnum peat samples. The table also contains the conductivity values recorded in the present study for Sphagnum peat at the depth of 25 cm and more (cf. Fig. 4).

It can be seen from the table that the laboratory method produced considerably higher hydraulic conductivity values than the field method; in the case of slightly decomposed Sphagnum peat the former values were 3.5-fold, in the case of moderately decomposed peat 5–9-fold and in the case of highly decomposed peats about 20-fold in comparison with those obtained by the latter method.

Boelter (1965, p. 229, Table 1) obtained differences of a similar magnitude as can be seen from the following table:

	Laboratory cores/ Piezometer
Undecomposed moss peat	3.9
Partially decomposed moss peat with wood inclusions	9.5
Decomposed peat	13.2

The fact that the laboratory method gives higher hydraulic conductivity values than the field method may be due to leakage at the soil - permeameter wall interface, despite the efforts which were made to eliminate it. A more probable reason, however, might be the disturbance caused to the structure of the peat during sampling and transportation and further handling of the samples. The influence of the possible occurrence of ruptures in the peat samples on the hydraulic conductivity values obtained is of course greater in the case of dense, and more decomposed peats than in the case of slightly decomposed peats with a loose structure. Moreover, in the laboratory the peat is not under the same pressure as in nature, and, as we know, the hydraulic conductivity decreases with increasing pressure (Hanrahan 1954). On the other hand, some investigations into the hydraulic conductivity of clay soils have given similar results irrespective of whether the determinations had been carried out in the field or in the laboratory (Collins and Schaffer 1967, Benecke and Renger 1969).

The laboratory measurements performed by Päivänen (1968) gave almost similar results to those presented by Sarasto (1963) and Korpijaakko and Radforth (1972). Nevertheless, it seems on the basis of the aforesaid, that hydraulic conductivity values obtained in the laboratory must be used with extreme reservation. The significance of the hydraulic conductivity obtained from laboratory samples is still decreased by the fact that the difference between the results from field and laboratory determinations increases with increasing degree of humification. It appears, consequently, that the results from measurements in the laboratory cannot be used even for examination of relative hydraulic conductivity values for peats representative of different degrees of humification. For this reason, data on the hydraulic conductivity of peats based on measurements in the laboratory will not be dealt with further in the present work (cf. Hasund 1910; Malmström 1923, 1928, 1939; Colley 1950; Segeberg 1952, 1958; Hanrahan 1954; Tveiten 1956; Weaver and Speir 1960; Sarasto 1963; Stewart *et al.* 1963; Schmeidl *et al.* 1970).

26 Discussion

Several factors which cause uncertainty are involved in the determination of the hydraulic conductivity of peats and interpretation of the results obtained. The very choice of method for the determinations may influence the results obtained.

The data of the present study was collected using the piezometer method. This method has earlier been applied to the study of peatlands, too. The choice of method was decisively affected by the fact that the measurements were intended for determination of the horizontal hydraulic conductivity *in situ.* In peat soils, it is mainly at the level of the ground water table that water moves in the direction of the slightly sloping ground. The horizontal hydraulic conductivity may be somewhat greater than the vertical one in the case of peat soils (cf. Malmström 1939, Sarasto 1963, Colley 1950), although results at variance with these have also been presented (Boelter 1965).

Stratification of the soil may affect the magnitude of function A (cf. p. 14), which in the present study was assumed to be constant, but this influence has proved to be negligible in studies carried out in order to develop the method (Luthin and Kirkham 1949, p. 355). The auger hole method would have been usable in studies carried out in peat soils, but it makes analysis of the influence of the sampling depth and of the degree of humification on the hydraulic conductivity uncertain.

If leakage would occur along the outer wall of the piezometer, the hydraulic conductivity values obtained would be higher than they really are. Errors of this kind were eliminated in the study, however, by continuous observation of the level of the ground water table outside the piezometer tube during the period of measurement.

In this instance, the dispersion of the hydraulic conductivity values obtained for a certain sampling depth could be as much as ± 40 % at the 95 % level. As, however, peats representing different degrees of humification and different sampling depths show extremely great differences with respect to their hydraulic conductivity, the reliability of the method must be considered sufficient (cf. Luthin and Kirkham 1949, van Beers 1958, Hove 1969). The dispersion proved to be due to local variation in the hydraulic conductivity of peat of the same depth layer. Other investigators, too, have observed a similar variation in the hydraulic conductivity (e.g. Ilyin and Dzerktser 1971). The fact that the ground water table has to be located above the soil layer which is under study must be considered a drawback of the method. Nevertheless, this is seldom a limiting factor in the case of peatlands, although it is in studies concerning mineral soils, and for this reason, other methods have been developed for use in them (e.g. Sillanpää 1956, 1959).

The material of the study was collected partly from peatlands which had been drained for forestry purposes, and partly from sample plots which simultaneously have been used for an investigation into the optimum water relationships of the substrate from the viewpoint of tree growth. Thus, the material was not the very best possible with respect to the peat species and the degrees of humification represented.

The influence of drainage on the hydraulic conductivity of peat was not specifically studied in the present connection. The increasing density of the peat due to drainage is included, it is true, in the bulk density of peat, which was used as an independent variable in the study (cf. BAZIN 1966). In the preliminary study (PÄIVÄNEN 1968), it was indicated that drainage leads to an increase in the density of peat and speeds up decomposition, which means that the hydraulic conductivity is decreased. On the other hand, an increase in the contents of wood remnants increases the non-capillary pore space of the peat, thus evidently increasing the hydraulic conductivity. The results presented by GETOV (1963), BADEN and EGGELSMANN (1963) and EGGELSMANN and MÄKELÄ (1964) concerning the influence of drainage on the hydraulic conductivity of peat are not necessarily contradictory if the influence of wood remnants is taken into consideration. The effect of forest drainage on the hydraulic conductivity of peat, however, cannot be considered a settled problem on the basis of the studies performed up to now.

Generally speaking, the study gave hydraulic conductivity values which were of similar magnitude to those obtained in the few previous investigations using field methods. In the preliminary study (PÄIVÄNEN 1968), experiments were performed to measure hydraulic conductivity using permeameters in the laboratory. Nevertheless, the results both of the present study and of the studies performed by BOELTER (1965) have proved that the methods used in the laboratory give hydraulic conductivity values which are too high.

3 WATER RETENTION CAPACITY

31 Methods of study

311 Principles of the determination of matric suction

Matric suction can be determined using various pressure, suction and tensiometer methods and by means of indirect measurement. As stated in the beginning of this paper, the free energy deficit of soil water (which in the case of peatlands can be placed on a par with the matric suction of the soil) is expressed in terms of the pressure which must be exerted on the soil water in order that its free energy would reach that of free water. At low matric suctions, a suction exerted on the soil water of the samples can be used instead of pressure. In the 1930's, it was possible to reach the pF value 3 using suction apparatuses; to reach higher values, however, indirect means had to be used such as lowering the freezing point and water vapor pressure. It was known already at that time that regulation of the pressure would be a simpler way to obtain the same results, but the necessary equipment was lacking (Schofield 1935, p. 39).

In the determinations, it is usually more important to assess the interrelationships between the matric suction and water content of the samples for the whole range of variation of the water content than to record the matric suction at the time of sampling. The relationship mentioned has been termed »moisture characteristic», »Wassersorptionskurve», »pF curve», etc. (Peerlkamp and Boekel 1960, p. 5; Richard 1963, p. 248; Puustjärvi 1963, p. 60). The level and the form of the curve describing this relationship are determined by the structure and the pore distribution of the soil.

The water contents corresponding to all matric suction values should be determined from undisturbed fresh samples, the natural structure of which has been preserved to the greatest possible extent. Drying and remoistening the samples or disturbing their natural structure have been observed to decrease significantly the water retention capacity of peat (Boelter 1964 b). In the case of mineral soils, on the other hand, corresponding conditions have led to a risk of overestimation of the soil water content (Young and Dixon 1966).

The direction of the change in the soil water content influences the interrelationship between matric suction and the water content (*hysteresis*) (e.g. Poulovassilis and Childs 1971). In the present study this relationship is examined only in the case of soil water desorption.

When using the suction and pressure methods, a matric suction of known magnitude is artificially exerted on the samples, and the corresponding water contents are then determined gravimetrically.

312 Water retention determinations in the laboratory

3121 Soil water content at pF 0 – 2

Determination of the water content of peat at matric suctions ranging from pF 0 to pF 1.0 (corresponding to a water column with a height of 0 – 10 cm) is possible by the artificial regulation of the surface of free water in steel cylinders enclosing the peat samples under study. The quantity of water required to reach saturation can be determined either by lowering or raising the water table (Boelter 1962, p. 45; Puustjärvi 1968, p. 20). As, however, the natural *water storage capacity* of peats is primarily studied in this way, this item will be left beyond examination in the present study.

In the Netherlands, Peerlkamp and Boekel (1960) introduced the »sandbox method» for determining the water content at low matric suctions. The method was further developed by van der Harst and Stakman (1965). «Blokzilj» sand is used as a porous medium. This sand is found in nature and has a texture which allows the pore space to maintain an unbroken water film up to a suction limit corresponding to a water column height of 130 cm. A constant suction is obtained by lowering the free water table with a so-called »suspended water column». The method was tested in connection with the present study, but without success. Its worst drawback is the fact that the contact between the sample and the sand is broken as soon as the desired equilibrium has been reached; this is because the water content at equilibrium has to be determined in each separate case by weighing. One of the advantages of the method is its cheapness in comparison with other apparatuses, and it also gives the possibility of handling a great number of samples (50) at the same time. In the studies mentioned above, the method was employed for water contents corresponding to pF 0.4—2.0.

Wolkewitz (1959, p. 43) has presented an apparatus in which an even suction is obtained by means of a vacuum valve. The undisturbed sample is placed in a steel cylinder, the bottom of which has been closed with a linen cloth and a glass sieve. The water which drains out of the sample is collected in a burette, thus making it possible to read the water quantity without breaking the contact with the glass sieve during the course of the measurements. The difficulty involved in the use of this method is the maintenance of a constant vacuum. Pressure plate apparatuses of corresponding kinds have been presented, for example, by Richards and Weaver (1944) and Czeratzki (1959).

In the present study single sample pressure cells were used for determination of the water contents corresponding to the matric suction values of pF 0, 1.0, 1.5 and 2.0. The use of equipment of this type has been described by Reginato and van Bavel (1962) and Boelter (1962). Fig. 8. shows a set of the pressure cells (Soil Moisture Equip. Co., Tempe Pressure Cell 1450) used. The apparatus consists of an exchangeable sampling cylinder with an inner diameter of 86 mm, and a height of 60 mm. Thus, the volume of the cylinder is 348 cm³. As there are several sampling cylinders for each pressure cell, samples can be collected in the field for the whole winter period, and the apparatus can be used without interruption throughout the year. By means of a sharp knife and the sharpened

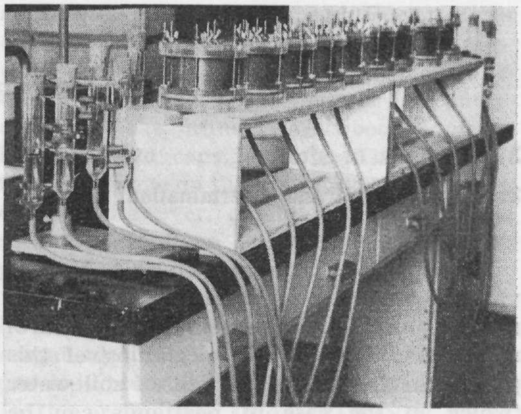

Fig. 8. Set of single pressure cells in the laboratory.

lower edge of the cylinder it is possible to obtain fresh samples from the topmost peat layer, each of which has exactly the same volume and the inner structure of which remains undisturbed.

The apparatus can be used either with pressure or with suction. In the present study, the suction required was obtained by lowering the free water table (the suspended water column). The work is performed as follows: A porous ceramic plate is left to become saturated with water for 24 hours outside the apparatus in order to remove air from the pores. When placing the plate in the apparatus, it is of essential importance to ensure that no air remains between the plate and the water column. The sample is then saturated by raising the water table above the apparatus for a period of four hours. In conjunction with saturation, the sample usually swells to some extent, and for this reason, some of the peat must be cut away from the upper surface of the sample using a sharp knife. The lid is put in place, the rubber tubing removed and the sample weighed, tare included. The water content of the sample at saturation is later determined on the basis of this weighing. The desired suction on the soil water of the sample is then adjusted. Instead of using a self-regulating water table, the water table is adjusted once every 24 hours to a constant level by means of a pipette. The rise of the water table leads of course to a slight decrease in the matric suction, but this will cause no error because it can be considered that equilibrium has not been reached until the height of the water table no longer rises during a 24-hour period. When equilibrium has been reached, the rubber tubing is unfastened and the sample is weighed, tare included. When the matric suction - water content series intended for measurement has been measured, the dry weight of the sample and the tare are determined and the water content of the sample at each matric suction is calculated in terms of volume per cents on the basis of the volume of the sampling cylinder. This apparatus has proved excellent in use, although reaching equilibrium between the matric suction decided on in advance and that of the sample may require several weeks. In the present study, determinations were made using four replications in the case of each sampling depth studied.

3122 Soil water content at pF 2–3

Water contents corresponding to the matric suction values of pF 2.0–3.0 were determined in the present study using a pressure plate extractor (Soil Moisture Equip. Co., Pressure Plate Extractor 1200). The pressure plate extractors used were all applications of the apparatuses used by RICHARDS and FIREMAN (1943) and by RICHARDS (1948). The pressure plate extractor has also been used for other purposes, for example, to assess the movement of water in unsaturated soils (JACKSON *et al.* 1963, RICHARDS 1965).

The most important parts of the extractor are the pressureproof cell and the pressure plates. The pressure plates are made of ceramic, and their underside is covered with a rubber membrane. A metal wire net keeps the membrane and the plate separated from each other and allows water to enter the space between them, from where it is then led out from the pressure chamber. The pores of the ceramic plate are so small that air can only penetrate them when the water has been removed, i.e., at a pressure of about 1 kp/cm² (pF 3.0). The pressure required is provided by a tank of compressed air from which it is led through pressure regulator into the chamber. Before use, the plates are saturated with water; moreover, a water layer with a thickness of a few millimeters is left on their surface.

Three pressure plates were used in the pressure chamber, each of which had room for 10 samples. In the measurement series, the following pressures were used: 0.2, 0.6 and 1.0 kp/cm² (pF 2.3, 2.8 and 3.0).

The samples which were used in the extractor were cut from larger peat samples which had been disturbed as little as possible during transport to the laboratory. Before treatment, they were kept in a freezer to suppress microbial activity. The size of the subsample was 5 × 5 × 1 cm, and the measurements were performed using ten replications. Each portion of the samples was used at only one pressure because the preliminary study showed that using the same sample at different pressures led to unreliable results. The contact between the sample and the pressure plate will be impaired if the sample is weighed between determinations. Evidently, too, the sample is not capable of retaining water in the same way once it has dried (cf. BOELTER 1964 b).

Equilibrium between the pressure used and the matric suction of the sample is usually reached within three days. This can be observed when the dribbling of water from the outlet tubes gradually ceases. White blotting paper can be used as an indicator. When equilibrium has been reached, the samples are weighed, the dry weight determined and the water contents obtained are converted into volume percentages on the basis of the bulk density, which has been determined separately.

3123 Soil water content at pF 3–4.2

In order to study water contents at high matric suctions, a pressure membrane extractor (Soil Moisture Equip. Co., Pressure Membrane Extractor 1100) was used. This apparatus, too, has originally been developed by RICHARDS (1941 a, 1947). The pressure membrane extractor has also been used to determine the hydraulic conductivity of unsaturated soils (YOUNGS 1964) and in studies of the chemical properties of soil water (TROEDSSON 1955, pp. 130–136).

The working principle of the pressure membrane extractor is similar to that of the pressure plate extractor, the only difference being that a celluloid membrane is used as the porous medium instead of a ceramic plate.

Preparation of the samples for treatment in the extractor and the measures to be taken after pressure treatment are similar to those used in connection with the pressure plate extractor. Equilibrium was usually reached within 3–6 days. It should also be mentioned that RICHARD and BEDA (1953) and BROWN (1972) came to the conclusion that the necessary time of pressure treatment is three days. Only nine samples could be treated in the extractor at one time. The water retention determinations were carried out using three replications, and the following pressures were used in the experimental series: 2, 5 and 10 kp/cm² (pF 3.3, 3.7 and 4.0). Determinations were even made on part of the material at the permanent wilting point (15 kp/cm² = pF 4.2). As in the case of the pressure plate extractor, each sample was treated at only one pressure.

313 Determination of the matric suction of peat in the field

Functioning of the tensiometers intended for use in the field is based on the negative pressure which is exerted on the water inside the apparatus so as to bring it into equilibrium with the soil water (through a porous, permeable wall or membrane). The negative pressure — the matric suction after equilibrium has been reached — can be read from the vacuum gauge of the tensiometer in terms of kp/cm² or mmHg. The principle of the tensiometer is rather old and it has been used to quite a large extent, particularly in mineral soils (RICHARDS and GARDNER 1936, RICHARDS 1949). The accuracy of tensiometers is usually poor at very low matric suctions, and consequently, the possibility of using them in studies concerning the water relationships of virgin or drained peatlands is limited (e.g. PAAVILAINEN 1963).

In connection with the present study, a tensiometer of Swedish manufacture (developed by Dr. ODÉN, Royal College of Agriculture) was tested. This apparatus had not been used in peat before. The lowest reading which can be obtained with the apparatus is 0.02 kp/cm² (pF 1.3), and this means theoretically speaking that the soil layer to be examined must be located at least 20 cm above the ground water table (cf. RICHARDS 1941 b, p. 778). Since the material of the present study was collected, an other type of tensiometer has come into use in Finland, the accuracy and usability of which are superior to those of the above-mentioned apparatus (AHTI 1971).

314 Measurements and observations for the description of peat structure

In addition to the water retention determinations, the following measurements and determinations were carried out on the peats under study:

The *peat type* and the *degree of humification* were determined as described in section 113. The *bulk density* of the peats was determined from the samples that had been treated in the pressure cells on the basis of their saturated volume and their dry weight. The samples were dried at 105° C in full awareness of the fact that some of the organic matter may char at this temperature (cf. MACFARLANE 1969, p. 80; BOELTER 1972, p. 4); however, only in this way could results be obtained which are comparable with those of other, corresponding studies (FARNHAM and FINNEY 1965, p. 130; ANDERSSON and WIKLERT 1967, p. 7; OLSEN 1968, p. 265; PUUSTJÄRVI 1968, p. 25; STURGES 1968, p. 263; OLSEN 1969, p. 66). Bulk density was determined using four replications.

Specific gravity was determined from air-dry peat samples at the Peat Research Center of Satoturve Oy, using the alcohol method developed by HEINONEN (1954). Determinations based on fresh peat samples would probably have led to similar results (cf. GÖTTLICH and BIRNBACHER 1956, SEGEBERG 1957), but the use of air-dry samples has usually been recommended (SEGEBERG 1955). In order to make sure that all the air was removed from the samples, the flasks used for the measurements were kept for a while in an ultrasonic washing apparatus. Measurements of specific gravity were carried out using four replications of each peat under study.

Total porosity was calculated from the following formula:

$$P_t\ (\%) = \frac{(G_s - D_b)\ 100}{G_s} \quad (8)$$

in which P_t = total porosity
G_s = specific gravity
D_b = bulk density.

Total porosity was consequently determined in the same way as in many other studies concerning the physical structure of peat (e.g. ANDERSEN 1968, IRWIN 1968).

Ash content was determined by igniting the dried peat samples in a muffle furnace at about 550° C until their weight was constant. Determinations were performed using ten replications from samples which had been treated in the pressure plate extractor. The ash content was expressed in terms of the percentage ignition residue from the quantity of dry matter.

32 Material of the study

321 Collection of the material

The peat sample material used in this study was collected during the years 1965—70 from sample plots located in the surroundings of the Forest Training Station, University of Helsinki (61°50'N; 24°20'E). The sample plots were representative both of virgin and of drained peatlands. The sample plots had also partly been used for collection of data for the aforementioned study of optimum drainage for tree growth. Some of the sample plots were also used for hydraulic conductivity determinations, the results of which were presented in the first part of this paper.

As the choice of sample plots was influenced also by aspects (site, drainage conditions, tree stand, etc.) other than those involved in peat research, the sample material which was collected is not evenly divided, for example, by peat type and degree of humification. Of the peats studied, 26 were dominated by Sphagnum, 14 by sedge and 7 by wood remnants. On average, the Sphagnum peats showed the lowest stage of decomposition, whereas the woody peats had reached the highest stage of decomposition (see Tables 8—10). In a report concerning a new international peat classification at present under preparation, it has been established that the humic acids derived from lignin accumulate in the peat and that, consequently, woody peats have usually reached a rather advanced stage of decomposition (ANON. 1973, p. 99). The material collected for the present study is thus probably representative of the most frequently occurring degrees of humification of various peats.

The samples were mainly collected from a depth of 10—15 cm below the ground surface to avoid the great unhomogeneity of the peat at the very surface of the ground. In drained peat soils the bulk of the tree roots are found in the 0—10 cm layer (HEIKURAINEN 1955). Thus, the sampling depth corresponds better to the mean root penetration as assessed for drained pine swamps by PAAVILAINEN (1966).

The pressure cell samples were kept in the sampling cylinders used in the field, for treatment in the same cylinders. For the water retention determinations to be performed in the pressure plate and pressure membrane extractors, several large peat samples were taken from the same peat layer. In the laboratory, 5 × 5 × 1 cm subsamples were then cut from these samples.

Tables 14—16 (pp. 43 and 44) show that complete water retention determinations were carried out in the case of all the peat types studied at saturation and at the matric suction values of 0.010, 0.032, 0.100, 1.0 and 10.0 kp/cm². These determinations were considered the most important ones. In addition, water retention measurements were carried out for at least one, and in several cases two matric suction values in the ranges of matric suction from 0.1 to 1.0 and 1.0 to 10.0 kp/cm². This was done in order to get a better picture of the shape of the water desorption characteristic for each of the peat types studied.

The water content of peat decreases only by a small amount when moving from pF 4.0 to pF 4.2, and for this reason it was considered sufficient to reach the former value. Nevertheless, water retention determinations were carried out even at pF 4.2, which is considered to be the permanent wilting point, on about one third of all the samples. So as to keep the amount of work required at a moderate level, determinations at 5.0 kp/cm² were not carried out in these cases.

In the case of each peat type under study, water retention determinations in the pressure cells were carried out using four replications, whereas, in the case of the pressure plate extractor measurements, ten replications were used, and in the case of the pressure membrane extractor, three. The interrelationships between matric suction and water content were examined in the present study on the basis of 188 determinations in pressure cells, 1 250 determinations in the pressure plate extractor and 405 determinations in the pressure membrane extractor, including replications.

In the case of six different peats, the water retention values corresponding to matric suctions of pF 2.0—4.2 were obtained from measurements carried out in a thermostat room at the Peat Research Center of Saturve Oy. All other determinations were carried out in the Department of Peatland Forestry, University of Helsinki. In the case of one peat (samples 48—51), the determinations were carried out in both of these laboratories in order to assess the possible influence of external conditions on the results.

Consequently, the data of the present study consists primarily of the results of water retention determinations carried out in the laboratory. In the summer of 1968, however, determinations of the matric suction were also carried out in the field, in seven sample plots, using tensiometers. In each sample plot concerned, the depth of the ground water table was recorded and the matric suction was determined using two tensiometers in the immediate vicinity of the ground water well at a depth of 5—10 cm below the ground surface. Measurements were not carried out regularly, but were done mainly in dry spells during the growing season as far as possible. The intention was to find out what values the matric suction can reach in the rhizosphere of peatlands that have been drained for forestry purposes.

Table 8. Data on the Sphagnum peats studied.

Number of sample	Specific gravity, g/cm³	Bulk density, g/cm³	Degree of humification	Ash percentage	Total porosity, %
181—182	1.49 ± .03	.037 ± .008	1	3.1 ± .3	97.5
173—176	1.37 ± .09	.047 ± .003	1	3.4 ± .2	96.6
53— 56	1.44 ± .04	.047 ± .003	1	1.6 ± .3	96.7
169—172	1.51 ± .13	.049 ± .003	1	1.5 ± .5	96.8
57— 60	1.41 ± .03	.056 ± .004	1	1.9 ± .6	96.0
8— 10, 52	1.42 ± .10	.058 ± .007	2	3.4 ± .6	95.9
5— 7, 15	1.48 ± .03	.061 ± .003	1	2.5 ± .6	95.9
48— 51	1.46 ± .02	.068 ± .003	1—2	1.3 ± .8	95.3
177—180	1.46 ± .05	.073 ± .005	3	4.6 ± .3	95.0
93— 96	1.39 ± .08	.075 ± .005	3	2.7 ± .5	94.6
157—160	1.47 ± .05	.081 ± .004	3	2.3 ± .5	94.5
77— 80	1.40 ± .04	.081 ± .010	3	2.6 ± .7	94.2
81— 84	1.41 ± .05	.085 ± .018	3—4	2.6 ± .4	94.0
89— 92	1.32 ± .05	.085 ± .005	3	2.6 ± .7	93.6
1— 4	1.41 ± .04	.087 ± .011	3—4	5.3 ± .5	93.8
192—194	1.39 ± .04	.089 ± .007	5	2.4 ± .3	93.6
101—104	1.36 ± .05	.090 ± .004	4	2.7 ± .6	93.3
105—108	1.34 ± .04	.093 ± .020	4—5	3.3 ± .4	93.1
30— 33	1.43 ± .01	.104 ± .003	5	3.0 ± .6	92.7
97—100	1.29 ± .03	.108 ± .005	5	2.7 ± .4	91.6
85— 88	1.37 ± .06	.108 ± .001	5	2.6 ± .4	92.1
73— 76	1.35 ± .03	.108 ± .008	5	2.8 ± .5	92.0
69— 72	1.40 ± .03	.110 ± .008	5	3.3 ± .7	92.1
189—191	1.45 ± .04	.111 ± .003	6—7	2.0 ± .4	92.3
20, 21, 42, 43	1.35 ± .04	.113 ± .008	6	5.4 ± .5	91.6
44— 47	1.23 ± .02	.179 ± .010	10	5.2 ± .5	85.4
Average	1.40	.085	3.6	3.0	93.9

322 Investigations into peat structure

3221 Correlation between factors describing peat structure

It was intended to relate to the greatest possible extent the water retention properties of the peats studied, to characteristics describing peat structure. For this reason the measurements presented in section 314 were carried out. The stage of decomposition of the peat was described by means of the degree of humification and the bulk density. Determinations of the specific gravity and the bulk density were performed on samples that had been treated in the pressure cells, and of which four replications were usually available for each category of peat. Based on the means of the specific gravity and bulk density values obtained, the average total porosity at saturation was calculated for each peat. The ash content was determined using ten replications from the samples that had been treated in the pressure plate extractor. Tables 8–10 show the averages obtained by peat type in order of bulk density. The sample numbers indicated in the tables refer to samples which have been treated in the pressure cells. Table 11 shows the correlation coefficients obtained by peat types for the interrelationships between various factors describing the properties of the peats.

These properties are dealt with in more detail in the following connection.

Table 9. Data on the sedge peats studied.

Number of sample	Specific gravity, g/cm³	Bulk density, g/cm³	Degree of humification	Ash percentage	Total porosity, %
185–188	1.47 ± .04	.054 ± .003	1	5.5 ± .6	96.3
145–148	1.31 ± .03	.079 ± .004	2–3	4.1 ± .7	94.0
165–168	1.37 ± .05	.084 ± .003	3	5.6 ± .3	93.9
121–124	1.30 ± .02	.084 ± .001	3	2.9 ± .4	93.5
117–120	1.37 ± .02	.093 ± .007	3–4	3.2 ± .2	93.2
161–164	1.41 ± .14	.112 ± .004	4–5	5.1 ± .4	92.1
11– 14	1.36 ± .04	.113 ± .005	4	4.7 ± .3	91.7
141–144	1.31 ± .04	.131 ± .005	5–6	3.4 ± .3	90.0
16– 19	1.35 ± .02	.135 ± .005	5–6	6.0 ± .3	90.0
34– 37	1.34 ± .07	.141 ± .010	6	5.6 ± .5	89.5
113–116	1.31 ± .03	.156 ± .008	7	3.4 ± .5	88.1
61– 64	1.31 ± .02	.161 ± .008	7	6.2 ± .9	87.7
38– 41	1.34 ± .02	.165 ± .007	7–8	6.6 ± .5	87.7
65– 68	1.33 ± .05	.190 ± .015	9	3.9 ± .4	85.7
Average	1.35	.121	4.9	4.7	91.0

Table 10. Data on the woody peats studied.

Number of sample	Specific gravity, g/cm³	Bulk density, g/cm³	Degree of humification	Ash percentage	Total porosity, %
153–156	1.43 ± .03	.099 ± .008	2–3	5.8 ± .6	93.1
133–136	1.35 ± .06	.100 ± .005	4	6.6 ± .6	92.6
129–132	1.35 ± .02	.109 ± .003	4	5.9 ± .8	91.9
26– 29	1.44 ± .02	.145 ± .007	7–8	7.9 ± 1.0	89.9
125–128	1.37 ± .05	.150 ± .003	7	9.7 ± .8	89.1
149–152	1.42 ± .05	.172 ± .016	9	12.1 ± .8	87.9
22– 25	1.39 ± .04	.207 ± .003	10	12.1 ± .6	85.1
Average	1.39	.140	6.3	8.6	89.9

Table 11. Correlation coefficients by peat type for the relationships between various variables which describe peat structure.

		x_1	x_2	x_3	x_4
S peats					
Specific gravity	x_1				
Bulk density	x_2	−.706***			
Degree of humification	x_3	−.669***	.972***		
Ash percentage	x_4	−.427*	.458*	.481*	
Total porosity	x_5	.763***	−.994***	−.962***	−.476*
C peats					
Specific gravity	x_1				
Bulk density	x_2	−.496			
Degree of humification	x_3	−.504	.996***		
Ash percentage	x_4	.339	.173	.140	
Total porosity	x_5	.544*	−.998***	−.995***	−.140
L peats					
Specific gravity	x_1				
Bulk density	x_2	.240			
Degree of humification	x_3	.249	.968***		
Ash percentage	x_4	.200	.945**	.939**	
Total porosity	x_5	−.162	−.997***	−.961***	−.941**
Entire material					
Specific gravity	x_1				
Bulk density	x_2	−.518***			
Degree of humification	x_3	−.495***	.964***		
Ash percentage	x_4	−.131	.658***	.605***	
Total porosity	x_5	.592***	−.995***	−.959***	−.619***

3222 Bulk density and degree of humification

In the Nordic countries, the degree of humification presented by VON POST (1922) is usually used to express the stage of decomposition of peat. As the peat decomposes, its porosity decreases and its density increases. Consequently, it is natural that a clear positive correlation exists between the bulk density of peat and its degree of humification (OLSEN 1969, PÄIVÄNEN 1969, PUUSTJÄRVI 1970, KARESNIEMI 1972, KORPIJAAKKO and RADFORTH 1972).

On the basis of the data of the present study, the following regressions were established between the bulk density (y) and the degree of humification (x) (see also Fig. 9):

		r^2	F
S peat	$y = 0.037 + 0.0134\,x$	.95	417.11***
C peat	$y = 0.035 + 0.0175\,x$	.99	1691.69***
L peat	$y = 0.053 + 0.0139\,x$	.94	75.58***
Entire material	$y = 0.035 + 0.0159\,x$	.93	589.59***

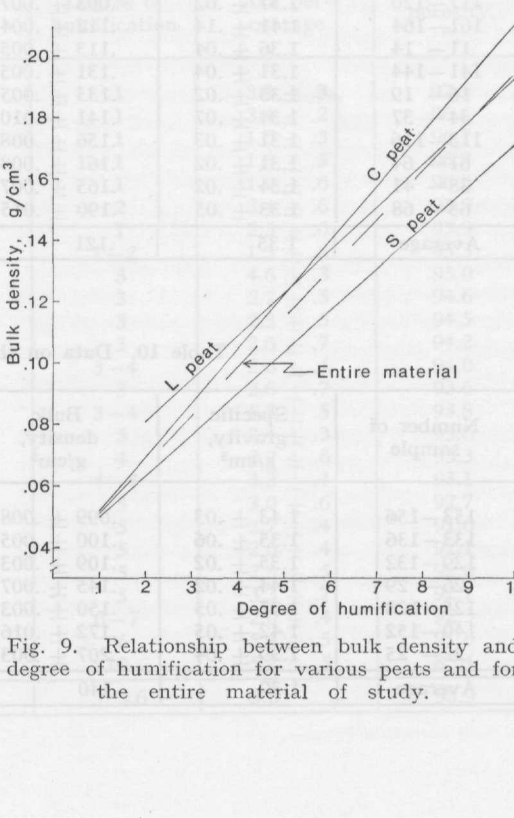

Fig. 9. Relationship between bulk density and degree of humification for various peats and for the entire material of study.

It appears consequently that there are clear differences between different peat types. With increasing degree of humification, the increase in bulk density is smallest in the case of Sphagnum peats and largest in the case of sedge peats. This result is in conformity with previous studies (PÄIVÄNEN 1969). The differences are probably explained by the fact that the ash content of sedge and woody peats is considerably higher than that of Sphagnum peat, and that the specific gravity of Sphagnum peat even decreases significantly with increasing bulk density, whereas in the case of sedge and woody peats, the specific gravity is independent of bulk density (Table 11, Fig. 10). It should be remembered, however, that the material used in the study was by no means homogeneous, for the Sphagnum peats were on average less decomposed than the sedge and woody peats. The peat samples had mainly been collected from peatlands which had been drained for forestry, and this fact has certainly also affected the results obtained (cf. KARESNIEMI 1972, p. 276).

The correlation between bulk density and degree of decomposition established on the basis of the present material is in good conformity with the results of previous studies. In the case of garden peat, the correlation is similar, although the line describing it is situated slightly lower in a coordinate system (cf. OLSEN 1969, PUUSTJÄRVI 1970).

Altogether, peat soils are light soils, their bulk density varying between 0.04 and 0.20 g/cm³. The bulk density of clay and sandy soils varies between 0.8 and 1.95 g/cm³ (HOLSTENER-JØRGENSEN 1958, p. 155; BRÜLHART 1969, p. 166).

3223 Specific gravity

The following average specific gravity values were obtained by peat type:

S peat	1.40
C peat	1.35
L peat	1.39
Entire material	1.38

On the basis of the entire material of the study, the following dependence was established between the specific gravity (y) of the peats studied and their bulk density (x) (see also Fig. 10):

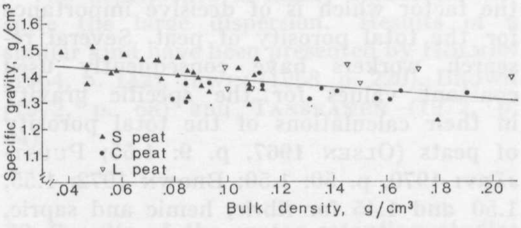

Fig. 10. Dependence of the specific gravity on bulk density.

$$y = 1.46 - 0.77\,x;\; r^2 = .27;\; F = 16.55^{***}$$

Examination of this correlation by peat type (Table 11) showed that it is significant only in the case of Sphagnum peat. Altogether, the variation in specific gravity by peat type and its decrease with increasing bulk density — or broadly speaking, decomposition — were extremely small. This has been established in other studies, too (e.g. FEUSTEL and BYERS 1930; OLSEN 1967, p. 9). The specific gravity (1.42) presented by PAAVILAINEN (1967, p. 9) for superficial Sphagnum-dominated peat is in conformity with the results of the present study. In their calculations, LUCAS and RIEKE (1968, p. 262) have used the value 1.40 for the specific gravity of peat. Somewhat greater values have also been presented (e.g. OLSEN 1967, p. 9: 1.55; MACFARLANE 1969, p. 88: 1.5—1.6; PUUSTJÄRVI 1970, p. 50: 1.4—1.6). The differences are probably mainly due to differences in the methods of determination.

For the sake of comparison, it could be mentioned that the specific gravity of mineral soils (clay and sand) has been assessed at 2.6—2.8 g/cm³ (ELONEN 1971, pp. 14—15), and that of raw peat ash at 2.65 g/cm³ (PUUSTJÄRVI 1970, p. 50).

3224 Total porosity

As was mentioned in conjunction with the description of the methods used in the study (p. 33), the total porosity of peat is dependent on its specific gravity and bulk density. Furthermore, the variations in the specific gravity of peat are small in comparison with those of bulk density. The latter is the factor which is of decisive importance for the total porosity of peat. Several research workers have consequently used constant values for the specific gravity in their calculations of the total porosity of peats (OLSEN 1967, p. 9: 1.55; PUUSTJÄRVI 1970, p. 50: 1.50; BROWN 1972: 1.55, 1.50 and 1.45 for fibric, hemic and sapric, peat respectively).

In the present work, however, the total porosity of the peats studied was determined on specific gravity and bulk density values both of which were based on four samples. On the basis of the entire material of the study, the following regression was obtained between the total porosity (y) and the bulk density (x) (see Fig. 11):

$$y = 100.38 - 76.7\,x;\ r^2 = .99;\ F = 4180.29^{***}$$

For comparison, the dependence of total porosity on bulk density as based on the materials presented by PAAVILAINEN (1967, p. 12) and PUUSTJÄRVI (1970, p. 50) have been inserted in Fig. 11. The regression line between total porosity and bulk density is the steeper, the smaller the specific gravity values used. The steepness of the regression line based on the present material is accentuated by the fact that the specific gravity values used decrease with increasing bulk density (see p. 37). The correlations between total porosity and bulk density do not differ much from each other in the case of Sphagnum and sedge peats, but in the case of woody peat, the corresponding regression line is not so steep as in the case of the former groups. This phenomenon, too, can be explained by the fact that the specific gravity, particularly in the case of peats that have reached an advanced stage of decomposition, is greater for woody peat than for the other peat types studied.

The magnitude of the influence of the specific gravity on total porosity can be further illustrated by means of the following table,

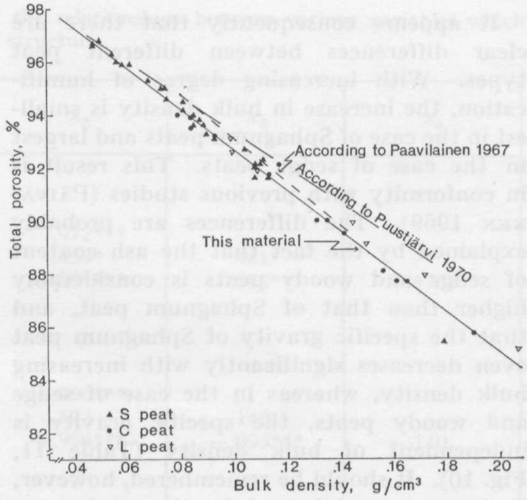

Fig. 11. Dependence of the total porosity on bulk density.

in which, on one hand, a constant value (1.55 g/cm³) (e.g. OLSEN 1967, ELOWSON and PERTTU 1970) is used for the specific gravity, and on the other hand, the average values obtained in the present study.

Table 12 shows that the difference between the total porosity values obtained when using constant and, on the other hand, true specific gravity values, is negligible in the case of slightly decomposed peats, whereas, in the case of peats that have reached a more advanced stage of decomposition, i.e., peats with a higher bulk density, it reaches a value between 1.5 and 2.1 unit per cents of volume. Differences in the total porosity of this magnitude can be expected when the variations in specific gravity due to differrences in the methods of determination are taken into consideration (see p. 37).

In summary, it can be stated that the pore space of peat soils is large (85—97 %) in comparison to that of mineral soils, which varies between 30 and 65 % of volume (e.g. HOLSTENER-JØRGENSEN 1958, p. 155; BRÜLHART 1969, p. 166). It ought to be mentioned

Table 12. Dependence of the total porosity on the specific gravity values used at varying bulk density.

Bulk density, g/cm³	0.05		0.10		0.15		0.20	
Specific gravity, g/cm³	1.55	1.43	1.55	1.39	1.55	1.35	1.55	1.31
Total porosity, %	96.7	96.6	93.5	92.7	90.3	88.8	87.1	85.0
Difference in total porosity	−0.1		−0.8		−1.5		−2.1	

that, in the case of mineral soils, too, a rather clear negative correlation has been found between total porosity and bulk density. This correlation has even been used for determination of the total porosity of soil, thus avoiding the use of time-consuming, pycnometric methods (HOLSTENER-JØRGENSEN 1958, p. 155).

3225 Ash content

The ash contents of the peat samples used in the study were as follows:

S peat	3.0
C peat	4.7
L peat	8.7
Entire material	4.3

It can be seen from these figures that the ash content increases when moving from Sphagnum peats to sedge and woody peats (cf. KIVINEN 1948, p. 120). For sedge peats, somewhat higher ash contents have usually been presented than those obtained in the present study (cf. KIVINEN 1948, p. 119; VAHTERA 1955, pp. 34–35; PJAVTSHENKO 1958, p. 5; SARASTO 1960, p. 8).

On the basis of the figures presented in Table 11, it can be seen that the ash content of Sphagnum and woody peats increases with increasing bulk density and degree of humification. For the entire material of the present study the following relationship was established between the ash content (y) and the bulk density (x) (see Fig. 12):

$$y = 0.20 + 39.65\,x;\; r^2 = .43;\; F = 34.27^{***}$$

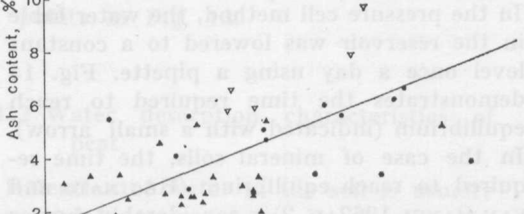

Fig. 12. Dependence of the ash content on bulk density.

The dependence is highly significant despite the large dispersion. Results of a similar kind have been presented by HOLMEN (1964, p. 142), IRWIN (1968, p. 220), BROWN (1972, p. 68) and TANSKANEN (1972, p. 64).

33 Results of the water retention studies

331 The water retention of peat

3311 Sources of error possibly involved in the methods used

In order to make sure that the original water content of the samples would be as large as possible, the samples to be used in the study were collected in the spring and fall when ground water table is highest. The samples were mainly taken from a depth of 10–15 cm below the ground surface. After they had become saturated in the pressure cells, the samples usually swelled to some extent, so that their upper surface had to be cut away with a sharp knife before the lid was put in place. Consequently, all water contents and the volumes of solid material and total pore space were calculated in terms of per cents of the volume of saturated peat samples. After treatment in the pressure cells, the samples were dried at 105 °C. The bulk densities used in the study are based on the volume (348 cm³) of the samples at saturation, and their dry weight.

The same bulk density values were used when the water contents of the samples treated in the pressure plate and the pressure membrane extractors were converted into volume percentages.

As mentioned in sections 3122 and 3123, each sample which was treated in the pressure plate or the pressure membrane extractors, was studied at one pressure only. The inevitable use of such a method has its drawbacks, inasmuch as the structure of peat is unhomogeneous. The true bulk densities of samples from adjacent places in the very same peat layer may vary, and consequently, the use of the average bulk densities obtained for the pressure cell samples may be a source of dispersion in calculations of the quantities of water retained by the peat at different pressures.