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Physical Properties of Organic Soils

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Introduction

Compared with research on mineral soils, the study of the physical properties of organic soils in the United States is relatively new. Always (1920) and Anderson et al. (1951) considered the value and reclamation of peats in Minnesota and nationally. Davis and Lucas (1959) summarized organic soil formation, utilization, and management in Michigan; however, most of the literature on the detailed physical properties of peat was published from 1956 to 2003. This is true in Europe as well (Parent and Ilnicki 2003), except for a study by von Post (1922) who developed a field method for determining the degree of humification (decomposition) that is used widely outside of the United States (Box 5.1). A comprehensive series of studies on peat physical properties were conducted by Don Boelter (1959–1975), first at the Marcell Experimental Forest (MEF) and later throughout the northern Lakes States to investigate how to express bulk density (D_b, weight or volume basis), water retention characteristics, hydraulic conductivity (K), fiber content, specific yield (drainable porosity), and the degree of decomposition (pyrophosphate test). Juhani Päivänen, a graduate student from the University of Helskinki, spent nearly a year at the MEF to learn the techniques developed there. Upon returning to Finland, he sampled extensively in central Finland and developed a physical-property data set similar to that of Boelter. Together, the data of Boelter and Päivänen represent one of the largest examinations of the physical properties of peat. After 1975, physical-property studies continued at MEF including a detailed examination of fiber contents in Lake State organic soils, a comparison of international methods for physical properties,

BOX 5.1 VON POST FIELD-TEST PROCEDURE FOR H VALUE

Take samples about 5 m from prospective well sites. A Russian peat corer (Macaulay) or bucket auger may be used. Each horizon with a different H value should be evaluated. Take samples to at least 1.3 m or until a mineral-soil contact is found. Part of each sample can be retained for verification but the H value should be determined immediately using saturated soil or with water added if the soil is dry. Place enough soil to fill the hand when the fingers are gently curved against the palm. Gently bounce this egg-shaped soil until it just fits your hand. Add or remove soil to fill the gently curved pocket in your hand. Squeeze the sample as hard as you can. In the other hand catch the amorphous material and water squeezed between the fingers. Note the color and turbidity of the free water (water that is separate from any amorphous material). Thinning the water by opening the second hand facilitates the examination of color and turbidity.

Use the fingers of the second hand to scrape amorphous material from between the closed, squeezed fingers of the first hand and consolidate the amorphous material in the second hand. Consolidate the material in both hands by gently bouncing the material. Open both hands and compare the relative volume of the fiber material and the amorphous material. The relative volume of the amorphous material (in percent) is used to assign the von Post H value for whole and half values in the mid-range (Table Box 5.1). In Europe and Canada, use of half classes is common. Half classes in the mid-range are helpful in differentiating peat layers that are encountered frequently in partially drained areas. Table Box 5.1 shows half classes in the range of H4–H7.5.

TABLE BOX 5.1

von Post Field Evaluation Adapted for Hydraulic Conductivity in the Mid-Range (H4–H7.5)

von Post H Value	Volume Passing through Fingers (%)	Additional Description of Free Water Expressed to the Second Hand
1	0	Expressed water is clear to almost clear and yellow-brown in color. Slowly open the second hand and observe color as the water depth thins
2	0	
3	0	Water is muddy brown and retained fiber is not mushy
4	0	Very turbid, muddy water and retained fiber is somewhat mushy
4.5	1	Amorphous material primarily stays on outside of squeezed fingers
5	2–10	Use the volume of amorphous material passed. As with H4 and H4.5, water at the edges of the amorphous material is very turbid and muddy
5.5	11–25	
6	26–35	
6.5	36–45	
7	46–55	Water around the amorphous material is thick, soupy, and very dark
7.5	56–65	Water around the amorphous material is thick, soupy, and very dark
8	66–75	There is essentially no free water; it is all amorphous material
9	76–95	There is no free water associated with the amorphous material
10	95–100	

and a comparison of the piezometer and salt-dilution methods for hydraulic conductivity. In this chapter we present the peat physical properties, compare methods, and describe how to use physical peat data in lateral-extent equations to evaluate the effect of drainage in peatlands.

Early work at the MEF underpinned the U.S. Department of Agriculture's (USDA) interpretation and classification of organic soils in the United States by showing the range of fiber content in a variety of peats. In 1962, Boelter (1964a,b) sampled nine peatlands at MEF (Itasca County, Minnesota) and three peatlands in Koochiching County, Minnesota, to begin measurements of water content, bulk density, and water retention at 0.0 kPa (saturation) and at 0.5, 10, 20, 100, 200, and 1500 kPa. The 12 sites yielded 119 samples. Nichols and Boelter (1984) reported on samples from northern Minnesota, northern and central Wisconsin, and Upper Michigan, adding 57 samples from 26 sites. In total, 176 peat samples from 38 peatlands were collected. The botanical composition of the plant residues in the peats are listed in Table 5.2. Moss peats were predominately of *Sphagnum* origin, whereas herbaceous peats were predominately sedge (*Carex*) which also is known as reed-sedge or sedge peats.

Fiber content in organic soils is the fundamental characteristic that determines bulk density, water retention, hydraulic conductivity, and drainable porosity. The inclusion of mineral ash in excess of plant cellular ash components (e.g., windblown dust) also contributes to bulk density. The bulk density of a peat can be corrected for its ash content to quantify the bulk density of the organic portion (Nichols and Boelter 1984). When fiber content is divided by size category (>2.0, 1.0–2.0, 0.5–1.0, 0.25–0.5, 0.1–0.25, and <0.1 mm), it parallels the primary particles (sand, silt, clay) in mineral soils. Organic material less than 0.1 mm is subcellular and amorphous (not fiber); it affords strong cation exchange and water retention (Kwak et al. 1986), but strongly limits hydraulic conductivity because the percentage of amorphous material increases.

The degree of decomposition can be estimated by the amount of material (<0.1 mm) or the solubility of peat in sodium pyrophosphate solution (Farnham and Finney 1965). Lynn et al. (1974) used rubbed fiber content (rubbing small portions of a peat sample between thumb and fingers 10 times using moderate pressure) and the pyrophosphate index as the basis for classifying U.S. soils at the suborder level (Soil Survey Staff 1975). Lynn et al. (1974) sieved the rubbed peat through standard soil sieves using a gentle stream of water. This is similar to the method of Boelter (1964a,b) except that Lynn et al. used a bottom sieve of 0.15 mm. In this method, which is used to determine fiber content in the United States and Canada, the smallest fiber class is 0.25–0.15 mm and all material <0.15 mm is placed in the amorphous class. Sieves of 0.15 or 0.25 mm that are sealed across a centrifuge tube were used in the former Soviet Union (Tolonen and Saarenmaa 1979). All these national laboratory methods were compared using peat samples, most of which were from the MEF and central Minnesota (Malterer et al. 1992). Additionally, these authors characterized the von Post field method on the same samples (von Post 1922; von Post and Granlund 1926). The degree of humification or H value in the von Post method is based on the amount of peat and the color of water expressed from an egg-sized sample of peat squeezed in the hand. The von Post method defines 10 classes for degree of humification (H1–H10). This field-based method is used extensively outside the United States because the method is quick and, with practice, is consistent, more precise, and more accurate than sieving methods.

Bulk density of the organic portion of peats also reflects decomposition and is strongly related to the hydraulic conductivity of peats (Boelter 1965). Boelter used the borehole and piezometer methods to determine hydraulic conductivity at MEF. Both methods measure the rate of fall in the water level in the hole or in the piezometer as water flows into the soil around the hole or pipe opening. The peizometer method can be adjusted to measure a specific peat horizon of a given fiber content, bulk density, or degree of decomposition. In 1970, techniques developed at MEF were introduced to central

Finland by Päivänen (1973), who duplicated measurements of hydraulic conductivity at 28 sites with *Sphagnum* peat, 23 with sedge peat, and 29 with woody peat. These samples were collected from pristine and drained peatlands at the University of Helsinki's Hyytiälä Forestry Field Station. Earlier, he found relationships between bulk density and von Post H values for 316 samples collected from the same peatlands (Päivänen 1969).

The values for hydraulic conductivity may be biased because the water column in a borehole or piezometer creates a sloping water table that increases the hydraulic gradient relative to undisturbed peats. Gafni (1986) measured the hydraulic conductivity of peats by injecting small volumes of concentrated salt solutions into piezometers with a site at the MEF and three in the Cromwell area of St. Louis County, northeastern Minnesota. Salt movement was measured by detection in downslope wells or by dilution of salt in the injection well over time. When these methods were investigated at the MEF, point dilution was far more reliable than the trace method. Gafni also measured the von Post H value and related it to hydraulic conductivity (Gafni 1986; Gafni and Brooks 1990). A comparison of the piezometer and salt-dilution method revealed that the salt dilution is suitable for porous peats and the piezometer method is suitable for moderately to well-decomposed peats. However, the use of piezometers for porous soils greatly underestimates hydraulic conductivity. Earlier work in the United States and Finland includes that of Feustel and Byers (1930) and Huikari (1959), respectively. Examination of data on hydraulic conductivity in Finland and at the MEF revealed that neither methodology piezometer or point dilution is suitable for the entire range of peat decomposition (von Post H values 1–10). In the large-pored (H1–H6) peats K_{sat} is best determined by point dilution; in small-pored (H7–H10) peats, K_{sat} is best determined by the piezometer.

Parent and Illnicki (2003) summarized the chemical and physical properties of organic soils and peat materials. They included physical-property data for moorish soils (granular peats over well-decomposed horizons developed with prolonged drainage and cultivation), and long-term data on hydraulic conductivity and bulk density collected in Poland (e.g., Okruszko 1993).

In the United States, the physical properties of hydraulic conductivity, drainable porosity, and horizon thickness are used to determine the lateral effect of drainage. Lateral effect is the distance from a ditch or tile line where the soil is drained sufficiently to affect Federal or State protection of wetland status. Many wet sites were drained prior to the wetland regulation and protection specified in the 1974 Clean Water Act. However, the degree of drainage within a wetland was variable: some areas qualified as drained (within the lateral effect) while some areas beyond the lateral effect retained their protected status. The von Post H value correlates well with hydraulic conductivity, fiber content, and drainable porosity and is recommended as an alternative to laboratory or field determinations of hydraulic conductivity using piezometer methods.

In this chapter we discuss the important physical properties of peat as they have been determined and tested over 50 years, and show examples of how to use drainage equations to evaluate whether a wetland site is drained. The data set on peat physical properties developed at MEF and throughout the Lake States is the largest and most comprehensive in the United States.

Expression of Water Content and Bulk Density

Water content in mineral soils (%) is routinely expressed as the mass of water lost on drying to the oven-dry mass of the soil. The mass of water lost on drying is relatively small compared to the dry mass of the mineral soil (20%–35%). The mass of water in an organic soil is large compared to the oven-dry mass of the soil (organic fibers and some mineral ash), from 300% up to 3000%. Although the intrinsic meaning of water content is the same for mineral and organic soils when expressed this way, comparison of water content among organic soils is difficult when the range of values is undefined (i.e., <100% in mineral soils but essentially open-ended in organic soils). However, water content based on bulk saturated mass (mass of water at soil saturation divided by the total mass of water and wet soil) may be used to predict bulk density if allowances for gas volume are made (Laine and Päivänen 1982).

Boelter (1964a,b) used the bulk volume of a saturated sample for water content (volume basis) in organic soils in the United States. Water content (Wv) is the amount of water lost from the soil upon drying at 105°C (determined by mass loss) and expressed as the volume of water per unit volume of bulk soil. The volume of bulk soil is the volume of the soil sample removed in the field. It usually is sampled with a cylinder (sharpened at one end) of known volume. The cylinder is pushed gently to just below the peat surface, the extruded peat on top shaved off, and the cylinder is dug around on the outside and then detached at the lower end with a knife. Below the water table, a large-diameter caisson (about 60 cm) is evacuated of water as the peat is removed, and then a smaller volume cylinder (10 cm diameter by 10 cm long) is used to sample the peat. The volume of the peat is the volume of the cylinder when the peat is saturated (<0.33 kPa of water tension, which leaves the sample at full volume). Bulk density also is determined by dividing the total sample mass (oven dry) by the volume of the cylinder.

Laine and Päivänen (1982) sampled peats with a standard cylinder as part of a detailed method for calculating bulk density and total porosity that accounted for the volume of gases in the water. Rather than expressing the volume of the cylinder as m^3, they expressed the volume of the cylinder as the mass of water (Mg). The oven-dry mass of the peat and water divided by the mass of the water is another calculation for bulk density. This method reduces the variation in correlations between bulk density and degree of humification (von Post H value) but only when corrections for gas volume are made. It is suitable for samples below the water table (assuming that ash from windblown dust is low).

Boelter and Blake (1964) found a highly significant correlation between bulk density determined on a saturated-volume basis and on a dry-volume basis. Saturated-volume bulk densities ranged from 0.02 to 0.26 Mg m^{-3}, though the standard error of estimate for a single value in the regression was 0.021 Mg m^{-3}. Päivänen (1969) also found a high correlation between fresh, field-volume bulk density and laboratory-volume density as determined by the consistent packing of dried and ground samples. In subsequent work, Boelter and Päivänen consistently used the saturated or near saturated field volume of peat as the basis for bulk density (oven-dry mass per saturated volume; Mg m^{-3}).

Correlation of Ash Content and Bulk Density

Both Nichols and Boelter (1984) and Päivänen (1973) correlated ash content as a function of bulk density. Both separated peat samples by botanical origin: *Sphagnum*, sedge (*Carex* or herbaceous), or woody. Lake States peats are from undrained peatlands while peats from central Finland are from peatlands drained for forestry. The results are plotted for woody peats (Figure 5.1) and for *Sphagnum* and sedge peats (Figure 5.2). The ash content of Lake States peat is about 5% higher in than that in woody peats of central Finland.

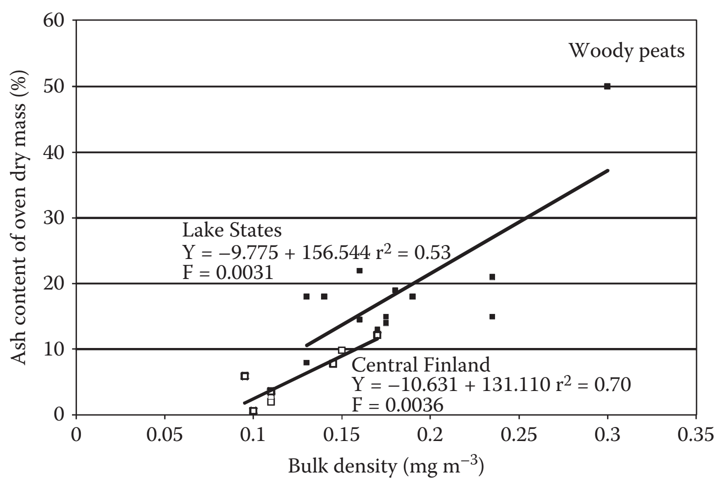


FIGURE 5.1
Relation of ash content to bulk density in the Lakes States and central Finland for woody peats as redrawn and regressed using data from Nichols and Boelter (1984) and Päivänen (1969). The F-value is the significance level of the regression.

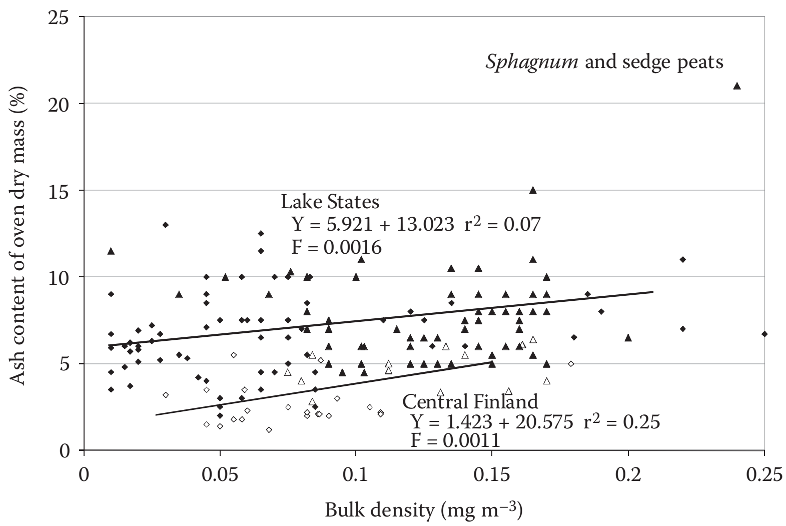


FIGURE 5.2
Relation of ash content to bulk density in the Lakes States and central Finland for *Sphagnum* and sedge peats as redrawn and regressed using data from Nichols and Boelter (1984) and Päivänen (1969). The open symbols are from central Finland (diamonds = *Sphagnum*; triangles = sedge); and the solid symbols are from the Lake States (diamonds = *Sphagnum*, triangles = sedge). The F-value is the significance level of the regression.

Higher ash contents in Lake States peat are traced to the continental position of the Lake States which are situated just east of large semiarid areas in the northern Great Plains. Mineral dust from these areas is routinely deposited in the Lake States. It is likely that peats in Manitoba and Ontario, Canada also have higher ash contents than peats in central Finland, which is just east of the slightly saline Gulf of Bothnia and south of the Arctic Circle. As such, precipitation in this region does not contain a large amount of mineral dust.

Correlation of Bulk Density and von Post Degree of Humification

Päivänen (1969) correlated bulk density with the von Post degree of humification for *Sphagnum*, *Carex* (sedge), and woody peats in central Finland (Figure 5.3). Similarly, a highly significant correlation between bulk density and degree of humification was found by Puustjärvi (1970), Karesniemi (1972), Päivänen (1973), Raitio and Huttunen (1976), Silc and Stanek (1977), Tolonen and Saarenmaa (1979), and Korpijaakko and Häikiö Leino (1981).

Most sedge and woody peats are found in fens fed by groundwater that is high in calcium and magnesium; they impart higher ash contents to ligneous

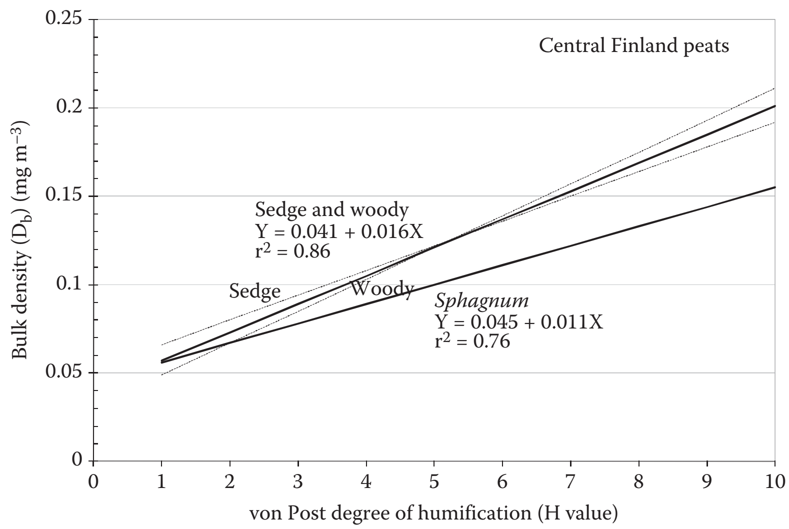


FIGURE 5.3
Relation between von Post degree of humification H value and bulk density, volume basis, for peats in central Finland as redrawn from Päivänen (1969). Sedge and woody peat regressions are not significantly different and are combined. (From Päivänen, J., *Acta Forest. Fenn.*, 129, 1, 1973.)

tree and sedge cells than to the nonligneous cells of *Sphagnum* peats occurring in poor fens or bogs (or in fens on hummocks, partially isolated from the groundwater below the hummocks). However, not all sedges are mesotrophic or eutrophic and high in lignins, some sedges that grow on poor fen sites are depauperate in minerals.

Available Water-Storage Capacity in Organic Soils

The handling of samples of organic soil can strongly affect available water-storage capacity (AWSC) and water retention characteristics. Boelter (1964a,b) measured AWSC at 3, 10, 33, and 1500 kPa of tension. Two sample-handling methods were compared: air-dried and ground peat samples and undisturbed field samples that were kept moist. AWSC at 3 kPa was about 13% less (by volume) in air-dried and ground samples about 5% less at 10 kPa, about 4% less at 33 kPa, and about the same at 1500 kPa. The irreversible shrinkage that occurs when organic soils are dried reduces the total porosity of the peat sample, no doubt altering the pore-size distribution such that more of the remaining pores are small and able to retain water only at higher tensions. The total loss of pore space with drying reduces total AWSC 5% at

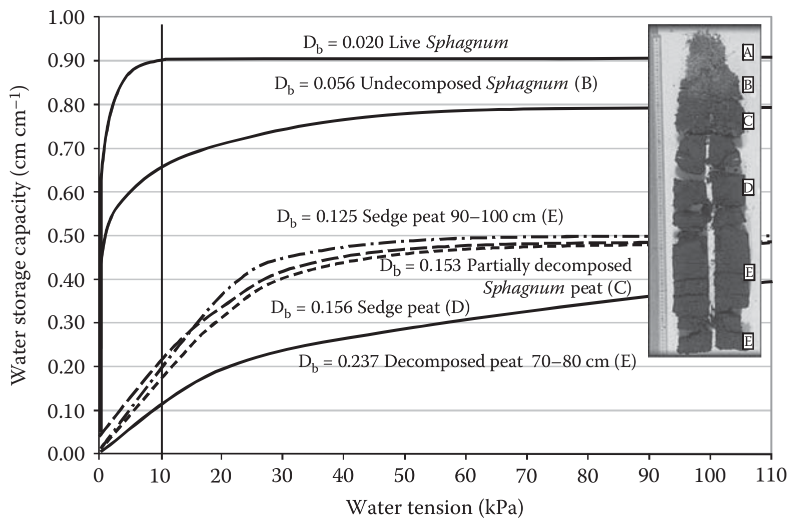


FIGURE 5.4
Available water storage capacity of undisturbed peats (S2 bog) at low water tensions for six peat samples with variable bulk density (D_b). Water storage capacity at 10 kPa is taken as field capacity in organic soils.

10 kPa taken as field capacity in peats. The use of moist field samples is recommended in determining water-storage capacity.

Boelter's first determinations of AWSC were with undisturbed, wet, peat core samples from the S2 bog. Six peat samples were taken from a single core. AWSC was measured on samples placed on large pressure plates or, for low tensions, on a single sample placed in a pressure cell that was the same diameter as the field-sampling core. In both instances, peat was seated on an asbestos slurry separated from the peat by cheesecloth. Changes in water content before and after application of the tension provided a measure of water-storage capacity (or a measure of specific yield). Water content was expressed as cm of water cm^{-1} of peat core thickness. In contemporary usage, drainable porosity is used synonymously with specific yield. From the outset at the MEF, basic science was undertaken to support applied science as related to soil, water, and forest management. This early work shows how fundamental water-storage characteristics in organic soils support field studies to calculate water balance, evaluate drainage and, years later, evaluate drainage lateral extent in wetlands. Figure 5.4 shows three major ranges in water storage or specific yield (live and undecomposed *Sphagnum*, three peats with D_b values of 0.125–0.156 Mg m^{-3}, and a well-decomposed peat with a D_b value of 0.237 Mg m^{-3}).

In mineral soils, field capacity (water content after 3 days of drainage from saturation) is represented by water content at 10 kPa for porous sands and 33 kPa for loams and clays. In organic soils, available water storage is taken at 10 kPa. The large-pored *Sphagnum* samples in Figure 5.4 (D_bs of 0.02 and 0.056 Mg m^{-3}) can store 0.75 or 0.90 cm of water cm^{-1}, that is, they have a specific yield or drainable porosity of 75%–90% of their volume. Likewise, more decomposed peats with a D_b of 0.125–0.156 Mg m^{-3} can store only 0.18–0.22 cm cm^{-1} and have a drainable porosity of 18%–22%. The most decomposed peat (D_b = 0.237 Mg m^{-3}) in Figure 5.4 can store only 0.12 cm cm^{-1} and has a drainable porosity of 12%. Water retention and drainable porosity of peat changes dramatically with degree of decomposition and bulk density, and must be accounted for by delineating horizons in natural settings. For instance, annual water budgets in peatlands account for changes in water storage from, say, the first day of the year when water tables are high to the last day of the year when, following a drought, water tables are low. The amount of actual water difference that left storage is dependent on the size of pores in the zone of water table fluctuation and their corresponding drainable porosity. On a daily basis, the water table response to precipitation is the inverse of drainable porosity (specific yield). A 1 cm precipitation addition to a raised-dome peatland (no immediate upland or groundwater input) with a water table in a horizon with a drainable porosity of 0.22 would have a water table response of 1/0.22 or 4.55 cm. A water table dropping 1 cm without precipitation would yield only 0.22 cm of water depth. Total porosity of the peat horizons in Figure 5.4 vary little (range of 84%–97%), but the size distribution varies greatly. The upper peats have many large pores and the deeper peats have many small pores. The distribution of pore space size is a principal correlate with degree of decomposition, bulk density, drainable porosity, and hydraulic conductivity.

Water Retention in Organic Soils

Samples from other peat cores in S2 bog were assessed for the amount of water retained under tensions of 0.5, 3.5, 10, 20, and 1500 kPa. Water retention in Figure 5.5 is on the same scale as that in Figure 5.4 (Boelter 1970). Although different peat samples (notice differences in bulk density) from the same peatland were used, water-retention curves (Figure 5.5) are nearly opposite of available water storage (Figure 5.4). These are large differences among peats with large differences in bulk density, but sedge peats with moderate decomposition and well-decomposed peats show similar water retention with different bulk densities.

Boelter (1970) illustrated the significant impact of bulk density on water retentions at 0.5, 10, and 1500 kPa (Figure 5.6). He also showed the impact of fiber content on water retention (Figure 5.7). It should be noted that

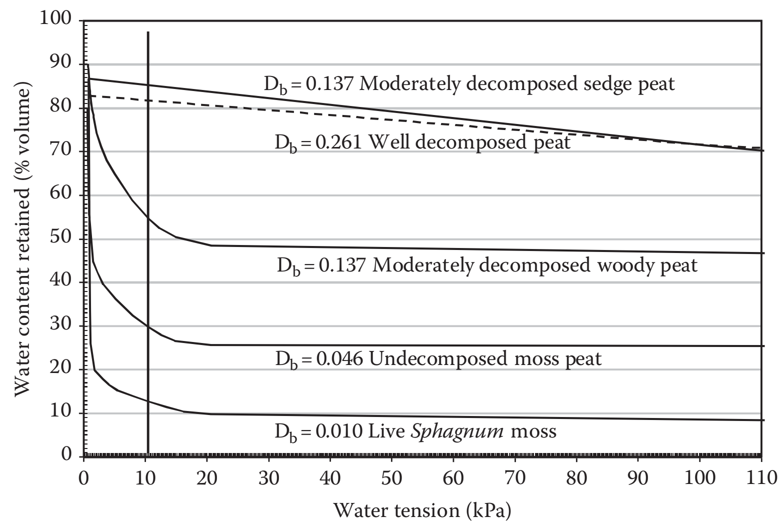


FIGURE 5.5
Water retention at various water tensions for a variety of peats from the S2 bog, MEF. Water tension at 10 kPa is considered field capacity. (Redrawn from Boelter, D.H., Important physical properties of peat materials, in *3rd International Peat Congress Proceedings*, Helsinki, Finland, 1970, pp. 150–154.)

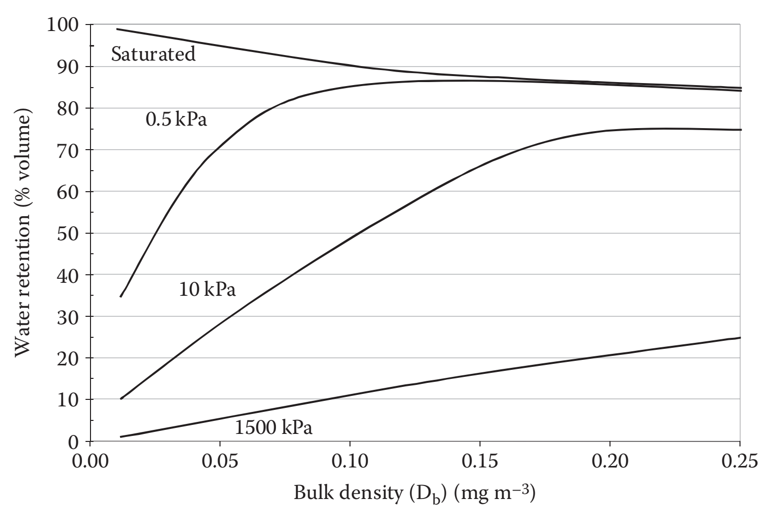


FIGURE 5.6
Water retention in peat as a function of bulk density. (Redrawn from Boelter, D.H., Important physical properties of peat materials, in *3rd International Peat Congress Proceedings*, Helsinki, Finland, 1970, pp. 150–154.).

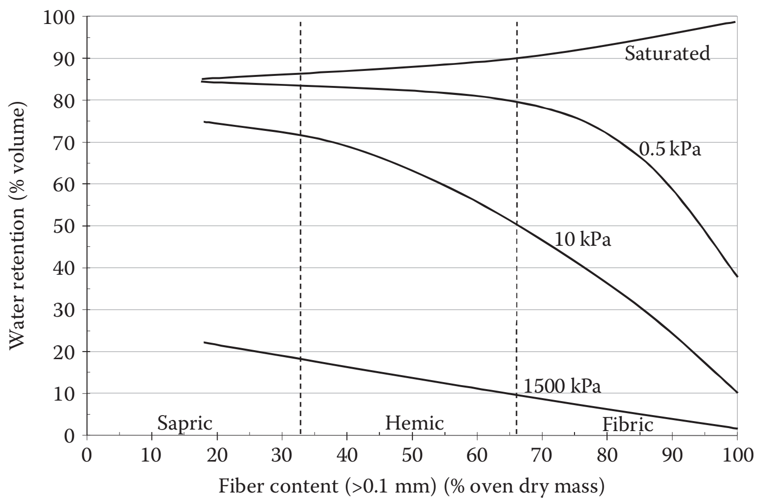


FIGURE 5.7
Water retention in peat as a function of fiber content. (Redrawn from Boelter, D.H., Important physical properties of peat materials, in *3rd International Peat Congress Proceedings*, Helsinki, Finland, 1970, pp. 150–154.) The vertical dashed lines illustrate USDA divisions for sapric (well decomposed), hemic (moderately decomposed), and fibric (least decomposed) categories used for soil-series classification (U.S. Soil Survey Staff 1975).

water-retention measurements at very low tensions require careful attention to sample volume and manometer column heights.

Figures 5.5 and 5.6 illustrate the dependence of water retention on bulk density and fiber content, particularly at 10 kPa of tension. Equations describing the relationship in Figures 5.6 and 5.7 are given in Table 5.1

TABLE 5.1

Regression Equations and R^2 Values for the Relationship between Water Retention (Y) at Saturation, 0.5, 10, and 1500 kPa and either Fiber Content (X) or Bulk Density (X)

Level of Saturation	Independent Variable (X)	Regression Equations by kPa of Tension	R^2
Saturated	Fiber content	$Y = 84.23 - 0.0279X + 0.00185X^2$	0.68
	Bulk density	$Y = 99.00 - 123.45X + 252.92X^2$	0.66
0.5 kPa	Fiber content	$Y = 52.45 + 1.5619X - 0.01728X^2$	0.69
	Bulk density	$Y = 39.67 + 638.29X - 2010.89X^2$	0.70
10 kPa	Fiber content	$Y = 67.91 + 0.4136X - 0.01064X^2$	0.80
	Bulk density	$Y = 2.06 + 719.35X - 1809.68X^2$	0.88
1500 kPa	Fiber content	$Y = 29.34 - 0.3420X + 0.00072X^2$	0.73
	Bulk density	$Y = 1.57 + 15.28 - 107.77X^2$	0.82

Source: Boelter, D.H., *Soil Sci. Soc. Am. Proc.*, 33(4), 606, 1969.

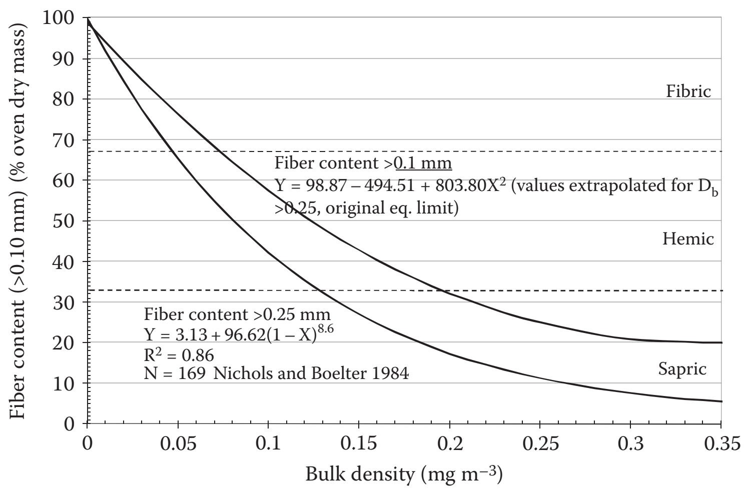


FIGURE 5.8
The relation between fiber content (>0.1 mm; Boelter 1969) and (>0.25 mm; Nichols and Boelter 1984) bulk density.

with R^2 values from 0.66 to 0.88. Figure 5.8 shows the correlation of fiber content (>0.1 mm) and bulk density. The correlations for other fiber content thresholds (>0.25, >0.50, >1.0, and >2.0 mm) are equally strong (Boelter 1969).

Fiber Content and Bulk Density in the Lake States

Nichols and Boelter (1984) measured fiber content and bulk density for samples taken from undrained peatlands in northern Minnesota, Wisconsin, and Michigan (Table 5.2). Moss peats are found throughout the entire range of fiber decomposition with most in the Fibric class. Sedge peats also found

TABLE 5.2

Numbers of Samples Used in Nichols and Boelter (1984) by Botanical Origin and USDA Fiber Class for 176 Peat Samples from the Lake States

Botanical Origin	Fibrists	Hemists	Saprist	Total
Moss peat (mostly *Sphagnum*)	48	21	9	69
Sedge peat (sedges, reeds, grasses)	9	53	4	66
Woody (at least one-third is wood remains)	0	1	13	14
Undetermined origin	0	7	20	27
Total	57	82	46	176

throughout the entire range with most in the Hemic class. Woody peats are rarely Hemists and most are in a Sapric class like peats of an undetermined origin. Note that bulk density tends to increase in the order of botanical origin shown in Table 5.3.

The most detailed relationship between fiber content (by size class) and field-volume bulk density (corrected for the mass of ash) is shown in Figure 5.9, which includes both unrubbed (field condition) and rubbed samples (USDA fiber-content protocol; Soil Survey Staff 1975). The bottom bars represent amorphous peat with bound water. The upper white bars

TABLE 5.3

Ash Content and Bulk Density of Lake States Peats

Type of Peat	Number of Samples	Mean Ash Content (%)	Range of Ash Contents (%)	Mean Bulk Density (Mg m^{-3})	Range of Bulk Densities (Mg m^{-3})
Moss	69	6.62 ± 0.61	2.2–13.4	0.067 ± 0.012	0.009–0.219
Herbaceous	66	8.54 ± 1.34	3.9–40.5	0.126 ± 0.010	0.010–0.201
Woody	14	18.47 ± 5.48	8.5–52.0	0.178 ± 0.029	0.126–0.314
Unidentified	27	12.67 ± 3.58	3.1–35.6	0.200 ± 0.030	0.071–0.374

Source: Nichols, D.S. and Boelter, D.H., *Soil Sci. Soc. Am. J.*, 48, 1320, 1984.

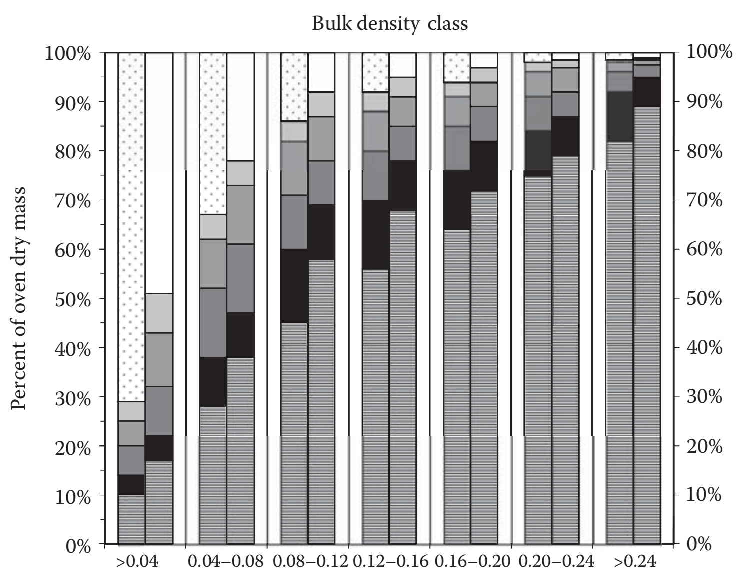


FIGURE 5.9
Distribution of fiber size for pristine (undrained) peats in the Lake States by volume-based bulk-density classes when corrected for ash content. (Redrawn from Nichols, D.S. and Boelter, D.H., *Soil Sci. Soc. Am. J.*, 48, 1320, 1984.)

(with small dots) represent water that runs from a saturated peat sample when picked up. The relatively narrow band of fiber size in the middle (<2.0 to >0.1 mm) represents peat horizons with values for bulk density, drainable porosity, and hydraulic conductivity that are critical for assessing the lateral effect of drainage. Peats with sufficient amorphous peat (<1.0 mm) to reach a bulk density of 0.18 or more is effectively an aquiclude. However, water level may vary upward or downward by several centimeters over a year.

In 1968, debate arose concerning the minimum size class for fiber to use for soil series classification. Original work by Farnham and Finney (1965) and Boelter (1964a,b, 1969) used tedious wet sieving to determine fiber content retained on a 0.1 mm sieve. However, the USDA Soil Conservation Service (Soil Survey Staff 1967) recommended a bottom-sieve size of 0.15 mm primarily to decrease time needed to carefully wet sieve highly decomposed samples. Because the national fiber categories for Histosol classification in the United States and Canada are large (Fibric, Hemic, Sapric), the size of the bottom sieve makes no significant difference to soil series description. Bottom sieve sizes of 0.1 and 0.25 mm and the three classification categories are compared in Figure 5.8. Similar curves can be drawn for any minimum size class.

Fiber content is a proxy measure of degree of decomposition as determined by a laboratory method. However, the widely accepted von Post H value also is directly dependent on the minimum fiber size. This is shown both in the strength of water bound to amorphous peat and water released from the peat matrix when peat is squeezed in the hand following field protocol (Box 5.1). For water-retention characteristics (Figure 5.7) and for field determination of degree of humification, 0.1 mm is an appropriate threshold for minimum fiber size. Plant fibers decompose to amorphous material that has a water-holding capacity similar to that of clays. This water cannot be removed by drainage or by squeezing because only prolonged or high-temperature drying will remove this water.

The von Post hand-squeeze method seems subjective; but the maximum pressure exerted by normal squeezing is about 138 kPa. In more decomposed peat (pores of less than 0.10 mm), holds water with a tension of 2800 kPa (Kwak et al. 1986). This 20-fold difference in tension marks the break where the first 10% of total peat volume, as amorphous peat, passes between the fingers (von Post H4: no peat passes between the fingers; H5: about one-tenth passes between the fingers).

Figure 5.10 illustrates how the amorphous material in peat (<0.1 mm) is the primary cause of increases in bulk density. The increase in bulk density is nearly linear as amorphous material (<0.1 mm) content increases. Except for undecomposed moss peat (D_b < 0.04 Mg m^{-3}), other fiber sizes show a minimal negative trend with increasing bulk density. Some fibers (0.1–2.0 mm) remain at high bulk densities (and have H values of 8–10). However, the large

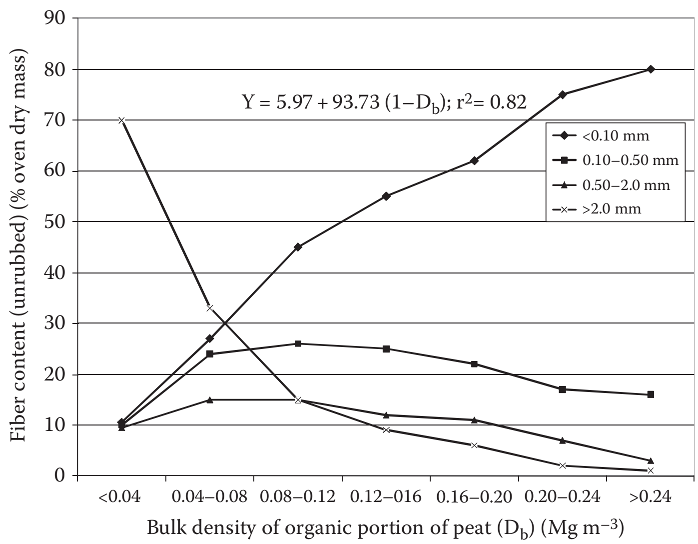


FIGURE 5.10
Percentage of fiber for four size categories versus bulk-density category. (From Nichols, D.S. and Boelter, D.H., *Soil Sci. Soc. Am. J.*, 48, 1320, 1984.)

amount of amorphous peat at these bulk densities and at high H values carries these remaining fibers (60%–80% of the bulk volume) through the fingers encased in the amorphous mass.

Fiber Content and Degree of Decomposition: An International Review

The debate about minimum fiber size (and its measurement) and use of field versus laboratory methods for degree of decomposition was prolonged by the adoption of a variety of methods by different nations since there are no internationally accepted methods. Malterer et al. (1992) reviewed national methods for degree of decomposition and fiber content and evaluated their precision and capacity to distinguish between classes of peat (von Post H value). Most samples were collected from S2 bog at the MEF (see H value description in Verry 1984) and from a site near Circle Pines in Anoka County, Minnesota. All 10 von Post classes were sampled (moss, sedge, and unidentified, well-decomposed peat).

The von Post degree of humification (Box 5.1), USSR humification index, and USDA pyrophosphate extract color are used to describe the degree of decomposition. The USSR method consists of centrifuging a small sample of peat through a screen sealed across a centrifuge tube. Screens of 0.25 mm (60 mesh) and 0.15 mm (100 mesh) were evaluated by Lishtvan and Kroll (1975). The volume of total sample and the volume passing the sieve are entered into one of five nomographs based on peatland trophic status and botanical origin of peat to yield a humification score (R%). The USDA pyrophosphate test consists of adding an aqueous sodium pyrophosphate solution and measuring the color intensity of the extract using the Munsel 10YR color chart (Soil Survey Staff 1975).

Fiber content is determined by the USSR centrifugation method (60 and 100 mesh) using the direct volume measurement of sample retained on the screen to total sample volume (in percent). In the ASTM fiber mass method, a moist unrubbed sample is soaked in a dispersing agent (sodium hexametaphosphate) and gently washed through a 0.15 mm sieve. This is similar to the method developed by Boelter who used a 0.1 mm sieve (Levesque and Dinel 1977). The original USDA method is determined by gently washing a peat sample through a 0.15 mm sieve; however, the percent fiber is calculated as the volume of sample retained divided by the volume of original sample. The USDA methods determines fiber volume by packing the original and retained fiber into a 35 cm^3 syringe with one-half of its length cut away and gently compressing with the plunger. Unrubbed and rubbed determinations are made in this way (Soil Survey Staff 1975). In a modified version, if more than 10% sapric material is retained on the screen, it is mixed with water, beaten with a whisk, and then washed through the sieve (Soil Conservation Service 1984). Coefficients of variation for the mean of 10 von Post H-value samples provide a measure of method precision (Table 5.4) and accuracy (Table 5.5). MUSSR 100-DFV was the most accurate fiber content method, distinguishing nine classes followed by MUSSR 60-DFV with eight classes. The ASTM method distinguished seven classes and the USDA methods distinguished four to six classes.

The sorting of fiber content methods into various accuracy categories likely relates to the method of determining fiber volume. The MUSSR method determines fiber volume directly in the centrifuge tube with volume calibration etched on a narrow portion of the tube. It "packs" material into this narrow tube portion with a constant centrifugal pressure sufficient to force amorphous material past the screen. The ASTM method determines percent fiber volume using the ratio of oven-dry mass of fibers passed divided by the oven-dry mass of the total peat sample.

In summary, the USSR centrifuge method with a nomograph (based on peatland site trophic condition and peat botanical origin) and the von Post field method are the most precise and accurate. Malterer et al. (1992) presented 42 regression equations and graphs comparing national methods. Staneck and Silc (1977) found that the von Post method was the most accurate for Ontario peats.

TABLE 5.4

Coefficients of Variation (%) for National Methods of Degree of Decomposition and Fiber Content

	Degree of Decomposition (%)				**Fiber Content (%)**						
Field von Post	USSR 60 N	USSR 100 N	USDA 1974 pyrophosphate	MUSSR 60 DFV	MUSSR 100 DFV	ASTM 100 FW	USDA 1974 100 URFV	USDA 1974 100 RFV	MUSDA 1977 100 URFV	MUSDA 1977 100 RFV	
H classes	8.0	5.2	5.0	23.6	7.2	5.2	11.3	12.7	21.7	15.8	22.6

Source: Malterer, T.J. et al., *Soil Sci. Soc. Am. J.*, 56, 1200, 1992.

Notes: 60- and 100-mesh are 0.15 and 0.25 mm sieve openings; N, nomograph; DFV, direct fiber volume; FM, fiber mass; U and R, unrubbed and rubbed peat samples. Values are means of 10 samples.

TABLE 5.5

Mean Values for Each Degree of Decomposition and Fiber Content Method for all 10 von Post H Classes

Degree of Decomposition Methods										
von Post class	1	2	3	4	5	6	7	8	9	10
von Post means	1.0	**2.4**	**2.7**	4.4	5.3	**6.5**	**6.7**	8.1	9.1	9.9
USSR 60 N	18.7	**26.0**	**27.0**	39.3	**44.7**	**46.1**	48.6	52.8	**58.8**	**60.1**
MUSSR 100 N	15.8	**21.7**	**23.3**	37.3	**40.2**	**40.5**	**42.5**	**43.1**	**51.8**	**52.4**
USDA pyrophosphate	6.6	**6.0**	**5.7**	2.6	**1.9**	**1.8**	**1.5**	**1.2**	***0.6***	***0.5***
Fiber content methods										
von Post class	1	2	3	4	5	6	7	8	9	10
MUSSR 60 DFV	85.6	**77.1**	**75.9**	58.4	49.9	**36.5**	**35.7**	23.3	19.5	11.6
MUSSR 100 DFV	89.1	**82.0**	**80.0**	61.7	56.8	49.2	45.8	36.9	29.8	2.34
ASTM 100 FW	71.4	**61.6**	**60.1**	37.5	**31.2**	**29.1**	27.2	**11.9**	**11.2**	7.7
USDA 100 URFV	95.6	**80.6**	**76.8**	**64.8**	**64.4**	**61.8**	**59.0**	**58.6**	44.6	30.4
USDA 100 RFV	84.0	**54.0**	**53.6**	*23.6*	*20.2*	14.6	12.8	**4.8**	**2.1**	**0.1**
MUSDA 100 URFV	94.8	**76.8**	**75.8**	58.0	43.8	**35.1**	**34.8**	21.2	17.8	17.4
MUSDA 100 RFV	86.4	**54.2**	**53.2**	25.2	18.4	**11.6**	**11.0**	**5.1**	**1.5**	**0.0**

Source: Malterer, T.J. et al., *Soil Sci. Soc. Am. J.*, 56, 1200, 1992.

Notes: The accuracy of each method is reflected in the number of von Post classes distinguished. Adjacent bold values (bold, underlined, or bold, underlined, and italicized) are not significantly different at the 0.05 level.

Hydraulic Conductivity

Early Work at the MEF: A Tabular Association with Drainable Porosity

Drainable porosity also known as water-yield coefficient, specific yield, AVWSC, and saturated hydraulic conductivity (K_{sat}) for MEF peats in 1965 were listed by the sampling depth and general peat type (Table 5.6). Hydraulic conductivity was measured by the piezometer method. Gafni (1986) measured effective porosity in the same MEF peatland as Boelter, and in a mined peatland near Cromwell, Minnesota (Table 5.6).

Hydraulic Conductivity and Fiber Content Correlations

Boelter (1969) provided a regression between hydraulic conductivity and fiber content (>0.1 mm; Figure 5.11). A similar relationship between hydraulic conductivity and bulk density was reported for Lake State peats (Boelter 1969) and peats in central Finland (Päivänen 1973; Figure 5.12). These relationships are reasonably close when D_b is at least 0.09 Mg m^{-3}. However, Boelter's relationship is more than twice Päivänen's for D_b less than 0.09 Mg m^{-3}. Both

TABLE 5.6

Drainable Porosity, Hydraulic Conductivity, and Bulk Density of Several Minnesota Peats

Peat Type	Degree of Decomposition	Sampling Depth (cm)	Hydraulic Conductivity (10^{-5} cm s^{-1})	Boelter's Drainable Porosity (cm cm^{-1})	Gafni's Drainable Porosity (cm cm^{-1})	Bulk Density (Mg m^{-3})
Sphagnum peat						
	Live, undecomposed moss[a]	10–0	[b]	0.85		0.100
	Live, undecomposed moss	0–10			0.63	
	Undecomposed moss	15–25	3810	0.60	0.58	0.040
	Undecomposed moss	45–55	104	0.53		0.520
	Moderately decomposed with wood	35–45	14	0.23		0.153
Woody peat						
	Moderately decomposed	35–45	496	0.32		0.137
	Moderately well decomposed	60–70	56	0.19		0.172
Sedge peat						
	Slightly decomposed	25–30	1280	0.57		0.069
	Moderately decomposed	79–80	0.70	0.12		0.156
Decomposed peat						
	Well decomposed	50–60	0.45	0.08		0.261
	Well decomposed, mined peat	130–140			0.21	

Source: Boelter, D.H., *Soil Sci.*, 100(4), 227, 1965; Boelter, D.H., Important physical properties of peat materials. In *Third International Peat Congress Proceedings*, Helsinki, Finland, 1970, pp. 150–154; Boelter, D.H., *Soil Sci. Soc. Am. Proc.*, 33, 1974.

[a] Sampled above the hollow elevation on a hummock.

[b] Drained too rapidly to measure.

equations use peats of different origin, but Päivänen's equation excluded samples in the upper 25 cm of the soil profile because this horizon had become well decomposed following drainage for forestry.

The piezometer methods for hydraulic conductivity are similar for Boelter and Päivänen. In each method, a narrow tube (3.2 cm) is driven into the peat near the middle of a peat horizon. The peat is augered from the tube and the hole augered another 10 cm below the tube. After the tube and hole are flushed with water pumped from the tube, the rate of water table rise

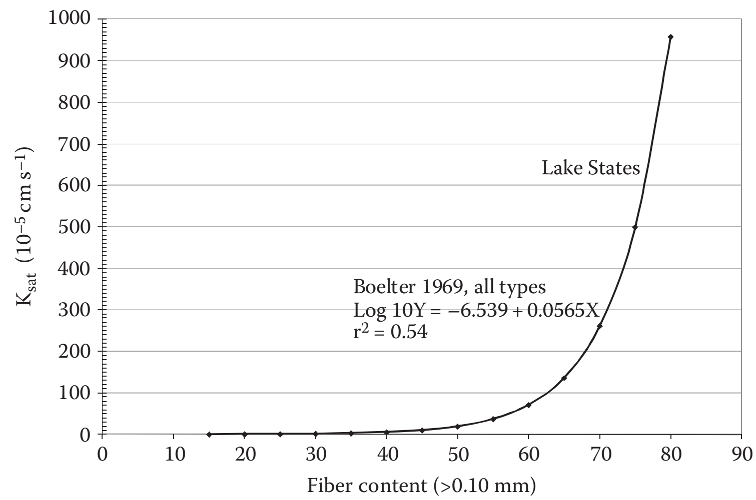


FIGURE 5.11
Relation between saturated hydraulic conductivity (K_{sat}) and fiber content (>0.1 mm) for all types of Lake States peat. (From Boelter, D.H., *Soil Sci. Soc. Am. Proc.*, 33(4), 606, 1969.)

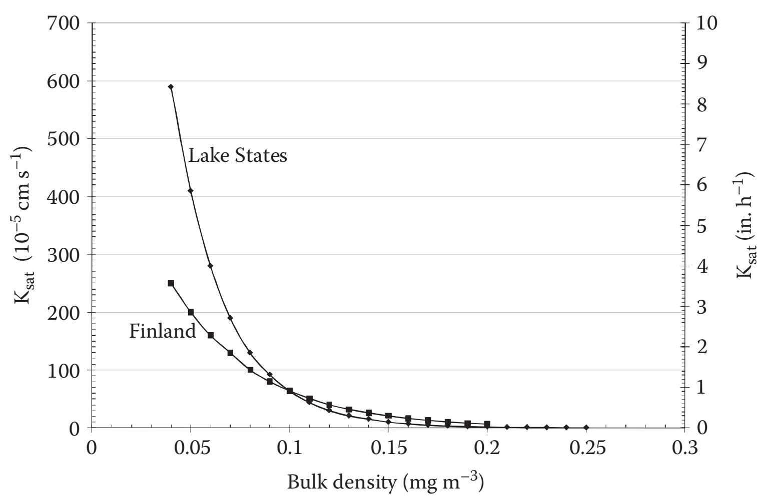


FIGURE 5.12
Relation between saturated hydraulic conductivity (K_{sat}) and bulk density (D_b) for all peat types in the Lake States (diamonds) and central Finland (squares). (From Boelter, D.H., *Soil Sci. Soc. Am. Proc.*, 33(4), 606, 1969; Päivänen, J., *Acta Forestalia Fennica*, 129, 1, 1973.)

is observed over time and hydraulic conductivity is calculated using the Kirkham equation (Frevert and Kirkham 1948; Kirkham 1951). In Päivänen's method, the water table was observed in a well hole near the piezometer. If the well water table dropped when the piezometer was pumped, the piezometer tube was not well sealed and was abandoned. While there is consistency

TABLE 5.7

Hydraulic Gradient and Groundwater Velocity in Four Northern Minnesota Peatlands

Depth in Peat (cm)	Northern MN Peatland	Hydraulic Gradient (%)	Groundwater Velocity (10^{-5} cm s^{-1})
0–10			
	S2 bog	0.0526	1361
	Transitional fen	0.0425	1319
10–20			
	S2 bog	0.0526	4.1
	Transitional fen	0.0454	2.2
	Raised bog	0.0024	3.4
20–30			
	S2 bog	0.0524	2.8
	Transitional fen	0.0454	0.7
30–40			
	S2 bog	0.0543	0.4
40–50			
	S2 bog	0.0537	0.3
	Raised bog	2.2850	0.9
	Mined site	2.0950	0.8

Source: Gafni, A. and Brooks, K.N., *Can. J. Soil Sci.*, 70, 239, 1990.

between the K_{sat}:D_b relationships in the United States and Finland, actual K_{sat} values likely were underestimated when the peizometer method was used for undecomposed peats (H1–H6).

Hydraulic Gradient and Groundwater Velocity

Gafni and Brooks (1990) examined the correlation of hydraulic gradient measured with closely spaced well transects arranged on different azimuths around a central well and groundwater velocity measured by the point-dilution method. Groundwater velocities are listed in Table 5.7. The range of hydraulic gradients in peatlands is similar to the range of water-surface gradients in many Lake States streams and rivers (0.001%–3.0%). Generally, peatland hydraulic gradients range from 0.001% to 0.05% but steepen greatly where large, raised-bog domes develop with steep dome sides or where drainage ditches greatly steepen gradients. Groundwater velocities (0.49–0.016 m h^{-1}) decrease with depth (5–45 cm), reflecting peats with greater decomposition at depth.

Hydraulic Conductivity and Degree of Humification

Detailed work in Poland on heavily farmed agricultural land with organic soils is documented in Okruszko (1960, 1993) and Parent and Ilnicki (2003). The hydraulic conductivity of peats also has been investigated in Russia

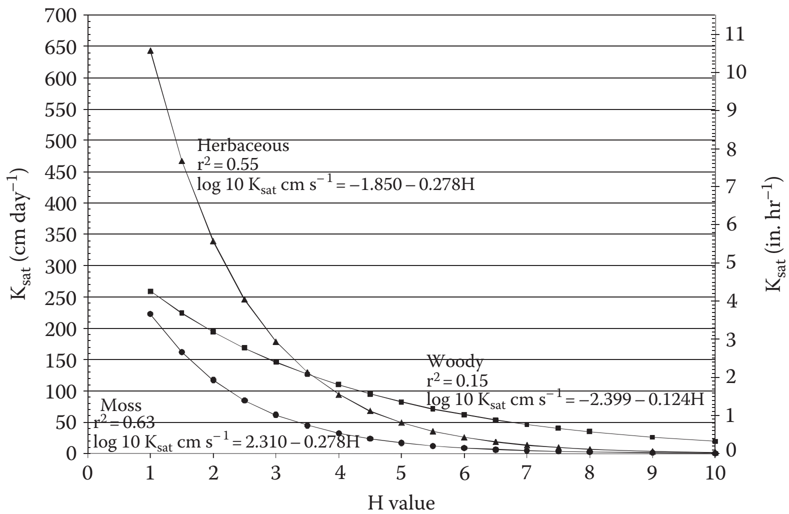


FIGURE 5.13
Relation between saturated hydraulic conductivity (K_{sat}) and von Post degree of humification (H value) using the piezometer method for central Finland peats. (From Päivänen, J., *Acta Forestalia Fennica*, 129, 1, 1973.)

(Ivanov 1953), Germany (Baden and Eggelsmann 1963), Great Britain (Rycroft et al. 1975a,b), and Canada (Stanek and Silc 1977). Päivänen (1973) developed regressions between K_{sat} and the von Post H value. Separate equations were developed for *Sphagnum*, *Carex*, and woody peats (Figure 5.13). The units are both cm h^{-1} and inches h^{-1} because inches h^{-1} is used in web-based evaluations of reverse drainage equations. The relationship for woody peats are the least precise ($r^2=0.15$). *Carex* peats are more conducive to water flow than *Sphagnum* peats, though the relationships for both peat types tend to converge at H7 and are higher when the amount of amorphous material increases significantly.

The piezometer method for determining K_{sat} in saturated soils is used widely and assumes a hydraulic gradient (HG) of 1; however, peatlands have low water table slopes. In 1984 and 1985, Gafni (1986) used both point-dilution and the well-to-well tracer methods (Gafni and Brooks 1990). He also measured the von Post H value. The tracer method did not detect movement of a salt injection at the source well, perhaps because the detection well was not aligned with the actual flow path. With point dilution, salt is injected into a piezometer and salt dilution is measured as groundwater travels through and past the well. Dilution is measured with a plot of electrical conductance over time (a correction for the natural diffusion rate of salt in the bog water is included). Groundwater velocity (GV) and the HG measured between transect wells, were used to solve for K_{sat} in the equation $K_{sat}=GV/HG$. Gafni found a significant relationship ($r^2=0.81$) between K_{sat} and von Post H value using 28 samples of *Sphagnum*, *Carex*, and woody peats combined

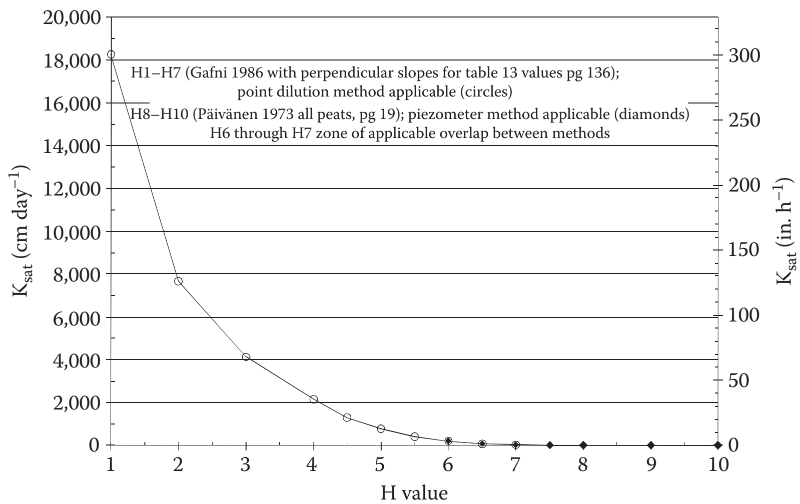


FIGURE 5.14
Relation between hydraulic conductivity (K_{sat}) and von Post H value using the point-dilution method (open circles) for estimating groundwater velocity and water table contour maps for estimating hydraulic gradient (H1–H7) (Gafni 1986), and the piezometer method (filled diamonds) for H8–H10 (Päivänen 1973). Values are from the respective equations and no combined equation is shown.

(for H1–H7; Gafni and Brooks 1990). This equation gave values for undecomposed H1 peat that were 150 times higher than those reported by Päivänen. However, at the H7 von Post value, K_{sat} values from both methods converged. The higher K_{sat} values measured by Gafni were largely due to the low, field-measured, water-slope values since $GV/HG = K_{sat}$.

Water levels in the transect wells were used to calculate HG and verify that it did not vary appreciably over the growing season when water levels declined. A water table contour map (Gafni 1986) revealed that well transects were not always perpendicular to the flow lines between water table contours. Water table slopes that were perpendicular to water table contour lines were higher, resulting in K_{sat} values that were 71%–86% less than Gafni's original equation relating K_{sat} to von Post H value. As before, the Gafni data still were 150 times higher for H1 values than those of Päivänen, but trended lower for H3–H7 where the two equations converged. The combination of the Gafni (1986) equation (H1–H7) corrected for steeper HG slopes and the Päivänen (1973) piezometer data for H8–H10 is shown in Figure 5.14.

Although hydraulic conductivity varies by more than 10 orders of magnitude, the values in Figure 5.15 vary only by 4 orders of magnitude. There are large differences in pore sizes from H1 to H10 (several μm to mm). In H1–H5 peats, pores are large, less than 10% of the peat volume in amorphous material, and the K_{sat} values are similar to sandy soils with 5% silt (25.4–30 cm h^{-1}; Table 5.11). As H values increase, K_{sat} values decline to about 0.25 cm h^{-1}.

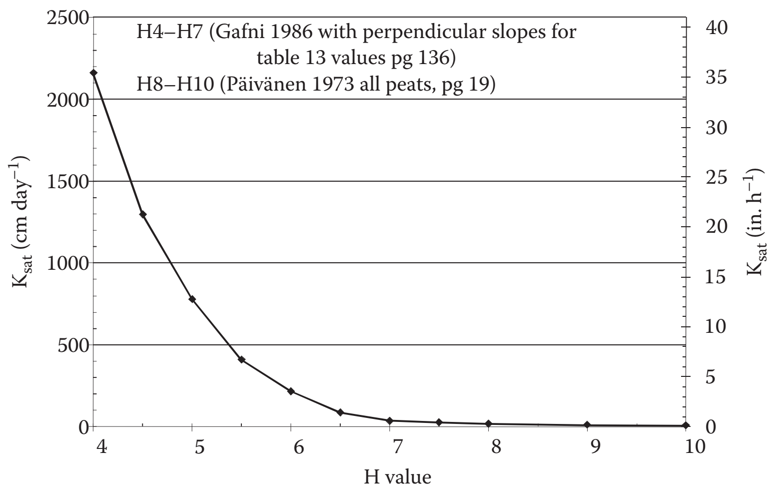


FIGURE 5.15
Relation between hydraulic conductivity (K_{sat}) and von Post H value using the point-dilution method for estimating groundwater velocity and water table contour maps for estimating hydraulic gradient (H4–H7) (Gafni 1986), and the piezometer method for H8–H10 (Päivänen 1973). Values are from the respective equations and no combined equation is shown.

Summary of Physical Properties of Organic Soil

Many laboratory values of K_{sat} for organic soil have been measured for soil series labeled fibric, hemic, and sapric, in the USDA soil classification system; these data are available in the U.S. General Soils Map (STATSGO2) inventory of soil data (NRCS 2006, http://soils.usda.gov/survey/geography/statsgo/description.html). However, laboratory values obtained with cylinders can be affected by trapped gasses or leaks that result in low or high values, respectively. Because hydraulic heads are greater in the laboratory than experienced in the field, K_{sat} values derived in the laboratory will be higher.

The data on peat physical properties collected at the MEF, across the Lake States, in Canada, and in central Finland show a consistent correlation among individual properties. Drainable porosity decreases from 0.60 to an asymptote of about 0.08. Bulk density increases from 0.04 to 0.24 Mg m^{-3} with complete decomposition and compaction (Boelter 1969). Bulk density values greater than 0.24 Mg m^{-3} indicate an admixture of mineral material with the organic material. Differences in bulk density among regions impart some variation to correlation data. Nonetheless, the higher ash contents yield higher bulk densities, primarily affect the bulk-density value, and have negligible effects on correlations of von Post H values with peat physical properties. Tables 5.8 through 5.10

TABLE 5.8
Peat Bulk Density Values and Drainable Porosity by von Post H Class

von Post Field Test by	Päivänen in Finland		Stanek and Silc in Ontario	Stanek and Silc in Ontario	Nichols and Boelter in Lake States	Boelter (1964) in Minnesota	Gafni (1986) in Minnesota
Degree of Humification von Post H Class	*Sphagnum* with Ash D_b (mg mg^{-1})	Sedge and Woody with Ash D_b (mg mg^{-1})	Sedge with Ash D_b (mg mg^{-1})	Woody with Ash D_b (mg mg^{-1})	All Types without Ash D_b (mg mg^{-1})	Drainable Porosity (cm cm^{-1})	Peat Volume Passing Fingers (% Volume)
1	0.06	0.06	0.04	0.07	0.04	0.60	0
2	0.07	0.07	0.06	0.09	0.06	0.34	0
3	0.08	0.09	0.08	0.11	0.08	0.29	0
4	0.09	0.11	0.10	0.13	0.10	0.23	0
4.5	0.09	0.11	0.10	0.13	0.11	0.20	1–2
5	0.10	0.12	0.11	0.14	0.12	0.18	3–10
5.5	0.10	0.13	0.12	0.15	0.13	0.16	11–25
6	0.11	0.14	0.13	0.16	0.14	0.13	26–35
6.5	0.12	0.15	0.14	0.17	0.15	0.12	36–45
7	0.12	0.15	0.15	0.18	0.16	0.12	46–55
7.5	0.13	0.16	0.16	0.19	0.17	0.11	56–65
8	0.13	0.17	0.17	0.20	0.18	0.10	66–75
9	0.14	0.19	0.19	0.22	0.20	0.09	76–95
10	0.16	0.20	0.20	0.23	0.24	0.08	96–100

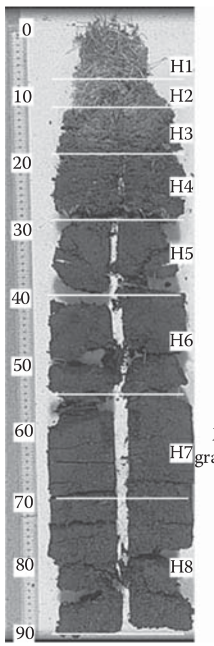
TABLE 5.9

Fiber Content, Water Retained at Saturation and at 10 kPa, and Drainable Porosity by von Post H Value Class

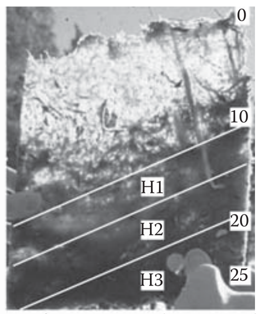
von Post Degree of Humification	Field Saturated Volume (%) >0.10 mm (Nichols and Boelter, Lake States)	Field Saturated Volume (%) >0.25 mm (Nichols and Boelter, Lake States)	Field Saturated Volume (%) >0.50 mm (Nichols and Boelter, Lake States)	Water Retained at Saturation (cm cm^{-1}) (Päivänen, Finland)	Water Retained at 10 kPa (cm cm^{-1}) (Päivänen, Finland)	Water Retained at 10 kPa (cm cm^{-1}) (Boelter, Lake States)	Drainable Porosity (Boelter 1964, Minnesota)	Peat Volume Passing Fingers (%) (Gafni 1986, Minnesota)
1	74	68	48	0.94	0.66	0.69	0.60	0
2	68	55	39	0.93	0.58	0.66	0.34	0
3	63	48	29	0.91	0.54	0.63	0.29	0
4	59	44	27	0.90	0.49	0.60	0.23	0
4.5	57	42	25	0.90	0.46	0.57	0.20	1–2
5	54	39	23	0.90	0.44	0.53	0.18	3–10
5.5	51	35	20	0.89	0.42	0.50	0.16	11–25
6	49	34	19	0.89	0.41	0.49	0.13	26–35
6.5	48	32	18	0.88	0.39	0.48	0.12	36–45
7	47	31	17	0.87	0.38	0.47	0.12	46–55
7.5	43	28	16	0.86	0.37	0.46	0.11	56–65
8	41	26	15	0.86	0.35	0.43	0.10	66–75
9	39	23	12	0.85	0.34	0.41	0.09	76–95
10	36	21	8	0.82	0.34	0.39	0.08	96–100

TABLE 5.10

Hydraulic Conductivity, Bulk Density, Fiber Content (>0.1 mm), and Drainable Porosity by von Post H Value Class



Marcell s2 bog grading to poor fen with depth



Poor fen near Bog Lake at Marcell

von Post H	K_{sat} (cm d^{-1})	Drainable Porosity (Decimal)	Peat Passing Fingers (% of Volume)
1	18,317	0.60	0
2	7,690	0.34	0
3	4,170	0.29	0
4	2,160	0.23	0
4.5	1,296	0.20	1–2
5	788	0.18	3–10
5.5	409	0.16	11–25
6	215	0.13	26–35
6.5	86	0.12	36–45
7	35	0.12	46–55
7.5	26	0.11	56–65
8	17	0.10	66–75
9	11	0.09	76–95
10	8	0.08	96–100

Notes: Profiles at Marcell showing depth below surface in cm and H value for peat of all origins. The K_{sat} values are from Gafni (1986) and Päivänen (1973). The drainable porosity values are from Boelter (1964) and Gafni (1986) list the most common values of bulk density, drainable porosity, fiber content, and hydraulic conductivity that are related to von Post H values and to the amount of material that passes between the fingers in the von Post H test.

Peats in Finland generally had 5% less ash content than those in the Lake States, where peats are denser because of dust from the Great Plains. In Ontario, woody peats are denser than sedge peats, probably reflecting the calcium and magnesium composition of wood cells. All peats are extremely light, only 0.002%–0.003% of mineral soil bulk densities. Ash content does not appreciably affect hydraulic conductivity or fiber content, but simply adds to the mass of volumetric peat samples without plugging pores.

Peats with H1–H5 values have large pores that drain quickly in 2 or 3 days. Boelter (1964) measured water table drawdown around a ditch in the S7 bog at the MEF. The S7 bog has peat similar to the S2 bog (Table 5.10). He found that the water table dropped rapidly to the interface between H5 and H6 peats before dropping farther with prolonged drainage. Note that K_{sat} values from H4 through H5.5 decreased from 89 to 17 cm h^{-1}. This pronounced drop in K_{sat} from free-flowing peats with no or low amounts of amorphous material (11%–25%) is similar to the drop in K_{sat} in mineral soils as they grade from sands to higher contents of silt or clay (e.g., 90% sand, 10% silt; Table 5.11). Applications of organic soil K_{sat} values to reverse-drainage equations for the determination of lateral extent nearly always include K_{sat} values for underlying mineral soils. Saturated hydraulic conductivity diminishes to about 0.25 cm h^{-1} in both mineral and organic soils. In organic soil, this occurs when the percentage of amorphous material exceeds two-thirds of the peat volume (Table 5.10). In mineral soils this occurs not in clay loams, not pure clay that typically has a K_{sat} of about 0.7 cm h^{-1}. The higher K_{sat} may be explained by the blocky structure of pure clays and the massive structure of clay loams.

Many peatlands in the Lake States are underlain by sandy outwash plains with a mixture of sand and silt. Various mixtures of sand and silt have K_{sat} values of 1.5–30.5 cm h^{-1}, a range similar to organic soil K_{sat} values in the range of H5–H7 (1.5–35.5 cm h^{-1}). Accurate determinations of weighted K_{sat} and drainable porosity values in lateral-extent equations depend on an accurate survey of K_{sat} and drainable porosity by horizon in both peat and mineral soil across the wetland of interest.

Evaluation of Wetland Drainage

On-site recording-well records provide the best estimates of lateral effect but may take several years to obtain. Models are an alternative used to evaluate the lateral extent of drainage. The Natural Resource Conservation Service (NRCS) provides hydrology tools for evaluating the lateral extent of wetland drainage. Hydraulic conductivity and drainable porosity are the primary parameters.

TABLE 5.11

Mineral Soil K_{sat} Values

Sand (%)	Silt (%)	Clay (%)	K_{sat} (cm d^{-1})	Sand (%)	Silt (%)	Clay (%)	K_{sat} (cm day^{-1})
100	0	0	1428	55	25	20	16
95	5	0	767	50	25	25	10
90	10	0	377	45	30	25	8
80	20	0	130	40	30	30	6
70	30	0	100	40	25	35	5
60	40	0	90	40	20	40	6
50	50	0	95	35	35	30	7
40	60	0	139	30	35	35	8
30	70	0	127	25	40	35	11
20	80	0	101	20	40	40	13
10	90	0	76	15	45	40	13
0	100	0	38	10	45	45	15
85	10	5	162	5	45	50	17
80	10	10	77	0	45	55	19
75	15	10	56	0	30	70	20
70	15	15	34	0	20	80	17
65	20	15	30	0	10	90	18
60	20	20	19	0	0	100	18

Source: Schaap, M.G., Rosetta version 1.2. Reverside, CA: USDA-ARS, U.S. Salinity Laboratory, 2000.

The von Post field-test procedure is suitable for assessing a wetland for lateral-effect drainage. In wetlands with horizons with different H values, both hydraulic conductivity and drainable porosity can be weighted by horizon depth for use in one of four drainage equations: Ellipse, Hooghoodt, van Schilgaarde, and Kirkham. In Minnesota, tests of efficacy at partially drained peatlands near Minneapolis–St. Paul has shown that the van Schilfgaarde equation best represents drainage recorded in long-term continuously recording wells. As with the other drainage equations, the van Schilfgaarde equation is used in reverse to determine the effectiveness of existing drains to lower the water table by 30 cm over 14 or more consecutive days. The area within a wetland where this occurs qualifies as a regulated wetland (water table remains at this level or higher) or a drained wetland (water table drops farther).

The NRCS uses a modified version of the van Schilfgaarde equation such that drainable porosity is replaced with an adjusted drainable porosity. The adjustment accounts for a small amount of water storage (s) on the surface (usually set to 0.025 cm). If surface roughness is ignored ($s=0$), the equation is identical to the original van Schilfgaarde equation (Chapter 19 in USDA NRCS Staff 1997). A diagram adapted to show appropriate equation terms for both ditch and tile drainage is shown in Figure 5.16. Application to a

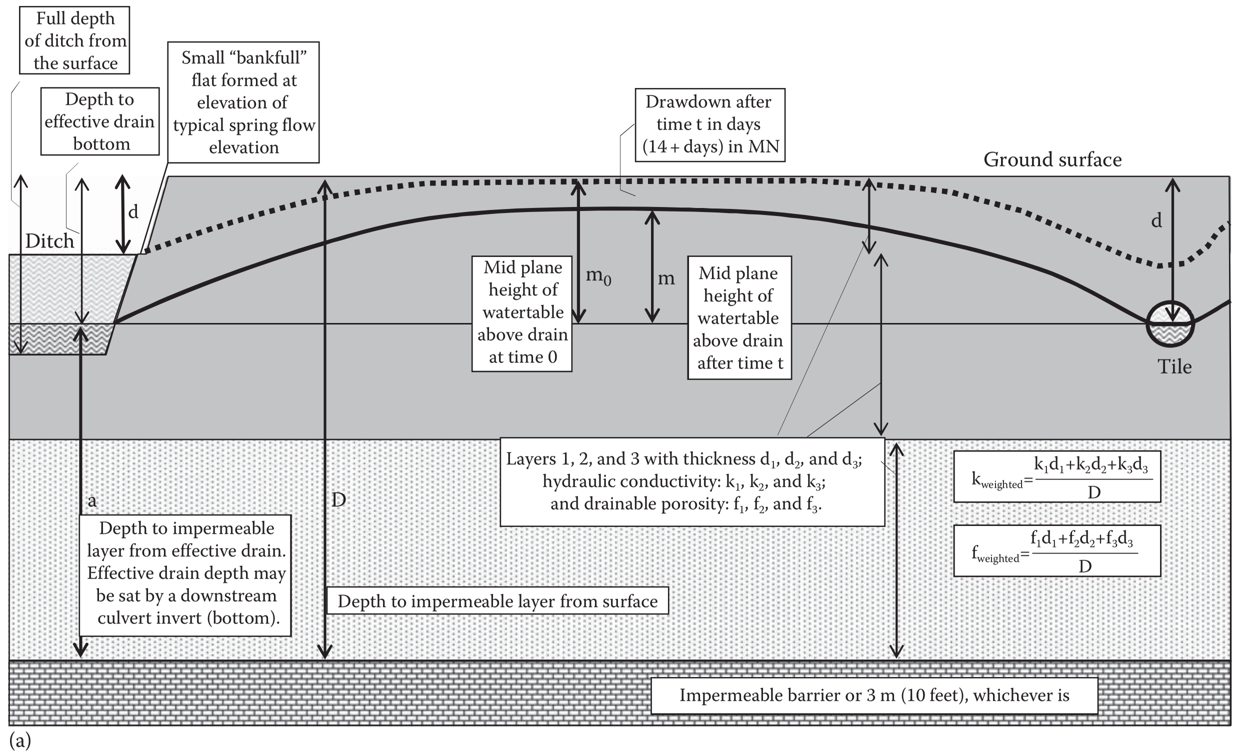


FIGURE 5.16
Important physical and hydrologic features of drainage systems for both ditched and tiled wetlands. In tiled systems, the value of d is taken at the center of the tile. In ditched systems, the value of d should be taken as the highest normal water level in the ditch that is maintained for 7–8 days during the growing season. This usually corresponds to the small flat developed within the ditch walls corresponding to approximately the 1.5 year recurrence interval flow (bankfull flat).

$$S = \sqrt{\frac{9Ktd_e}{f'[\ln m_o(2d_e + m) - \ln m(2d_e + m_o)]}}$$

The equation is first used with "a" in place of "d_e" to determine an estimated spacing S′. Equation variables are:

S = drain spacing, ft

K = hydraulic conductivity, ft day^{-1} (program takes ([in hr^{-1}] and converts to correct units)

d_e = equivalent depth from drainage feature to impermeable layer, ft

m = height of watertable above the center of the drain at midplane after time t, ft

m_0 = initial height of watertable above the center of the drain at t = 0, ft

t = time for watertable to drop from m_0 to m, days

a = depth from free water surface in drainage feauture to impermeable layer, ft

f′ = drainable porosity adjusted for surface roughness, dimensionless (ft ft^{-1}), = f + (s(m_o − m)$^{-1}$)

f = drainable porosity of the water conducting soil, dimensionless

s = water trapped on the surface by soil roughness, ft; s = 0.0083 ft (0.1 in) would be typical

S′ = estimated drain spacing, ft

(b)

FIGURE 5.16 (continued)

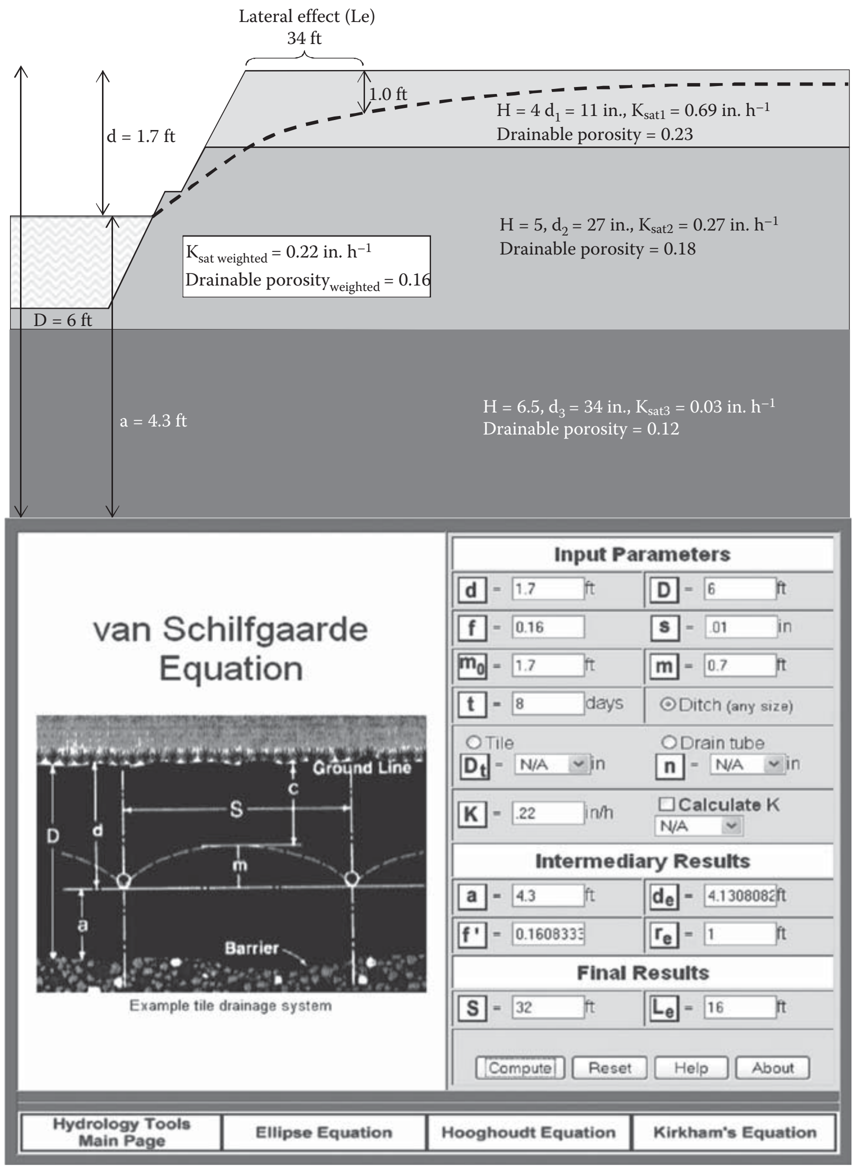


FIGURE 5.17
A ditched peatland in Minnesota showing the extent of lateral effect from the ditch edge (top). Lateral effect is the distance from the ditch edge (or tile center) where the water table is 30 cm below the ground surface. In Minnesota, that portion of a wetland site where the water table is within 30 cm of the surface for 8 or 9 days qualifies as a regulated wetland. If the water table is below 30 cm the land is not regulated and is considered drained. The Web site (USDA NRCS Staff 1997, http://www.wli.nrcs.usda.gov/technical/web_tool/Schilfgaarde_java.html, accessed June 1, 2010) displays only a tiled wetland (bottom), but Figures 5.16 and 5.17 (top) show how parameters are used for a ditched wetland too.

drained peatland in Minnesota is shown in Figure 5.17 and the range of lateral extent in organic soils with uniform peat soils and corresponding K_{sat} and drainable-porosity values shown in Table 5.12. von Post H1–H4 peats are fibric with no amorphous material; they drain at fast rates. The water table surface away from the drainage ditch tends to pass quickly below H1–H4 fibric peats; the primary impact of ditching is controlled by peat of H5 or greater and underlying layers of mineral soil.

Boelter (1972) measured water table drawdown away at S7 bog at the MEF and at a peatland drained for *Sphagnum* peat harvest near Floodwood, Minnesota. He found significant drawdown out to 5 m in late August at the S7 bog; H-value horizons were similar to those at the S2 bog. There, H1–H4 peats were in the horizon 0–30 cm below the hollows. A rapid progression of peat horizons followed: H5–H9 over a horizon of 30–115 cm. At the Floodwood peatland, there is no record of the H values; however, this peatland has relatively thick horizons of fibric peat near the surface. There, significant drawdown occurred to 30 m in both mid-June and late August. The values in Table 5.12 are estimates that assume that the peat is 3.3 m thick and has only one H value. A peat with one H value never occurs, but is useful for demonstrating the possible range of values.

Application of the van Schilfgaarde lateral-extent equation to drained or partially drained wetlands requires that K_{sat} and drainable-porosity values be weighted by horizon thickness (Figure 5.16). First determine the

TABLE 5.12

Range of Lateral Extent in Peatlands with the Average K_{sat} and Drainable Porosities of *Carex* Peat Shown for Each von Post H Value Class

H Value	K_{sat} (in. h^{-1})	K_{sat} (cm h^{-1})	Drainable Porosity	Lateral Extent (m)
1	300	762	0.60	105
2	126	320	0.34	82
3	68	173	0.29	65
4	35	89	0.23	52
4.5	21	53	0.20	44
5	12.7	32	0.18	36
5.5	6.7	17	0.16	27
6	3.5	9	0.13	22
6.5	1.4	4	0.12	14
7	0.56	1.4	0.12	9
7.5	0.43	1.1	0.11	8
8	0.28	0.7	0.10	7
9	0.18	0.5	0.09	6
10	0.12	0.3	0.08	6

Notes: Units are given in both English and metric units to correspond to units of in. h^{-1} in Figure 5.17.

TABLE 5.13

Lateral Extent Parameters for Well 8 at Village Meadows CRWP, Anoka County in Blaine, Minnesota, Ditch 53-62

Depth (cm)	H Value or Texture	K_{sat} (cm h^{-1})	Drainable Porosity (cm cm^{-1})
0–45	4	8.9	0.23
45–75	6	8.9	0.13
75–300	Sand = 70%, silt = 25%, clay = 5%	2.6	0.38
300		4.2	0.32

thickness of organic and mineral soil horizons on-site using a 60 m × 60 m sampling grid. Determine either von Post H value or soil texture at each location and for each horizon to estimate saturated hydraulic conductivity and drainable porosity for organic soils from Table 5.10. The procedure for horizon weighting for both organic and mineral soils should be modified if overlying horizon K_{sat} values exceed 15.2 cm h^{-1}. Horizons of rapid flow should not be included in the weighted K_{sat} or drainable-porosity estimates because their speed overwhelms the weighting procedure. Instead, assign a K_{sat} value of 5.0 or 8.9 cm h^{-1} for mineral or organic soils respectively (next value in the sequence of Table 5.10 and 5.11) to the thickness of these overlying horizons.

Detailed studies of drainable porosity and water table response to precipitation have been conducted in Anoka County, Minnesota (Emmons and Olivier Resources 2005). This is a partially drained peatland with organic soil overlying a sandy loam outwash. The U.S. Geological Survey (USGS) groundwater model, MODFLOW, was used to assess the lateral effect of ditches about 130 m apart. Soil horizons with estimated K_{sat} and drainable-porosity values are shown in Table 5.13 with peat values for H4 and H6 from Table 5.12. Weighted K_{sat} was estimated at 4.2 cm h^{-1} compared to the MODFLOW estimate of 4.3 cm h^{-1} at well 8. When these values were entered into the van Schilfgaarde model for lateral extent, a value of 9.8 m was obtained which was identical to the value obtained with MODFLOW.

Two points are emphasized for this comparison. First, the K_{sat} and drainable-porosity values for the MODFLOW model were calibrated manually until a good fit between the model and measured-well records was obtained. Second, horizons with the greatest thickness and greatest K_{sat} values dominated the results. Third, for overlying organic-soil horizons with K_{sat} values that exceeded 15.2 cm h^{-1}, the values immediately below were used because weighted values were biased due to the logarithmic function between H value and K_{sat} and because these horizons drained quickly.

Impact of Wetland Drainage

Wetland drainage significantly increases the growth of natural vegetation when the depth to the water table between ditches (m_0–m in Figure 5.16 or c in Figure 5.17) is increased from 5 to 25 cm (Figure 5.18). When the amount of drainage exceeds one-third of the watershed area, streamflow peaks can increase two to four times (Figure 5.19). Although the actual

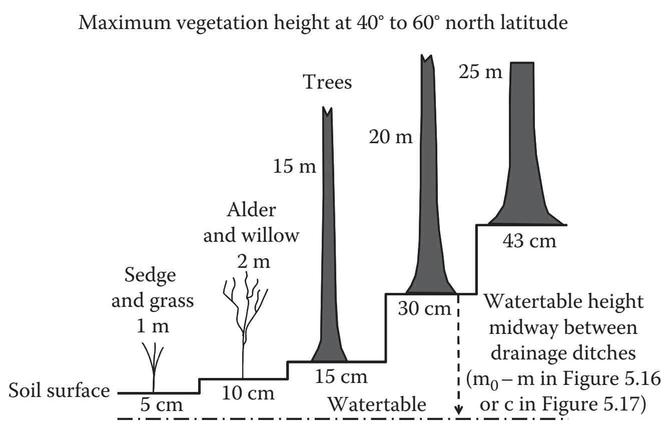


FIGURE 5.18
Response of natural vegetation growth (height) to wetland drainage. Depth to water table is measured midway between ditches.

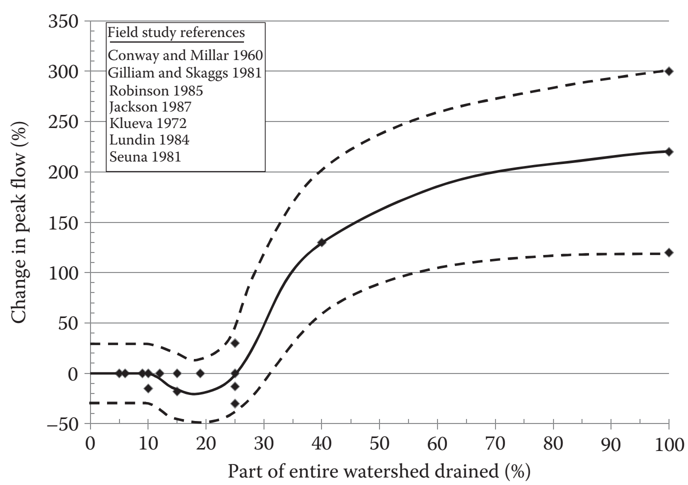


FIGURE 5.19
Change in streamflow peak flows as the percent of the entire watershed in drainage increases.

recurrence interval of the peak flows shown in Figure 5.19 is unknown, a similar response curve for upland watershed changes (Figure 13.13) indicates the recurrence interval affected varies from the 1 year to the 30 year storm and can significantly impact channel width and depth and accelerate channel erosion.

Conclusions

Research on the physical properties of organic soil should include both field and laboratory work to further refine correlations of degree of decomposition, bulk density, fiber content, water retention, drainable porosity, and hydraulic conductivity. Although fiber content is a suitable measure of fibric, hemic, and sapric peat categories in soil series classification, USDA laboratory methods are considerably less precise and less accurate than ASTM or USSR centrifuge methods or the von Post method (degree of humification). In the United States, the von Post field method should be given equal status with laboratory methods as it is elsewhere in the world. Few studies of the physical properties of organic soil have achieved the level of precision obtained by Boelter, Päivänen, Stanek and Silc, Okruszko, and Ilniki; such precision is required especially for various herbaceous peats and woody peats.

Field measurements of hydraulic conductivity are the most difficult to obtain. Piezometer methods greatly underestimate K_{sat} for high H1–H5 peats where there is no or little amorphous peat material because they assume a hydraulic gradient of 1. Point-dilution methods are erratic for H7–H10 peats where amorphous material exceeds half of the peat volume. Piezometer methods more accurately represent vertical water movement through peats that are 2–5 m thick with high HG in the vertical direction and are best for H7–H10 peats. Point-dilution methods are best for determining K_{sat} in H1–H6 peats because they more accurately represent actual water table HG in the horizontal direction. They may over estimate K_{sat} values by 30% or more if hydraulic gradients determined in well transects are not perpendicular to actual water table contour lines. Five or six radial transects are adequate to define actual water table contour lines and measure hydraulic gradients that are truly parallel to groundwater flow using the point-dilution method. The experiments and relationships discussed in this chapter and the modifications to the application of data on peat physical properties to lateral-extent equations allow a relatively quick determination of lateral extent when needed.

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