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## 4 Physical Processes and Properties of Mires

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### 4.1 PEAT FORMING PROCESSES

#### 4.1.1 INTRODUCTION

Peat is not a homogeneous substance. The physical composition of peat deposits varies as a result of their botanical composition, mineral content and degree of decomposition. For example, weakly decomposed peats contain well-preserved and recognisable plant residues whereas highly decomposed peat consists almost entirely of a homogeneous, humic substance with only very small quantities of plant tissue remains. These properties are examined in greater detail in Section 4.2. The degree of decomposition of most peats generally lies somewhere between these two extremes. Furthermore, no peat deposit is completely free of mineral material because the original plant material always contains inorganic components. An additional admixture of mineral materials may be present in the peat as a result of, for example, inundation by flood waters or gravitational waters. This means that there is a continuous gradation for peat deposits, from genuine peats to peaty, or more or less humic, soils, as the mineral content increases and the organic fraction decreases. The nature and composition of plant remains in peat are evaluated in Section 4.3.

The stratigraphy of a mire usually includes non-peat formations such as freshwater sediments and mire minerals. The freshwater sediments, which commonly underlie the peat in terrestrialised mires, are distinguished from it by their 'limnic' sedimentation. The sedimentary evolution of freshwater sediments differs from that of the 'sedentary' peat although, like peat, limnic sediments have a variable mineral content. Mire minerals largely consist of isolated or precipitated products carried into the mire by groundwater or gravitational water. For example, in West Sedgemoor in the Somerset Levels, southwest England, high concentrations of gypsum in crystalline form are recorded at the colluvium/alluvium interface with the underlying fen peat deposits (Heathwaite, 1987). The source of the gypsum is the Lower Lias and Keuper Marl upland which surrounds the moor.

In addition to the above basic contrasts in peat properties, mire profiles vary hydrologically and with depth between the permanently waterlogged lower layers and the upper aerated peat layers. A knowledge of mire hydrology is essential to understanding, quantifying and evaluating mire functions and processes. The interaction between precipitation, groundwater, and surface water controls both the hydrological regime (Section 4.5) and the water chemistry of mires (Chapter 5) and strongly affects the

floristic composition of the vegetation (Chapter 1). Even small changes in the relative magnitude of these three components of the hydrological cycle may induce shifts in the species composition of mires (Van Wirdum, 1982; Koerselman, 1989a). Hydrological processes are important in the breakdown of organic matter. When recently dead plant material decomposes, a loss of organic matter, either as a gas or as a solution, takes place, both as a result of microbial attack and hydrological mechanisms (leaching, in particular). The loss of organic matter is accompanied by the loss of physical structure of the plant material (Section 4.4) and changes in its chemical composition. Finally in this chapter, which examines the physical processes in mires, the role of microclimate in controlling both the water balance of a mire and its vegetation composition must be evaluated. This is covered in Section 4.6.

#### 4.1.2 HUMIFICATION AND MINERALISATION

In weakly decomposed peats, the plant residues are often found in a good state of preservation. They may have undergone some (usually brownish) discoloration, but in shape they differ little from the living plants from which they were formed. Mosses with intact leaves are usually visible to the naked eye, as are tree roots which often retain their bark; layers of straw-like rhizomes or even dense masses of root fibres are usually well preserved. Microscopic examination usually confirms that many plant tissues, whether wood and bark, with their complex anatomical structure, or the leaflets of mosses, appear virtually unchanged. The well-preserved structure of such weakly decomposed peats visually suggests that the original plant material, although discoloured and more or less compacted, has not undergone substantial losses of organic matter as it was transformed into peat. This impression is deceptive, as will be shown below.

The annual biomass produced by a mire greatly exceeds the annual production of peat, hence peat formation involves considerable losses of organic matter. Most of this transformation takes place in the biologically active layer or acrotelm (Ingram, 1978) which is usually <40 cm deep. In ombrotrophic mires, peat accumulation depends on the amount of moss produced on the surface and the amount of peat decayed and compacted in the entire mire (Johnson, Damman and Malmer, 1990). Thus the residence time and decay rate in the acrotelm determine the growth rate of the mire. Compaction also influences the rate of increase in mire height. Thus, knowledge of both decay and compaction are essential in understanding the growth and development of mires. Their measurement is, however, difficult, and decay rates in mires are not well known (Clymo, 1965; Coulson and Butterfield, 1978). Compaction has rarely been measured. The calculation procedures commonly used to derive the annual rate of peat formation are indirect and yield only average values. For example, peat samples at different, but known, depths may be dated using the  $^{14}\text{C}$  method (see Chapter 3); their age difference allows the average thickness of an annual layer of peat to be calculated. For ombrogenous peat deposits, with ages in the range 200 to 20 000 years, the  $^{14}\text{C}$  technique may be used. However, for minerotrophic, especially highly calcareous, peat deposits the technique may be less suitable (Clymo, 1983). The dry matter production of the peat layer can also be determined by calculating the average dry matter content of a unit volume of undisturbed peat (bulk density on a dry weight basis). The bulk density of peat with a low mineral content generally falls within the range 0.08 to 0.14 g cm<sup>-3</sup>. Direct measures of the rate of decomposition of peat material include the use of 'litter bags' of

known mesh-size, organic matter composition and weight which are buried in the peat for a known period of time and the loss of organic material recorded. An alternative direct measure records the evolution of carbon dioxide or methane from peat enclosures. Clymo (1983) suggests that this method has a number of limitations, notably the limited field-representation of the enclosures, the diurnal variation in gas flux and the erratic nature of gas evolution. An alternative, indirect approach is to model the pattern of peat accumulation and organic matter decomposition. A detailed review of this and other approaches is given by Clymo (1983). More recently, Johnson, Damman and Malmer (1990) suggested that macrostructural changes in *Sphagnum* with depth in ombrotrophic mires may be used to estimate compaction and decay in the relatively short but critical time period that peat remains in the biologically active surface layer.

The average annual production of peat in the majority of mires amounts to scarcely more than 0.5 mm; only under extremely favourable conditions do thicknesses of over 1 mm per year occur. At this average rate of peat production, the weight of peat material deposited annually ranges between 80 and 2100 kg per ha but it is more likely to be in the range 100–700 kg per ha. This compares with an average annual biomass production of mire plant stands between 2 and 10 tonnes of dry matter per hectare. Therefore, considerable material losses are associated with peat deposition. This applies even when only the underground parts of the plants are taken into consideration, because in most cases these make the largest contribution to peat formation.

The rate at which plant material in mires is decomposed is affected by a large number of factors which do not necessarily act independently of each other, and often vary with depth and the age of the peat layer. The key factors are temperature, moisture, oxygen supply, the composition of the plant material and the composition and numbers of peat organisms (Chapter 6). The key processes are humification and mineralisation. Mineralisation involves all the processes which bring about the conversion of organic matter into simple inorganic compounds. Mineralisation results in the microbial utilisation of the organic matter and the release of carbon dioxide, water and nutrients originally taken up by the plants. Humification is the process by which organic matter loses its original cellular and tissue structures and is converted into humic substances that are light or dark brown to black in colour and contain varying quantities of nitrogen. Humification does not normally take place without simultaneous mineralisation.

The products of humification are found in the upper horizons of almost all soils and are closely associated with plant growth from which the new source material for the humification process is derived. Despite this, in mineral soils there is no continuous increase in the organic matter content of the soil because an equilibrium is eventually reached between the supply of new plant material and losses through mineralisation, so that a part of the humic materials formed by humification is constantly being utilised in mineralisation. In mires, the continuous deposition of peat denotes a positive balance or excess of organic matter despite the loss of material through mineralisation. In peat, humic substances and primary plant material coexist and the structure of the plant material is more or less unchanged in appearance (see Section 4.2).

#### 4.1.3 THE DECOMPOSITION PROCESS IN MIRES

In living mires, it is possible that the positive balance of organic matter and the high water content may restrict the activity of microorganisms which, at least in mineral soils,

are assumed to be essential for the breakdown of organic matter. As a result, a number of authors (see Eggelsmann, 1990) initially suggested that the peat forming process can be regarded as 'non-biological', being primarily the result of chemical transformations in the peat. On a geological timescale, it was the coalification series which originally led to the assumption that purely chemical rather than biological transformations took place in the formation of peats. The coalification series (fuel deposits, peat, brown coal and anthracite (apart from rare exceptions)), not only forms a series of increasing age but also a series of increasing carbon and decreasing oxygen contents. The hydrogen content remains constant relative to the falling carbon content. Thus the percentage oxygen content of peat is about ten times that of anthracite, which in turn contains about  $1\frac{1}{2}$  times the carbon content of peats (the ratios result from the relative oxygen and carbon content differences of about 30%). These chemical differences were interpreted as evidence of an ageing effect; similar chemical tendencies were initially expected from the comparison of postglacial peats of various ages. This assumption, however, proved unfounded: peats with age differences of several thousand years were practically alike chemically provided they were of the same degree of decomposition. The coalification process, although it provides a formal framework for describing the differences between the unaltered plant substance and peats of different degrees of decomposition, is of no significance in the real chemical processes of peat formation. A non-biological decomposition process has never been proved conclusively, save perhaps in the initial hydrolytic or oxidative phases of decomposition after the plants have died. Microorganisms are generally accepted as being essential in the breakdown of plant remains to form peat.

#### Decomposition by microorganisms

Figure 4.1a and b gives some information on the variation in the composition of microbial populations with depth and degree of aeration in a wide range of mire habitats. The data suggest that in the upper part of the profile, decomposition is mediated by the large numbers of aerobic microorganisms recorded (Figure 4.1a). The humification of plant material is restricted to the aerobic upper peat layers. Where aerobic microorganisms are recorded in the deeper parts of the profiles, they occur in much smaller numbers and are probably dormant bacteria or possibly optionally anaerobic bacterial types.

Anaerobic bacteria (Figure 4.1b), although not normally present in very large numbers, can be identified microbiologically in all mires even at considerable depths. Their activity reaches a peak directly under the zone of aerobic decomposition, where plant material not yet decomposed by aerobes is available for anaerobic disintegration by mineralisation. The anaerobic reduction process sometimes leads to the accumulation of methane (marsh gas) and other gases in the deeper layers of mires; the amount of plant material or peat thus transformed can be quite large. At atmospheric pressure, 100 litres of methane can be produced from a 1.5 to 2 mm thick layer of peat 1 m<sup>2</sup> in area, provided its carbon content is fully transformed.

#### Transformation by soil animals

In contrast to faunally 'active' forest, pasture and arable soils, animals play a minor role in transforming the organic substance of virgin, undrained mires, and only in exceptional cases can their traces be found in peats. If a mire is drained, a more extensive soil fauna

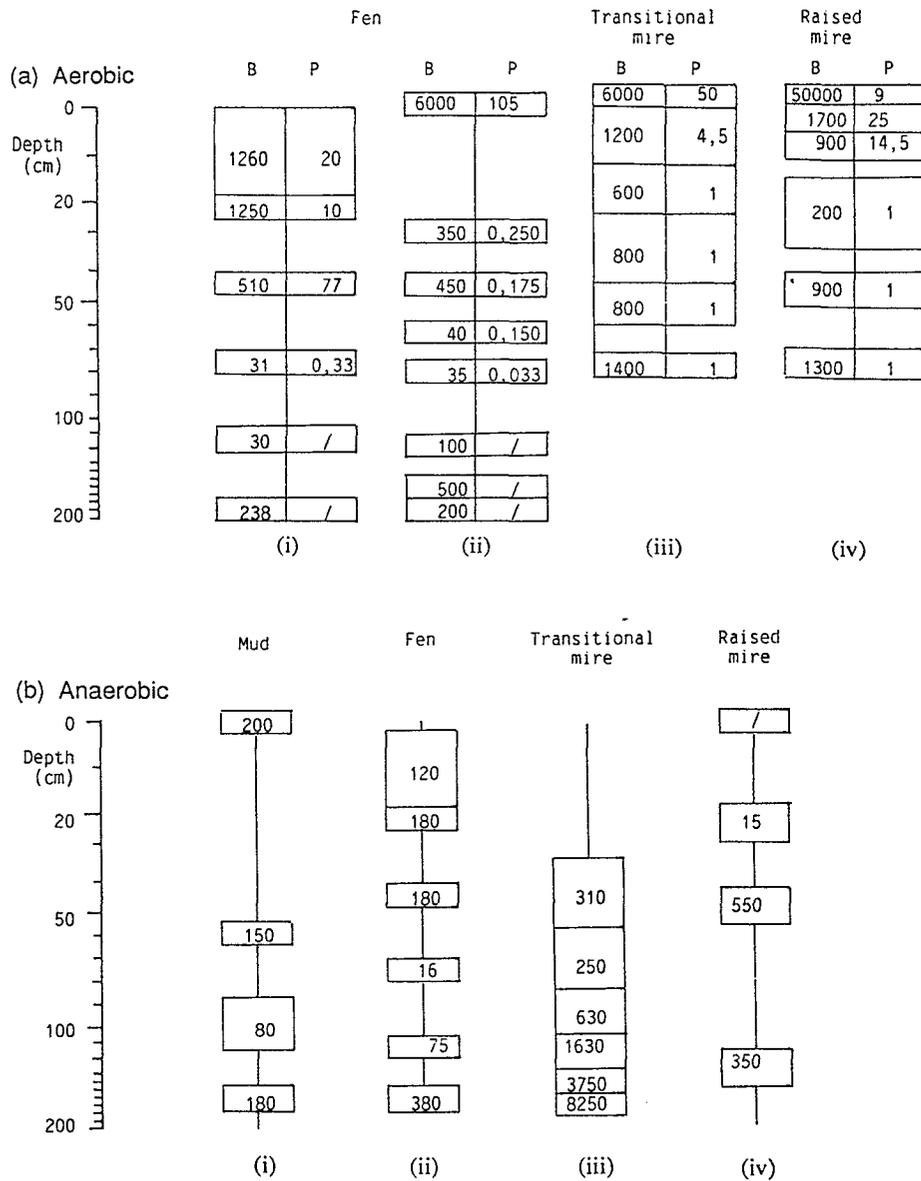


Figure 4.1 Microorganisms in various mire profiles (all measurements in thousands per gram of raw peat). (a) Aerobic organisms (P = fungi, B = aerobic and optionally anaerobic bacteria and actinomycetes). Left to right: (i) undrained and (ii) slightly drained fen, based on North American examples (after Waksman and Purvis, 1932; Waksman and Stevens, 1929); (iii) *Sphagnum*-rich and (iv) secondarily forested mire, both slightly drained (data derived from the alpine forelands, cited in Lutz *et al.*, 1957). (b) Anaerobic bacteria. Left to right: (i) mud, surface 90 cm under water, (ii) undrained fen (both in Florida, after Waksman and Purvis, 1932); (iii) partly drained mire (Lower Bavaria, after Beck and Poschenrieder, 1958), (iv) undrained raised mire, Maine (after Waksman and Stevens, 1929)

becomes established which includes earthworms, a wide spectrum of arthropod larvae and mites which migrate into the now aerated peat. The peat fauna, once present in the upper aerated peat layers, begin to participate in comminuting, decomposing and finally in mineralising the plant material (see Section 1.5).

## 4.2 HUMIC SUBSTANCES

### 4.2.1 THE DEGREE OF DECOMPOSITION

In considering the transformations by which peat originates from plant materials, a general distinction is made above (see Section 4.1.3) between the processes of humification and mineralisation, although both processes take place simultaneously. There is no peat deposition without humification, no humification without loss of organic matter and hence no humification without mineralisation. From the appearance of the resulting peat, neither the amount of organic matter lost during formation, nor the part played by mineralisation, is immediately evident. Despite this, it is usual to use the term peat degree of decomposition. This expression, rather than defining all the transformations that have taken place, describes the proportion of humic substance relative to the tissue residues in the peat. To this extent 'humification degree' might be more appropriate; 'decomposition degree' is, however, the commoner term. Thus 'weakly decomposed' peats contain only small amounts of humic substances, which frequently show up only as a brown discoloration and infiltration of the plant tissues. In 'highly decomposed' peats, histologically amorphous humic materials outweigh the clearly recognisable plant tissue remains, whereas in the (theoretically) extreme case of 'completely decomposed' peat, the tissue residues have completely disappeared. This extreme case, of course, never occurs in practice because at least a few microscopically detectable fragments of plant tissue or single cells, including spores and pollen grains, are preserved. A high decomposition degree is usually a sign of very high losses of organic matter during peat formation. In this case, the general statement made above, that the organic matter losses that occur during peat formation cannot be quantified from the peat deposits, has to be slightly modified here.

Most of the changes in the degree of decomposition of peat deposits occur in the biologically active upper layers of the mire. The degree of decomposition of the peat matrix is governed by the nature of the environment in which the plant material was initially deposited and by the subsequent position of the peat water table relative to the ground surface. The water table position is important owing to its influence on the degree of aeration or anaerobiosis, and hence on the activity of microorganisms. The rate of decomposition is accelerated by drainage activities (see Chapter 8). If the water table is lowered, the rate of oxidation and decomposition increases and mosses and vascular plants, which shrink more on drying relative to woody remains, will introduce gaps between the wood remains and the surrounding peat. Such changes emphasise the local heterogeneity and anisotropy of the peat (Chason and Siegal, 1986).

With the exception of drained mires, the degree of decomposition of the deeper layers of peat deposits is usually very stable. Where some variation does occur, it is commonly the result of differences in the rate and duration of mineralisation and humification in the surface layers of the peat at an earlier stage of mire development when the peat

in question formed the upper layers of the mire. In deep peat layers, waterlogging and an unlimited supply of organic matter create a reducing environment in which further transformation by aerobic soil organisms is prevented. Any nitrogen remaining in the peat is largely immobilised in humic materials and is no longer susceptible to microbial attack, so that even for anaerobic microorganisms, the possibility of survival is limited.

4.2.2 METHODS OF DETERMINING THE DEGREE OF DECOMPOSITION

If it is accepted that the degree of decomposition is the proportion of humification products relative to the total peat substance, then a number of more or less objective and reproducible determination methods can be established. Complete reproducibility is never attainable because peats, as the products of the vegetation of a mosaic of different individual plants, are not homogeneous. The degree of decomposition is difficult to quantify objectively. Surrogate measures such as the carbon : nitrogen ratio, rubbed and unrubbed fibre content and the von Post humification scale may be substituted. The principal determination methods are summarised below.

The von Post humification scale

This technique involves taking a subsample of raw peat which is squeezed in the closed fist to ascertain if water of different coloration and turbidity or slurry-like material (in various quantities) is expressed between the fingers. The result is expressed in degrees of humification (H: see Figure 4.2) on a ten-point scale (the 'H' originates from the term 'huminosity'). Although it is subjective, the advantage of this method, devised by L. von Post (von Post and Granlund, 1926), is the simplicity, speed and ease with which it can be

Symbol	Plant structure in peat	When squeezed there escapes between the fingers	Residue after squeezing
H1	Clearly evident	Colourless, clear	Not pulpy
H2		Faintly yellowish-brown, almost clear	
H3		Brown, quite turbid	
H4		Brown, very turbid	
H5		Very turbid	
H6	Evident	Up to 1/3 of the	Slightly pulpy
H7	Still barely recognisable	About 1/2 of the	Very pulpy
H8	Very unclear	About 2/3 of the	Plant structures more recognisable than before
H9	Almost no longer recognisable	Almost all of the	Mainly resistant residues, e.g. fibres, wood
H10	No longer recognisable	All the	No residue

Figure 4.2 The ten-point von Post humification scale (after von Post and Granlund, 1926)

used in the field. It has proved adequately reproducible, taking the natural heterogeneity of peat into consideration. The major disadvantage of the squeezing method is that it cannot be used on the drier peats. Furthermore, the results from peat layers near the surface of drained and exploited mires, where the peats are crumbly and weathered and therefore non-compressible, are frequently not in agreement with their generally low content of plant tissue residues. Nevertheless, this is the most widely used method of characterising the degree of decomposition of peats in central and northern Europe.

#### **Visual estimation of fibre content**

Visual estimation of the relative proportions of plant structures and humic substances is the commonest method of determining decomposition in eastern Europe (particularly Poland and the former Soviet Union). The technique involves the examination of peat material under a microscope for structured and amorphous components. The percentage of (amorphous) humic substances is estimated from the area of the slide they occupy, and usually stated in steps of 5% (Farnham and Finney, 1965). In using this technique, the problems of sample deterioration and sample distortion must not be underestimated.

Macroscopic estimation of the proportion of plant tissue remains preserved in peat is also used, particularly where the squeezing method has been attempted but where some samples are too dry for it. Here the estimated proportions must of course be converted to H-values which is possible as long as the peat is of uniform character.

#### **Determining the degree of decomposition from peat bulk density**

The bulk density of peat (and mineral soils) is defined as the weight per unit volume of peat found in the natural, undisturbed state (see Section 4.4). In addition to the volume of solid material, there is also a considerable pore volume, so that the bulk density on a dry weight basis (apparent density) will always be lower than the actual density of the peat substance. The pore fraction is greater in weakly decomposed than in highly decomposed peats, so bulk density increases with degree of decomposition. Consequently, it is possible to calculate the ratio of pore space to total peat volume for peats of different degrees of decomposition and thereby to infer the decomposition (stated as percentage decomposition) from the bulk density (Boelter, 1965). In doing so, the variation in the mineral fraction of the peat must be taken into account. Furthermore, for peats of different botanical composition, different constants are needed. Despite the routine nature of this method it is less extensively used than the techniques described above.

#### **Chemical determination of the degree of decomposition**

Some of the chemical properties of both humic materials and plant residues permit the use of chemical analytical methods for characterising peat decomposition. One method of determining the 'peatification degree' (after Keppeler, 1920) is based on the difference between plant residues, which consist mainly of hydrolysable cell wall substances and humic substances which similarly treated (with 72–80% sulphuric acid) leave an unhydrolysable residue. The limitation of this method is that the original plant materials also contain an unhydrolysable fraction which varies with plant type. Peat mosses, for example, have approximately 10% unhydrolysable residue. It is possible

that the proportion of the unhydrolysable residue of peat material dissolved during hydrolysis (mainly glucose) could be used as a measure of decomposition; however, simple determination methods are not yet available. The extraction of the soluble humic materials in peats using, for example, alkalis, combined with photometric measurement of the extinction of the extract also yields relative values of the degree of decomposition (Aaby and Tauber, 1974). Such results are only useful for comparative determinations of peats of similar botanical composition and origin.

Except for the determination of the hydrolysis products in the processes described above, low numerical values indicate slight decomposition and high values indicate high decomposition, and it is possible to estimate approximately the values determined by the various methods that correspond to each other. Naturally this is only a matter of correlations, which of necessity are non-linear because their terms are not functionally related, as will be seen from the summary of data for raised mire peats of different degrees of decomposition presented in Table 4.1.

**Table 4.1** Data for raised mire peats from the various techniques for the determination of the degree of decomposition

Technique	Weakly decomposed raised mire peats	Highly decomposed raised mire peats
H number (von Post)	H2-H5	H6-H10
Microscopic remains (%)	5-30	35-80
Unhydrolysable residue (%)	20-50	50-90
Degree of decomposition	ca. 10-30	ca. 35-55

### 4.3 PLANT REMAINS IN PEAT

#### 4.3.1 PLANT REMAINS AND THEIR OCCURRENCE IN PEATS

##### General observations on preservation

Plant remains in peat—even in weakly decomposed peat—are not all equally well preserved. Often only certain parts of plants are preserved and, of these, it is only certain tissues that may be visible under a microscope. Differential preservation is the result of both internal (plant) and external (mire environment) factors. Differences in the histological and histochemical properties of plant tissues, which vary between plant species and genera, result in very different preservation conditions. Furthermore, the decomposition or preservation conditions prevailing in the mires obviously play a decisive part. External factors depend partly on the embedment of the plant parts being converted into peat and partly on the local decomposition intensity which differs, due to ecological peculiarities, from mire to mire. These differences in the decomposition intensity are determined by both the hydrological and the chemical properties of the mire layers in which decomposition is taking, or has taken, place. The acidity of a mire is a particularly important factor in the intensity of decomposition. This is a consequence of the pH-dependency of the microbial population of the mire. At low pH values, which

are unfavourable to most bacteria, the decomposition intensity is also low. Although all degrees of decomposition are, in principle, attainable at all pH levels, on average the (less acidic) fen peats are more highly decomposed than the (acidic) transitional and raised mire peats. The nitrogen content of peat is usually positively correlated with pH value. The degree of decomposition thus tends to parallel N content or to run counter to the C:N ratio of peats.

Hydrological controls are superimposed on the chemical criteria described briefly above. Most critical is the position of the peat water table. If the average groundwater position in a mire is low, or if the groundwater fluctuation is wide, a high rate of decomposition will result. Conversely, when the water levels are high and fairly stable, the peat material which is deposited is weakly decomposed; this even applies to fen peats.

A further environmental factor influencing the rate of peat decomposition is temperature: the higher the temperature, the more intensive the decomposition processes. For example, the highly decomposed 'black peat' deposits which form the lower part of many of the raised mire profiles in northwest Germany have been attributed to the higher temperatures which are thought to have prevailed during their formation (see Chapter 3).

The different decomposition conditions in the various mire types mean that raised mire peats are relatively rich in many kinds of fairly well preserved plant remains, even though the number of plant species capable of living on raised mire is quite limited. Conversely, fens, which contain many vegetation types and species, usually show only a very limited number of structured plant remains in their peat deposits. Transitional mires, which are commonly acidic, resemble raised mires with respect to their preservation conditions, but since the number of species in their vegetation is larger than in raised mires, their peats have the greatest botanical diversity.

#### **Peat deposition and the embedment of plant parts in the evolving peat**

The higher plants (vascular plants, such as pteridophytes and spermatophytes) and mosses, which are the key components of the mire vegetation contributing to peat formation, are differentiated by fundamentally different modes of growth. Thus for each of them, the processes by which their dead residues are incorporated into the originating peat are different. Mosses die at their base as their tops continue to grow. Thus if a mire surface is covered with moss vegetation the starting point of new peat formation is directly under that carpet of living, green parts of the individual moss plants and the peat 'grows' from its outermost surface, by constantly acquiring new layers. This also applies to the various growth forms of the bryophytes. In species with an erect growth habit, which, besides some ('brown') mosses, include all the peat (*Sphagnum*) mosses, the dead lower parts sink down into the underlying peat layers and, under the weight of the living moss cover above them, form a dense, shallow layer (see Johnson, Damman and Malmer, 1990). In moss cushions, where the individual plants stand close together and are tightly interwoven, this sinking is associated with irregular crumpling of the dying layer, whilst in loose moss mats the sinking moss plants all lie in one direction, forming a peat layer of parallel moss stalks (as with most *Sphagna* of the *Cuspidata* group (see Figure 4.3)). Similar strata also evolve from moss species of low creeping habit, but never from *Sphagna*.

The behaviour of the higher plants contrasts quite sharply with that of the mosses. Their vegetative structure is always strictly divided into subterranean and aerial organs. The latter structure contains the leaves and most parts of the shoot system. Thus,

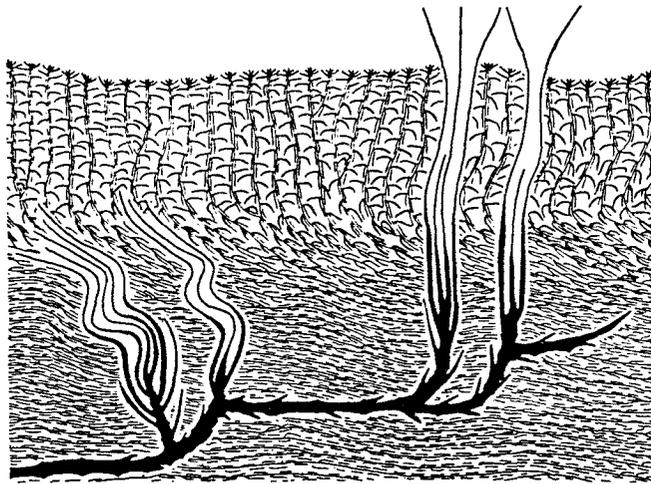


Figure 4.3 Growth habit of a *Sphagnum* cover showing *Sphagnum recurvum* or related species of the spidata group, penetrated by *Scheuchzeria palustris*, as an example of a rhizomatous plant with a rhizome that branches higher year after year

when the aerial organs die, they lie on the mire surface where the rate of decomposition is fastest, so complete humification or mineralisation rapidly takes place. This is irrespective of whether the mire surface is bare or is covered with moss vegetation. As a result, the aerial parts of these plants are very seldom recorded in peat deposits. The exception is their fruits and seeds which are produced in large quantities and are easily preserved. Where the aerial parts of plants are recorded they almost always point to special preservation conditions. For example, dead leaves that have fallen on vigorously growing moss cushions may be very quickly engulfed, overgrown and thereby incorporated in the deeper layers. Similarly, dead leaves may be deposited in the shallow, permanent bodies of water often recorded in mires. Here, due to the exclusion of air and to reducing conditions, the milieu is favourable to preservation.

As with the mosses, the degree of preservation of the subterranean parts of the higher plants varies. The deeper organs which extend into the water-saturated and reducing milieu are preserved best. However, because all the deeply penetrating roots of mire herbs are equipped with well-developed aeration tissue through which some oxygen is diffused into the deeper layers, some anaerobic breakdown of easily decomposable plant substances can take place immediately below the aerobic zone. This is a mineralisation, rather than a humification, process (see Section 4.1.2).

In mires whose vegetation is composed mainly of higher plants, the accumulating layers of peat are not confined to the mire surface, but instead to the newly accumulating organic matter, whether as tissue remains or humified material which is dispersed through the full depth of the rhizosphere. Here the younger components are mixed with the older existing material and the upward growth of the mire cannot be attributed to the new material alone. This deposition mechanism was termed 'displacement peat' formation (by C. A. Weber, 1911) because the peat already present in the rhizosphere was thought to be 'diluted', and partially displaced by the penetration of root material. Deep rooting

plants such as purple moor grass (*Molinia caerulea*) or cottongrass (*Eriophorum*) species may be able to form displacement peat in the deeper layers of mires whose surface layers have dried out. Weber (1911) originally used the term 'displacement peat' to describe temporarily dried out raised mires.

In addition to the penetration of roots into the underlying peat layers, the horizontally creeping rhizomes of many mire plants may also be important in peat deposition. In particular these include the vigorous rhizomes of water horsetail (*Equisetum fluviatile*) and of the common reed (*Phragmites australis*). For such species, which have rhizomes equipped with a highly efficient aeration system, because they have spent all their lives in a largely anaerobic milieu (from which aerobic microorganisms are excluded), only limited decomposition takes place after they die and they may be extremely well preserved.

Higher plants are found in almost every type of vegetation dominated by mosses and conversely, in many mires dominated by higher plants, mosses are also plentiful. Thus the two modes of peat formation described separately above, are frequently found in combination with one another (see Figure 4.3). For example, the thin, dark grey roots of hare's tail cottongrass (*Eriophorum vaginatum*) often penetrate vertically through dense layers of *Sphagnum* peat in which the *Sphagnum* leaflets are obviously pressed flat by the weight of the peat layers above them. This suggests that the roots must have penetrated the highly compressed peat prior to its deposition, otherwise they would have been much more distorted. A certain 'concertina' type of distortion often occurs in the shoot axes and leaf sheaths of common cottongrass (*Eriophorum angustifolium*) in the raised mires of northwest Germany. When these plant parts develop in the topmost peat layers (probably within 5 to 20 cm of the surface of the moss cover) they displace the existing loose *Sphagnum* material; once they die they become distorted as they are compressed by the increasingly thick *Sphagnum* peat layers above them.

#### The preservation of plant tissues

It is not possible to summarise simply which plant materials are well preserved in peats. Some species virtually never leave their remains in the peats; these include lichens and liverworts (except *Kurzia pauciflora* (= *Telaranea* = *Microlepidozia setaceta*) and a few other species) even though they are found in the living vegetation of certain mires. The same applies to the easily decomposable fungi, with the occasional exception of hardy tree fungi on mire wood. Conversely, mosses, despite their tender single layer leaflets, have excellent preservation characteristics. In weakly decomposed peat it is possible to identify many mosses using the shape and arrangement of their leaflet cells. However, under more intensive decomposition conditions these structures disappear, often leaving only the stem and the leaf midribs. Under these conditions, identification is no longer possible because the characteristic, loose-celled and thin-walled leaf auricles, which are relatively easily decomposed, together with the tips and margins of the leaves, are not preserved.

In comparison with the mosses, many tissues of the higher plants, including their subterranean organs, are readily decomposed. In the peatified state, the thin-walled loose internal tissues together with the parenchyma in the central cylinder of the rhizomes and the inner bark of the roots have generally disappeared and only the robust,

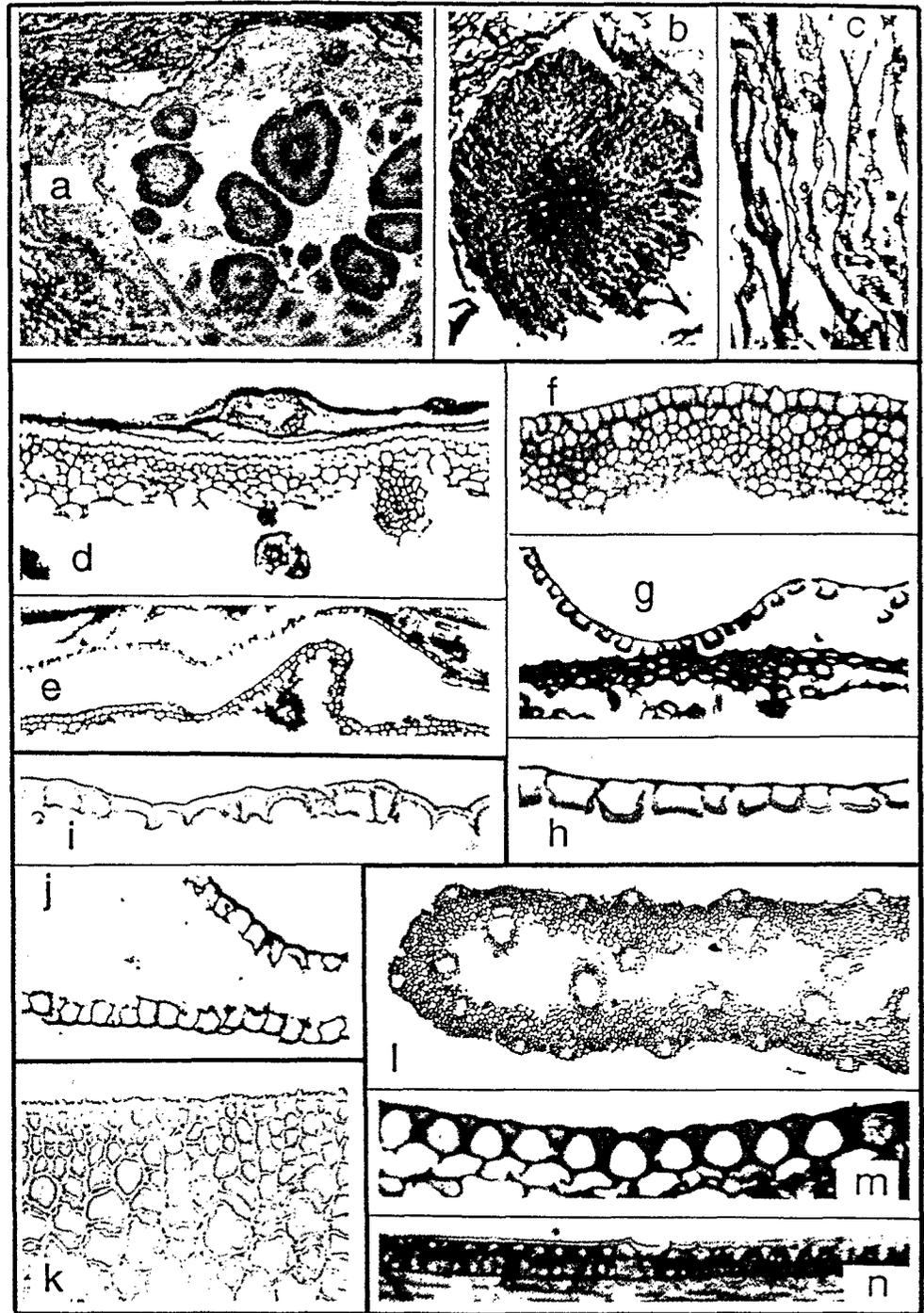
thick-walled and frequently encrusted tissues remain more or less well preserved. In the roots of herbaceous plants, for example, only the epidermis (or rhizodermis) together with the robust outer bark is preserved. When the inner bark has decomposed the outer bark surrounds the thin, thread-like central vascular bundle like a loose tube. For the rhizomes, the leaves are rarely preserved; the epidermis, sometimes with a few neighbouring cell layers of the (primary) bark, is the only tissue preserved (Figure 4.4, photographs d to n), and the central cylinder is usually fully decomposed. Often the same is true even of its vascular bundle (Figure 4.4, photograph l). In other cases, especially where thick-walled sclerenchymatous sheaths are developed, the fibrous residues of the vascular bundles also remain (Figure 4.4, photographs a and b). In some plant remains there is not even the epidermis, but only its outer cell walls (Figure 4.4, photographs g to i) or perhaps parts of its cuticles, of which the cell pattern remains easily recognisable.

Wood remains found in fresh peat appear particularly well preserved (Figure 4.5) and indeed the anatomy of mire wood often seems completely unaltered. Nevertheless, evidence that considerable decomposition has taken place is shown by the extent to which the wood shrinks during drying. Alder roots often provide striking examples of this. In mire wood, the appearance of anatomical perfection is totally deceptive: the histological pattern of the cell walls may be more or less perfect but the walls themselves will have suffered considerable loss of matter. This is usually quite evident from the reduced thickness of the cell walls, and consequently from the ease with which they can be crushed (see Figure 4.5, photographs f and g). The best state of preservation is generally exhibited by the suberized peridermas (see Figure 4.5, photographs h and i) and also by the (secondary) bark because these tissues shrink only slightly during drying. The reason for this is clearly the suberization—just as the good preservation characteristics of epidermis are a result of the cutinization of its outer walls and its layer of cutin (the cuticle).

Lignification also seems to protect plant tissues to a certain extent against decomposition. Lignin is considerably slower and less completely decomposed by microorganisms than cellulose. It is therefore understandable that in addition to their suberized and cutinized tissues, the wood of trees and shrubs and also the sclerenchyma of herbs, with their usually lignified cell walls, should remain. The good preservation of *Sphagna* is also associated with the considerable quantities of lignin-like substances that they are known to contain. In addition to the histochemical conditions described above, the thickness of a cell wall may contribute to its preservation. It can be shown, also histochemically, that considerable quantities of cellulose, in addition to lignin, are preserved in peats, as might be expected from the possible partial hydrolytic decomposition mentioned above.

#### **Raised-mire peats and their plant remains**

Raised-mire plants are a relatively small and easily surveyed group of species; they are well differentiated from the 'mineral water indicators' (see Chapter 1) which cannot survive on the extremely poor, acidic, rainwater-fed (ombrogenous) raised mires. The raised-mire environment enables good preservation of the plant remains.

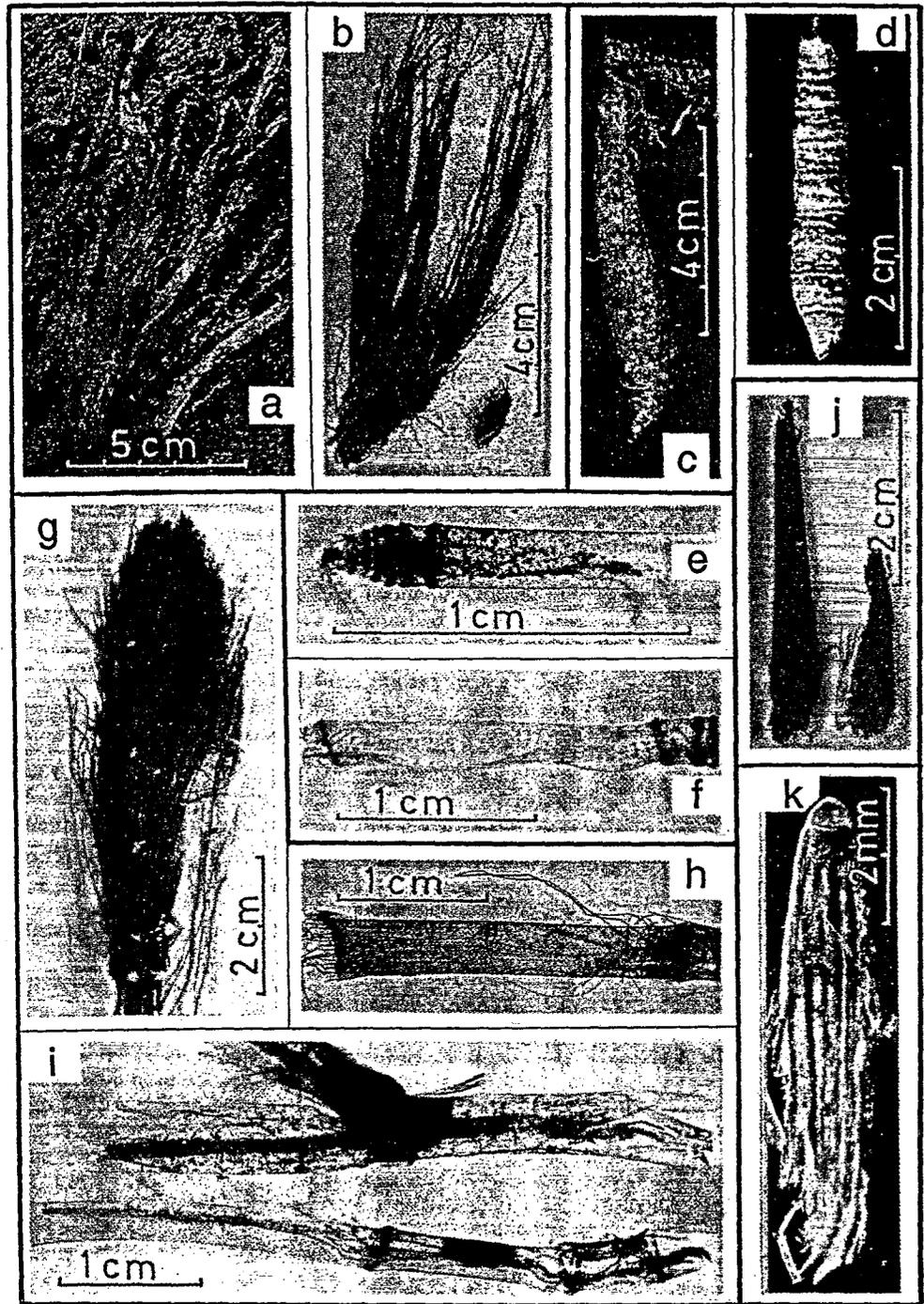


*Raised-mire mosses and their remains in peats*

The *Sphagnum* mosses are usually well preserved in raised mires; sometimes long pieces of their stems carrying all the branches together with their closely spaced leaflets can be identified. Weakly decomposed peats almost entirely consist of *Sphagnum* remains, whereas in more decomposed peats, the *Sphagnum* remains may be so insignificant as to be almost unidentifiable to the naked eye. Because of their characteristic structure, it is possible to identify quite accurately most peat mosses in the peatified state, or at least to determine to which of the three groups of species (Sections) that occur on raised mires they belong. Thus the representatives of the *Cymbifolia* Section (Figure 4.6a and b(i)) have very large, wide, broadly ovate and very convex leaflets, while the other two groups usually have much narrower leaflets that run to a point and are not so convex. Within these narrow-leaved representatives there is one group, namely the *Cuspidata* Section ('spear-leaved' group, Figure 4.6b(ii) and (iii)), which in typical cases may be distinguished in the field by a notable characteristic: peats formed from this species are light, often pale or straw-yellow in colour and contrast strongly with the darker reddish-brown of the other *Sphagnum* peats. The *Cuspidata* peats differ from the other *Sphagnum* peats by a second property: as a rule they have a distinctive horizontal cleavability, often of paper-thin layers, which even when highly decomposed, remains quite evident. Such peats, as they dry, break up into sheets like cardboard, and when fully dry (especially if very decomposed) the sheaf of thin layers undergoes a kind of wavy distortion brought about by the varying shrinkage of the individual layers. The cleavability of these peats occurs because a few peat mosses of the *Cuspidata* group have floating forms which live in shallow, water-filled hollows. This in particular includes *Sphagnum cuspidatum* whose long, horizontal floating stems form floating mats which, when they die, sink layer upon layer to the bottom. Thus they form a sediment in which the peat moss stems are criss-crossed in every direction. In other *Cuspidata* peats, the moss stems lie uniformly parallel in the layer. Such peats are often formed from the looser peat moss covers of *Sphagnum recurvum* and related species of the *Cuspidata* group which occur in habitats not covered by water. In such swards the dying parts of the mosses mostly fall in one direction (Figure 4.3).

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**Figure 4.4** The microtome sections of peat plant remains used to illustrate the state of preservation of the various tissues in peats. Shown are mainly the epidermises of the rhizomes of various plant species which are sometimes found in isolation, and sometimes with their adherent sub-epidermal layers. Some illustrations testify to the high preservation potential of plant parts with thick cell walls; here the single cell contours are often scarcely recognisable, as in the case of the hare's tail leaf sheath. (a-c) Sheathed cottongrass, *Eriophorum vaginatum*: (a) axis surrounded by highly decomposed peat material, which has numerous 'schlerenchyma spindles' in its interior ( $\times 50$ ); (b) one of the schlerenchyma spindles ( $\times 125$ ); (c) a transverse section of a leaf sheath bundle ( $\times 50$ ). (d-h) *Scheuchzeria palustris* rhizome remains with numerous layers of sub-epidermal tissue still clinging to the epidermis: (d and f) well preserved (d,  $\times 125$ ; f,  $\times 250$ ); (e) moderately preserved ( $\times 125$ ); (g and h) rather badly preserved (g,  $\times 250$ ; h,  $\times 500$ ), in this case the epidermis is largely isolated. (i and j) Bogbean, *Menyanthes trifoliata*, isolated epidermal tissues (i,  $\times 250$ ; j,  $\times 125$ ). (k) Reed, *Phragmites australis*, very well preserved rhizome tissue ( $\times 250$ ). (l-n) Purple moor grass, *Molinia caerulea*: (l) the tissue from a well-preserved (swollen) culm base ( $\times 50$ ); (m) a transverse section ( $\times 500$ ); (n) a longitudinal section ( $\times 500$ ) of one specimen, badly preserved



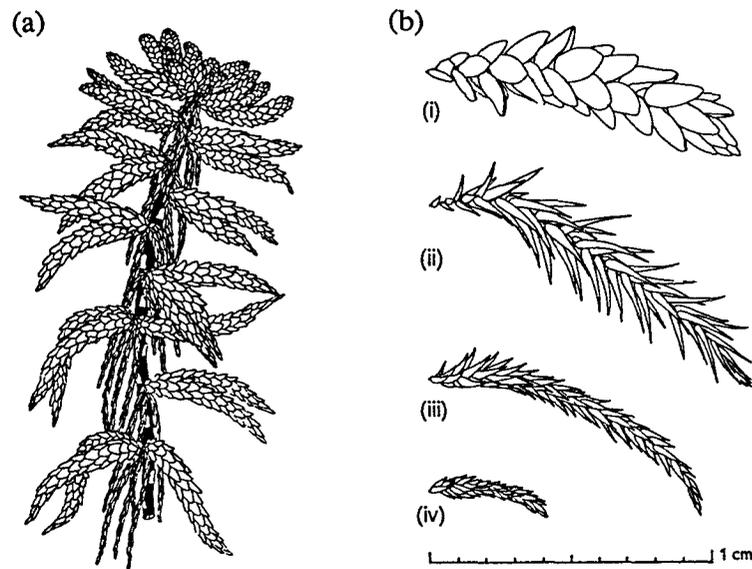
Parallel deposition generally does not occur with the representatives of the last of the raised-mire mosses: the *Acutifolia* ('sharp-leaved', Figure 4.6b (iv)) Section. These never occur as floating forms; their sward is usually denser and their peats are always darker, rather cinnamon or reddish-brown in colour. More or less horizontal cleavages may sometimes be recorded in *Acutifolia* and *Cymbifolia* peats, but this is rarely the result of any special deposition mechanism but rather of the compression inevitably associated with peat deposition. Here the initially rounded shapes are pressed flat so that horizontal cleavages are pre-formed. In such peats the cleavage never leads to the thin layers recorded in *Cuspidata* peats and the split halves are almost always held together by *Sphagnum* stems which, even though tossed and lying criss-crossed, permeate the peat from bottom to top.

Apart from these broad peat moss groups, it is impossible to make a positive identification, either with the naked eye or by hand lens, of the other peat mosses. Instead their microscopic features must be analysed. In many cases, these are features of the stem leaves and because these, compared to the much more numerous branch leaves, are very seldom found in peat, for every stem leaf that remains all the leaflets of several branches are also present so it is often difficult to identify their distinguishing features. Even with the aid of a microscope identification is easy only in the case of the *Cymbifolia* group, of which only *Sphagnum magellanicum*, *Sphagnum papillosum* and *Sphagnum imbricatum* occur in raised mires. The last two species are particularly numerous in the peats of northwest Europe and other areas with an oceanic climate; *Sphagnum magellanicum* is considerably more widely distributed. The *Cuspidata* group has already been discussed; of the *Acutifolia* group, the most important representatives are *Sphagnum fuscum*, more widely distributed eastward and northward in Europe, and *Sphagnum rubellum* as a more widely distributed species. The characteristic colour differences of these two species when living are lost in the peatified state.

In raised-mire peats, only two further mosses are commonly found and these, in contrast to the peat mosses, are hardly ever exclusive to a single peat type. They occur rather as 'accessory' elements, either loosely dispersed or embedded in layers of other peat types. This is particularly notable in the case of *Polytrichum strictum* whose gleaming black, stiffly spreading leaflets often contrast strikingly with the brown background of

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**Figure 4.5** These photographs show various remains of woody plants, especially those of Ericaceae, both stems (some highly magnified), leaves and seeds with particular reference to the structure of their tissues. They also show the great variety of the plant remains found whose characteristics provide a reliable means of their identification. The different states of preservation are illustrated by the contrast between the two sections of birch wood (f and g). The holes in both are due to herb roots that grew along the inside of the already soft, 'fossilised' birch roots. The herb roots later became almost totally decomposed, but the compression they applied to the soft birch wood is still quite evident. In g it extends, evidently owing to more intensive decomposition, over the whole section obliterating its cellular structures and annual rings, in contrast to the obviously less decomposed and, therefore, less softened wood in f. The flowers and leaf-bearing stems of heather (b and c) with their still clearly recognisable marginal leaf bristles are examples of an exceptionally good state of external preservation. (a-d) Heather, *Calluna vulgaris*: (a) a flattened seed coat ( $\times 40$ ); (b) flowers ( $\times 8$ ); (c) pieces of branches with leaves ( $\times 8$ ); (d) the epidermis of the underside of a leaf with characteristic hairs ( $\times 100$ ). (e) Bog myrtle, *Myrica gale*, part of a terrestrial shoot (natural size). (f and g) Birch, *Betula alba*, root wood ( $\times 16$ ). (h and i) Pine, *Pinus sylvestris*, root periderm ( $\times 100$ )



**Figure 4.6** (a) Upper portion of a *Sphagnum* plant (*Sphagnum magellanicum*, from Section *Cymbifolia*) slightly stylised. Of the immature, bud-like parts no residues remain in the peat; normally only the mature parts of mosses are deposited. (b) Branchlets of *Sphagnum* species from various Sections showing their characteristic differences: (i) *Sphagnum magellanicum* (Section *Cymbifolia*); (ii) *Sphagnum cuspidatum* an especially long-leaved aquatic form (Section *Cuspidata*); (iii) *Sphagnum recurvum* (Section *Cuspidata*); (iv) *Sphagnum fuscum* (Section *Acutifolia*)

the *Sphagnum* peats. Often only its (equally black) stems surrounded by leaf-sheaths are preserved. Another fairly common species is *Aulacomnium palustre* which, in terms of its colour, does not differ much from the surrounding Sphagna but which can easily be distinguished from them, at least under a lens, by its elongated, almost brush-like, closely-spaced leaves. Under a microscope its long leaves are recognisable by their rolled margins and their very papillose short cells. Other mosses whose remains are found infrequently include *Dicranum bergeri* and occasionally varieties of *Dicranum scoparium*. Some species occur only in very small quantities that are nearly hidden in the peat, for example *Pohlia nutans*, *Hypnum cupressiforme* and *Pleurozium schreberi*.

#### *Ericaceae and their remains*

Both in living vegetation and peat, the Ericaceae are among the characteristic elements of raised mires. Particularly numerous are the stems of heather (*Calluna vulgaris*) which are characterized by a rather loose pattern of regularly decussate pits which were the points of attachment of leaflets. On the short shoots, the leaflets are more densely decussate; these 'catkin-like' shoots are often recorded in the peat (Figure 4.5, photograph c) but because they are small they are not readily visible. The flowers and fruit capsules of

*Calluna*, together with its minute seeds are not usually found unless the peat is specially treated (Figure 4.5, photographs a and b). Numerous characteristic remains of another ericaceous plant, the cranberry (*Vaccinium oxycoccus*), are recorded in raised mire peats. These include long and almost bristle-like thin stems, commonly less than 1 mm in diameter, together with small leathery ovate to triangular leaflets with recurved margins. However, the seeds from its large, red berries which are numerous in the living vegetation, are almost never found in peats.

#### *Remains of herbaceous plants*

The tufts of fibres from hare's tail cottongrass (*Eriophorum vaginatum*) are recorded in both weakly and strongly decomposed peat (Figure 4.4, photographs a to c). The tough fibres, which can be quite an obstacle to peat cutting, have earned it the name of calf- or bull-meat, amongst peat cutters. These remains are found both individually, like flattened paint brushes, and as dense, mat-like layers. They are the decomposed remains of bundles of the subterranean leaf sheaths of the dense, grass-like tussocks of this plant (Figure 4.4, photograph c). Additionally, the subterranean, very shortened axes (Figure 4.4, photograph a) are also preserved together with the long, unbranched vertical roots. The leaves and stems and fruits of *Eriophorum vaginatum* are rarely found.

The remains of the narrow-leaved common cottongrass (*Eriophorum angustifolium*) are not as well preserved as those of the hare's tail cottongrass because the fibres of its leaf sheaths are much more delicate and decompose fairly easily. The only remains of this species preserved in peat are the stronger parts of the subterranean axes, which sometimes resemble small cigars. They have often lost all remnants of their leaves, roots or rhizomes. The fruits of *Eriophorum angustifolium* are seldom recorded. The same is true for deer grass (*Scirpus caespitosus*), another typical representative of the sedge family (Cyperaceae). In the peats of some mires the lower parts of its dense tufted shoots are found. They are distinguished by their reddish-brown, gleaming, rather thick and elongated triangular lower leaves. In contrast to the preceding species, it is precisely the fruits of another member of the sedge family, white beaked sedge (*Rhynchospora alba*), that occur in abundance, but because they are so small (about 1 mm long) they may be easily overlooked when examining peat samples with the naked eye. Remains of the vegetative organs of this species are seldom found in peats, even though the plant is very widespread in raised mire vegetation.

Some plant remains found in raised mire peats are relicts of once common mire vegetation. A good example is *Scheuchzeria palustris*, a grass-like or rush-like plant with an inconspicuous flower. It has horizontally creeping subterranean rhizomes whose outer layers are very resistant to decomposition (Figure 4.4, photographs d to h) and which leave very striking remains. The plant remains lie on horizontal cleavage surfaces like wide, yellow, more or less flattened straws with which they have conspicuous nodes in common. They are particularly numerous in *Cuspidata* peats because the habitats in which the *Cuspidata* mosses thrive are also optimal for *Scheuchzeria*. Further important raised mire species are the sundew species (*Drosera rotundifolia*, *intermedia* and *anglica*) whose delicate leaves are hardly ever preserved in peats, although the minute and very characteristic seeds and their equally typical pollen grains are usually well preserved.

### The botanical composition and preservation of raised mire peats: 'black peat' and 'white peat' in northwest Germany

In addition to the botanical composition of raised mire peats which are distinguished by the presence or predominance of certain plant remains, there are characteristic and rather abrupt contrasts in their decomposition degrees, especially in northwest Germany. Here a distinct division of the peat profile into a highly decomposed lower and a weakly decomposed upper layer is commonly recorded. These layers were formerly known as older and younger raised mire peats, respectively, but are now usually referred to as 'black peat' and 'white peat'; terms which are taken from the vernacular of northwest German peat cutters, but should not be taken literally. 'Black peat' in its unoxidised state, is light yellowish-brown and only darkens when exposed to air to the deep-brown colour which it retains when dried. It is only in the dry state that its colour contrasts obviously with the 'white peat', which in fact is mid-brown in colour. Black peat and white peat are not distinguishable in terms of their plant constituents, but they do represent fundamental classification units of the raised mire peats, at least in northwest Germany where such mires are numerous. The distinction is important for peat exploitation: the highly decomposed (black) raised mire peat was formerly the preferred product of both peasant and industrial fuel peat winning whilst the weakly decomposed peat was in demand for peat litter, soil improvement, peat manufacture and as a substratum in the agricultural use of mires (see Chapter 7).

The boundary between black peat (decomposition degree usually H6 to H8 or H9) and the overlying white peat (usually H2 to H4) is often sharp. The black peat often ends in the form of a 'boundary peat' rich in cottongrass and heather remains deposited under relatively dry conditions, and the white peats often begin with layers that indicate very wet deposition conditions and are termed 'precursory peats'. The white peats are usually *Cuspidata* peats, with or without *Scheuchzeria*; they often fill structures such as hollows in the vicinity of the black/white peat interface. This interface was originally referred to as the 'boundary horizon' or *Grenzhorizont* (Weber, 1908), a term originally introduced to describe the heather and cottongrass layers of the boundary peat (for further discussion see Chapter 1).

Apart from their degree of decomposition there are certain differences between the plant constituents of raised mire peats. These differences do not result in a wide variety of peat types because only a small number of species (especially conspicuous species) occur and only very few of them become dominant peat components. As indicated above, the dominant peat components in raised mires are *Eriophorum vaginatum*, *Calluna vulgaris* and *Scheuchzeria*, the rest of the dwarf shrubs and herbs and the leafy mosses as a rule contribute only minor, apparently accidental, elements to the peats. The principal raised mire peats can be classified and characterised by the plant remains they contain, as follows:

- (1) *Moss peats*—*Sphagnum* or moss peats are subdivided into *Cuspidata* peats deposited in extremely wet conditions and the *Cymbifolia* and *Acutifolia* peats that evolved in uniformly wet conditions. A more detailed characterisation of the *Sphagnum* species requires microscopic examination; usually only one *Sphagnum* species is present in any one peat sample. Dwarf shrubs and herbs may be intermixed with the mosses to a greater or lesser extent but are unlikely to radically alter the *Sphagnum* character of the peat.

(2) *Cottongrass peats*—These forms of black peat usually only contain macroscopic remains of the leaf sheaths of *Eriophorum vaginatum*. They occur frequently and it is difficult to distinguish between a highly decomposed raised mire peat containing cottongrass remains and a 'purer' cottongrass peat of the type defined above. In both the black and white peats there are clear cottongrass peats which largely consist of cottongrass remains. Sometimes they form uninterrupted, but horizontally limited beds, whose shape and distribution in the profile indicate their evolution from individual raised mire hummocks. These 'hummock beds' often occur at decomposition interfaces, especially at the black/white peat interface, where they frequently alternate with 'hollow beds' of *Cuspidata* peats; in other cases the adjacent hummock beds can merge into one another and so give rise to continuous layers of cottongrass peat. In hummock beds or at decomposition interfaces rich in cottongrass, as a rule heather remains are also found and when in large proportions these should be described as cottongrass-heather or cottongrass-dwarf shrub peats. Pure or almost pure dwarf shrub peats which may contain the remains of other ericaceous plants are relatively seldom found, except in the layers immediately under the surface of drained and, therefore, heath-covered mires. Such peats must always be regarded as resulting from intensive drying of the mire and for that reason other plant remains scarcely occur in them.

(3) *Scheuchzeria peats*—The *Scheuchzeria* peats often contain peat mosses of the *Cuspidata* group because they favour the same habitat conditions. The *Scheuchzeria* or *Scheuchzeria*-rich *Cuspidata* peats are characterised by the thin-leaved layers which they form; hence their Dutch name *Spalterveen* (splitting peat). *Scheuchzeria-Cuspidata* and pure *Scheuchzeria* peats are found both in isolated hollow beds in raised mire profiles and in uninterrupted layers one or more decimetres thick, which suggests extensive waterlogging at the time of deposition.

While *Scheuchzeria* peats, cottongrass peats and a few of the other peat types mentioned above occur frequently in, and are very typical of, raised mire profiles they must not be regarded as confined to them. Where peats contain mineral soil water indicators, they are considered to be transitional peats. Here the remains of *Scheuchzeria*, cottongrass and other raised mire plants also predominate but due to the associated plant species they are quite distinctive.

#### Transitional and fen peats and their plant remains

In contrast to the homogeneous, and in many respects uniform, characteristics of raised mire vegetation, transitional and fen peats have a multiplicity of mire plant communities, including a considerable number of mosses, herbs and woody plants that greatly outnumber the small range of the raised mire species. However, the majority of species cannot be identified without appropriate sample preparation in a laboratory and even then only under a microscope. This applies especially to almost all mosses, about 40 species of which are limited to transitional and fen peats. It also applies to the several higher plants whose fruits or seeds are their only identifiable remains preserved in peats. Taking the common and rarer species together, these amount to about 50 plant species.

For the botanical identification and differentiation of transitional and fen peats in the field only a relatively small number of macroscopically identifiable plant species

are available. Even in favourable conditions, where they are profuse and well preserved, scarcely more than 15, or at most 20, species are identifiable, including a few particularly conspicuous mosses and fruits or seeds. These 'identifiable' species will be examined below. Only the commonest and most typical transitional and fen peat types will be described with the emphasis on those that can be found and differentiated from one another in the field. The transitional and fen peats will be classified below according to the nutrient demand of their original peat-forming vegetation; peats that contain raised mire plant remains in addition to those of mineral soil water indicators will be included in the transitional mire peats.

#### *Wood and other remains of trees and shrubs*

By far the greater part of the wood found in mire profiles consists of the remains of roots and sometimes whole stumps of former trees; the remains of trunks or even branches and twigs occur much less frequently. The state of preservation differs from species to species: pine often seems scarcely altered whilst alder, despite its well preserved tissue pattern, is usually so strongly decomposed that it could easily be squeezed together between the fingers. These differences do not depend only on the species-specific decomposition properties of the wood but also on the habitat-specific decomposition intensity. On average this is considerably weaker in the rather acidic and low-nutrient pine habitats than in the richer and weakly acidic to neutral alder habitats. Such differences between habitats as well as between the water balance during or after peat formation are also the reasons for the very different states of preservation of the wood residues of even the same tree species.

Identification of the species or genus is reasonably easy from the microscopic characteristics of the wood unless it has been very badly preserved. Macroscopic identification of remains in the field is practically confined to the bark and here it must be noted that there are considerable structural differences between roots and stems or branches; the silver-grey roots of birch with their distinctive strong transverse structures are a good example of this. Ignoring tree species whose remains are found only at the bottom of mire profiles as relics of a vegetation of an originally dry habitat (for example, oak woodland), then the following species leave their remains in the peats:

(1) *Pine*—Pine remains come from the widespread Scots pine (*Pinus sylvestris*) but also from a mire-inhabiting sub-species of the mountain pine (*Pinus mugo*) which in Germany is confined to the mires of southern Germany (to the foreland of the Alps, the Bavarian and Black Forests). The base and nutrient requirements of both these species are extraordinarily low and as a rule their remains are found only in very poor peats: in transitional mire peats and, for the mountain pine, in deposits of raised mire character. The wood remains of these two species cannot be differentiated; in both cases they are usually firm and tough with a distinctive scaly bark. The only unmistakable characteristics of either of them are those of their cones and the anatomical structure of their needles, both of which are sometimes found in peats. Wherever pine wood is found it must be remembered that the Scots pine was much more abundant at the beginning of the Postglacial than in the subsequent periods and also that it occurred in districts where pines no longer grow naturally (at least not to any extent).

(2) *Birch*—Birch remains, like those of the Scots pine, date mainly from the beginning of the Postglacial. Beside small occurrences of shrub-like birch (*Betula nana*, *B. humilis*) which can be identified with certainty by their leaves, the remains consist mainly of arborescent birches, essentially of brown birch (*Betula pubescens*). It is impossible to distinguish between its subspecies without examining their fruits and catkin scales which are often found in the peat. As a rule, owing to their decomposition-resistant and typical bark, birch remains in peat are easily identified, even macroscopically. Larger stumps are seldom found, and where they are recorded they are usually less than two decimetres in diameter. Birch remains are concentrated in transitional peats but compared with those of pine that often occur with them, tend towards more nutrient-rich conditions. Birch remains are not found in raised mire peats.

(3) *Alder*—Alder remains which are recorded only since the beginning of the Atlantic Age, are found in the richer habitats in fen peats, often intermixed with birch remains. Of the indigenous alder species only the black or red alder (*Alnus glutinosa*) occurs as a mire tree. Its highly decomposed timber remains are often difficult to identify macroscopically; its complete stumps are seldom found.

(4) *Salix*—*Salix* remains in peats of central Europe and Britain are commonly derived from two widespread species: the eared willow (*Salix aurita*) which has a very low nutrient requirement and the larger common willow (*Salix cinerea*) which has a higher nutrient requirement. Some further mire-inhabiting species are much rarer and occur only infrequently in the area mentioned. It is impossible to distinguish between the remains of all of these species either macro- or microscopically unless leaf remains can be found (which seldom happens). *Salix* remains occur in practically all Postglacial transitional mire and fen peat layers. It should be mentioned here, that many native willows prefer different habitats, mainly by rivers and streams, where mire formation never takes place.

(5) *Bog myrtle*—Bog myrtle or sweet gale (*Myrica gale*) during the Postglacial seems never to have gone beyond its present day sub-oceanic and oceanic distribution, which is more or less centred on northwest Europe and the coastal landscapes of central Europe. Its wood remains which resemble birch roots (Figure 4.5, photograph e) and its very decomposition-resistant leaves are found not only in a wide range of transitional peats but also in fen peats.

(6) *Alder buckthorn*—The wood remains of the alder buckthorn (*Frangula alnus*) are only found in peats in exceptional cases, which is hardly surprising because when this shrub occurs in mires (it is also very widely distributed over the wetter mineral soils), it is not found in the wettest habitats.

#### *The remains of herbaceous plants*

In many peats the most numerous remains of herbaceous plants are those of their roots. For want of sufficient distinctive features they cannot, with few exceptions, be assigned with certainty to any particular species. Many of them probably come from *Carex* or other Cyperaceae species which generally represent a large proportion of the herbaceous species of mire plant communities. Easier to identify, even macroscopically, are some of the

subterranean shoots which are often pressed flat on horizontally splitting surfaces of peat samples. These are principally the strong, light-coloured, wide rhizomes of the common reed (*Phragmites australis*), the delicate ones of bog bean (*Menyanthes trifoliata*), the dark-brown ones of horsetail (*Equisetum fluviatile*) and the only millimetre-wide ones of mud sedge (*Carex limosa*); occasionally, well-defined remains of the relatively rare saw sedge (*Cladium mariscus*), or purple moor grass (*Molinia caerulea*) and of the marsh fern (*Thelypteris palustris*) are recorded.

Plant remains which are macroscopically identifiable, without preliminary preparation, include a few seeds, especially those of bog bean (*Menyanthes trifoliata*) and the conspicuous fruits of sedge species (*Carex rostrata*, *C. paniculata*, etc), saw sedge (*Cladium mariscus*) as well as those of marsh cinquefoil (*Potentilla palustris*) and gypsywort (*Lycopus europaeus*). These species, however, never amount to a large proportion of a peat sample. This is also more or less true of the tissue remains of all herbaceous plants: quantitatively they are usually few relative to the other plant components, whether moss or root remains or amorphous humic materials, yet they are extremely significant elements of the peat matrix.

#### *Mosses*

Mosses in transitional and fen peats are less important than in raised mire peats. This applies particularly to the peat mosses, only a few of which are genuine non-raised-mire species, for example *Sphagnum palustre* and *S. teres* as well as the *S. subsecundum* group. These species cannot be distinguished macroscopically from their raised mire analogues. Even the true mosses (*Bryales*) play only a minor part in the non-raised mire peats; only a few species can be regarded as genuine peat-formers. In particular these are species of the genera *Drepanocladus* and *Calliergon*, also (rarely) *Tomenthypnum* (= *Camptothecium nitens*), *Scorpidium scorpioides*, *Paludella squarrosa*, and *Meesia triquetra*. The majority of these species or genera can be identified using a hand lens where they are found in abundance and are well preserved; their precise determination requires a microscope.

#### **The botanical composition of the principal transitional and fen peats**

In the classification of transitional and fen peats, the degree of decomposition is not as fundamental a criterion as it is in raised mire peats. This is because the diversity of the plant communities, and hence their plant remains, is much greater in transitional and fen peats than in raised mire peats. Therefore, botanical composition is the principal criterion of classification. Furthermore, on average the range of decomposition degrees encountered is narrower: weakly decomposed peats are rare, especially amongst fen peats. This is because of the more intensive decomposition processes in the moderately acidic to neutral fens which are usually rich in nitrogen and calcium. However, it must be noted that the hydrological conditions prevailing during peat formation have a decisive effect on decomposition, so it is possible that very weakly decomposed fen peats are found. The characteristic peats derived from transitional and fen systems will be briefly described below.

Pure reed peats are easily recognisable owing to their characteristic reed rhizome remains and because they are easily related to a particular peat-forming vegetation:

reedbeds which have high nutrient requirements but are composed of few species. Reed peats are often found in 'terrestrialised mires' usually lying above lake sediments. It is sometimes difficult to make a sharp distinction between the peats proper and the lake sediments that are more or less heavily interspersed with reed rhizomes and roots. Reed peats that occur thus in terrestrialisation profiles may be quite weakly decomposed (H4 or H5) where, as a rule, their principal components are not the distinctive rhizomes of the reed but its fine root mat instead.

Reed peats of low decomposition are also widely distributed outside genuine terrestrialised mires. They occur both where coastal subsidence or sea transgression result in temporary flooding and the deposition of silt and sand, and where a rising water table and the backing up of inflowing rivers create a waterlogged environment. In regions unaffected by clay and silt deposition, pure reed peats are formed, elsewhere silty reed peat forms; here the deposit is predominantly mineral with varying proportions of reed but there are no sharp boundaries between these deposits.

The mineral content of a clayey or silty peat does not become visually recognisable (by its differing and mostly light blue-green colour) until it exceeds about 60%. Even a clay or silt content of 40-45% (on a dry weight basis) cannot be identified with certainty by its feel ('finger test'). In some regions, for example parts of northwest Germany, clayey peats have a brackish water origin which is easily recognisable under a microscope from the presence of certain diatoms occurring only in brackish water. Many reed peats found in low-lying clay areas are rich in ferrous sulphide which has evolved in reducing conditions. When the peat is aerated (for example, by excavation from trenches) considerable quantities of phytotoxic sulphuric acid may evolve.

*Sedge peat* is a term that can only be applied to peats that consist totally or predominantly of the unmistakable remains of sedges (*Carex* species). Strictly speaking this means that when classifying peats in the field the only ones that can be so designated are those that contain the conspicuous residues of mud sedge (*Carex limosa*) because the remains of other sedges cannot be identified unless the peats are specially prepared in a laboratory. It is often usual, however, to designate as sedge peats all those in which only the fine rootlets are found and which, for the most part, cannot be macroscopically assigned to any particular plant species. These should be more properly described as radicle or root-mat peats even though it is very likely that *Carex* species participated in their deposition. Many characteristic plant remains, such as those of bogbean (*Menyanthes trifoliata*) and water horsetail (*Equisetum fluviatile*) even when they are visibly obvious on horizontally splitting surfaces of peat, are seldom found to be the dominant components of peats. Thus, if large quantities of radicles are present it is better to refer to them as *Menyanthes* radicle peat or *Equisetum* radicle peat rather than bogbean-sedge or horsetail-sedge peats. The very common terms sedge-reed or reed-sedge peat are used in a similar sense for peats containing few reed rhizomes and a large proportion of radicles, even though it is never possible, at least in the field, to determine the size of the actual fractions of reed, sedge or other radicles.

*Moss peat*, depending on its components (moss radicle, radicle-moss-peat, even *Menyanthes*-moss peat) are the terms used for peats dominated by otherwise unspecified mosses. In many cases, the moss species involved can be more accurately characterised. However, where only small quantities of mosses are recorded or the degree of decomposition is high, it is difficult to determine the moss fraction in the field. In mire profiles which date back to the late Pleistocene and the Boreal Age, occasional deposits

of pure moss peats are recorded. They are usually found only in individual mires where special ecological and deposition conditions prevailed.

Only small quantities of peat mosses are found as an admixture in fen peats. In transitional peats, the peat moss proportion may be greater and largely consists of minerotrophic *Sphagnum palustre* which belongs to the *Cymbifolia* group. *Sphagnum palustre* cannot be distinguished macroscopically from the more ombrotrophic *Sphagnum papillosum* and *S. magellanicum*. It is, however, possible to distinguish minerotrophic Sphagna peats by the botanical composition of the other peat remains; minerotrophic Sphagna peats contain no cottongrass or Ericaceae, species which are never totally absent from ombrotrophic peats. Some transitional mire peats are macroscopically indistinguishable from raised mire peats, particularly where single, quantitatively insignificant remains of mineral soil water indicators (fruits, seeds and mosses) are recorded in a predominantly ombrotrophic peat matrix. Peats dominated by *Scheuchzeria* remains are an example of this transitional mire. These have a raised mire boundary but, as minerotrophic *Scheuchzeria* peats are mostly characterised by the macroscopically identifiable remains of mineral soil water indicators, especially mud sedge, bogbean and mosses (for example, *Drepanocladus* species), the surrounding peat matrix may be used to derive the correct classification.

Peats containing tree remains are usually known as forest or forest swamp peats, at least when the wood remains in them are rather abundant and uniformly distributed. There are, however, a whole series of objections to the use of this term which refers to a swamp forest as a peat-forming plant association. First, some peats contain wood in the form of roots which are very thin (10–15 mm diameter in the case of birch) or stumps which are very small (under 15 cm diameter in the case of pine), suggesting that they are derived from low-growing mire shrubbery rather than from a genuine swamp forest. Second, peats with a small number of wood remains can only be regarded as deposits of a vegetation in which woody species are almost an accidental addition to a peat matrix which is otherwise a vegetation without trees and shrubs. Third, detailed analysis of the species composition of most peats which contain wood (even those with a high wood content) shows that there is no fundamental difference in the composition of the herbs and mosses between wood peats and woodless peats. This means that there are no characteristic 'swamp forest species', and it may be argued that wood remains are only accessory elements from which, in the botanical sense, specific peat types cannot evolve and certainly none that could be related to genuine swamp forests.

Peats derived from genuine swamp forests do occur but only where wood forms a dense horizon of stumps in the mire profile. Various data (see Chapter 3) suggest that such swamp forests date from a period in which mire growth was largely stagnant, so that they should not be included among the peat-forming plant communities. This view is supported by the general botanical finding that the plant communities of swamp forests survive on what are, relative to other peat-forming plants, the lowest water tables. Furthermore, the peat deposits are characterised by a high degree of decomposition of the peat substance found between the tree stumps. This also suggests a low water table during peat deposition. In addition to wood, the few (decomposition resistant) plant remains which are preserved in these peats are also indicators of a moist, rather than permanently wet, habitat (raspberry, blackberry and a few other fruits and seeds, and some mosses). Such a conclusion is also supported by the occurrence of the fungus-sclerotia known as *Cenococcum geophilum* which resemble round black fruits. These

data suggest that the character of the peat is considerably altered during a low water table phase which would have prevented the formation of any appreciable amount of new peat. Any organic matter newly deposited would have been offset by (secondary) peat decomposition including (apart from tree root residues) the humification products of the lignin-rich and, therefore, only slowly convertible, organic matter produced by the swamp forest.

Thus, in summary, there are two types of peat that contain, or are rich in, wood remains, neither of which can in the strict sense be regarded as swamp forest deposits. The first peat type cannot be directly related to swamp forest but only to open, herb- and moss-rich, bushy plant communities. In the second peat type, the peat substance largely developed before the colonisation by swamp forest.

#### 4.4 THE PHYSICS OF PEAT SOILS

Peat is a complex system comprising solid, liquid and air fractions which interact through changing position, changing volume and mass fractions. It is very difficult, if not impossible, to define completely the exact physical status of peat and mineral soils at any time. But there is a need to describe the physical status, because the soil supplies organisms with nutrients (including water and oxygen), inhibits growth of roots by, for example, high concentrations of carbon dioxide, serves as an anchoring system for roots, and determines the distribution of nutrients, roots and organisms. Models to describe the physics of soils are still fragmentary.

##### 4.4.1 BASIC RELATIONSHIPS

###### Peat as a disperse three-phase system

The three phases in peat and mineral soils are represented by: (i) the *solid* phase or soil matrix, which in peat soils consists mainly of organic matter; (ii) the *liquid* phase or soil solution, which is mainly water with associated dissolved ions and organic matter; and (iii) the *gaseous* phase, consisting mainly of nitrogen, with variable amounts of oxygen and carbon dioxide. In peat soils  $\text{CH}_4$  and, more rarely,  $\text{H}_2\text{S}$  may be present.

###### Volume and mass relationships of soil constituents

The most commonly used relationships are given below. Figure 4.7 illustrates the dimensions involved:

$$\text{Density of solids } \rho_s = m_s/V_s$$

$$\text{Dry bulk density } \rho_b = (m_s/V_t) = m_s/(V_a + V_w + V_s)$$

$$\text{Porosity } f = V_f/V_t$$

$$\text{Air filled porosity } f_a = V_a/V_t$$

$$\text{Mass wetness } w = m_w/m_s$$

$$\text{Volume wetness } \theta = V_w/V_t$$

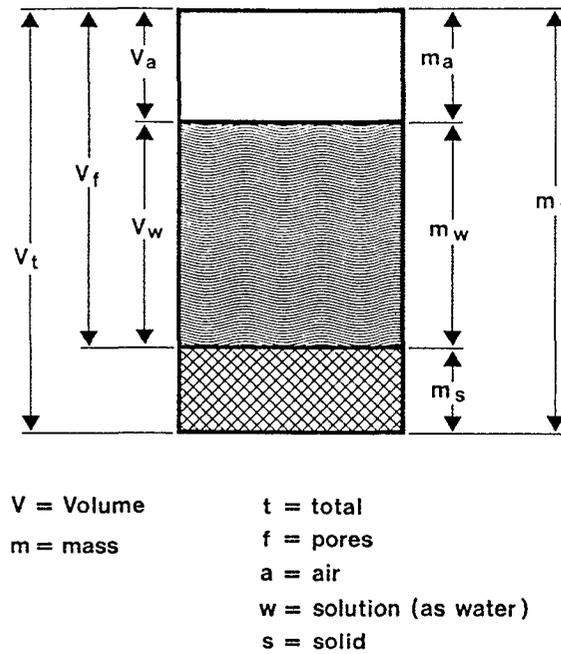


Figure 4.7 Schematic diagram of the soil as a three-phase system

where  $V$  = volume,  $m$  = mass,  $t$  = total,  $f$  = pores,  $a$  = air,  $w$  = solution (as water),  $s$  = solid;  $V_s$ ,  $V_t$  and  $m_s$  are constants.

The bulk density of peat deposits varies according to the botanical composition of the plant remains and the degree of decomposition of the peat. Thus in *Sphagnum*-dominated profiles the bulk density is usually about  $0.02 \text{ g cm}^{-3}$  except in the upper 1 cm where the capitula of the mosses tend to be tightly packed and the bulk density is higher. In peat deposits, the bulk density increases with increasing depth, primarily as a result of the load of the overlying peat layers. Highly decomposed peats have a higher bulk density which is commonly around  $0.12$  to  $0.15 \text{ g cm}^{-3}$  (Clymo, 1983).

The degree of decomposition and the peat bulk density are intrinsically related. Decomposition decreases pore size (and hence active porosity) and, as a result, increases the amount of solid material per unit volume (the bulk density) (see the following section). The total porosity ( $V_t$ ) is independent of peat type or degree of decomposition. Active porosity, however, dictates the tenacity with which water movement is resisted within the peat matrix. Boelter (1972) found that although the total porosity for the catotelm (see Section 4.5) in a *Sphagnum* bog was approximately 90% by volume, the small pore size significantly lowered the saturated hydraulic conductivity relative to the acrotelm. Päivänen (1969), Puustjärvi (1970) and Karesniemi (1972) confirm the positive relationship between peat bulk density and degree of decomposition. The relationship varies with peat type (Table 4.2) and is probably controlled by the depth and ash content of different peats (Päivänen, 1973; Heathwaite, 1987).

**Table 4.2** The influence of depth on the hydraulic conductivity of fen peats (after Heathwaite, 1987, and Päivänen, 1973)

Peat type	Depth (cm)	Hydraulic conductivity ( $\times 10^{-6} \text{ cm s}^{-1}$ )
Sedge	25	1480 $\pm$ 473
Sedge	35	1730 $\pm$ 460
Sedge	45	1751 $\pm$ 153
Wood	25	3317 $\pm$ 1009
Wood	35	3028 $\pm$ 1212
Wood	45	1417 $\pm$ 264

### The properties and pore system of peat

All soils peds are characterised by the vertical, horizontal and temporal variation of their properties. Soil peds develop from parent material which is altered by climate and other factors (including vegetation and land use). The characteristics of a soil ped may be expressed in terms of the parent material (for example, different soil layers) or in terms of the soil genesis (expressed in different horizons). Peat soils may vary both in terms of their parent material (different plant residues, sedimentation processes and plant growth characteristics) and soil genesis (for example, degree of decomposition of the plant residues and amount of soil organisms). Peat is a porous body whose pores differ in size and shape and are largely dependent on the plant residues and the degree of decomposition. The size and shape of the pores determine the amount of available water for plants, the rate and amount of water movement and the trafficability of peat soils.



**Figure 4.8** Inter-residual (a) and intra-residual (b) pores of *Sphagnum cuspidatum* peat (after Puffe and Grosse-Brauckmann, 1963)

The porosity of peat cannot be easily defined because the organic residues both contain pores and form pores. The higher the decomposition of the peat or organic matter, the higher the volume of the inter-residual pores and the lower the volume of the intra-residual pores (Figure 4.8 and the previous section). Other relationships (see Figure 4.7) are:

$$\text{Dry specific volume } V_b = 1/\rho_b$$

$$\text{Wet bulk density } \rho_t = m_t/V_t$$

$$\text{Void ratio } l = V_f/V_s \text{ (for } m_a = 0)$$

$$\text{Degree of saturation } s = V_w/V_f$$

The preferred relationships are those in which the reference remains constant and where the variable parameter is not combined with a constant parameter. The relationship between mass wetness ( $w$ ) and volume wetness ( $\theta$ ) is:

$$w = \theta(\rho_w/\rho_b)$$

where  $\rho_w$  is the density of the soil solution (usually  $1 \text{ g cm}^{-3}$ ) and  $\rho_b$  is the dry bulk density of the solid material (see above). Typical values in peat soils for the density of solids ( $\rho_s$ ), dry bulk density ( $\rho_b$ ), porosity ( $f$ ), mass ( $w$ ) and volume ( $\theta$ ) wetness are given in Table 4.3.

**Table 4.3** Typical values for density of solids ( $\rho_s$ ), dry bulk density ( $\rho_b$ ), porosity ( $f$ ), mass ( $w$ ) and volume ( $\theta$ ) wetness in peat soils

Degree of decomposition (von Post)	Compaction	$\rho_b$ ( $\text{mg m}^{-3}$ )	$\rho_s$ ( $\text{mg m}^{-3}$ )	$f$ ( $\text{m}^3 \text{ m}^{-3}$ )	$w$ ( $\text{mg mg}^{-1}$ )	$\theta$ ( $\text{m}^3 \text{ m}^{-3}$ )
H1	Loose	0.05	1.4	0.96	$\leq 19.2$	$\leq 0.96$
H4	Loose to dense	0.10	1.4	0.93	$\leq 9.3$	$\leq 0.93$
H6	Dense	0.15	1.4	0.89	$\leq 5.9$	$\leq 0.89$
H9	Very dense	0.20	1.4	0.86	$\leq 4.3$	$\leq 0.86$
Mineral soil (A <sub>p</sub> horizon)		1.0	2.5	0.60	$\leq 0.6$	$\leq 0.60$
Mineral soil (B <sub>v</sub> horizon)		1.5	2.65	0.43	$\leq 0.3$	$\leq 0.43$

#### The swelling and shrinking ability of peat soils

The swelling and shrinking of peat soils is expressed by the coefficient of linear extension ( $\Omega$ ):

$$\Omega = [(\rho_b^*/\rho_b^{**})^{1/3} - 1]$$

where  $\rho_b^*$  is the dry bulk density at wilting point, and  $\rho_b^{**}$  is the dry bulk density at field capacity. In practice,  $\Omega$  is usually measured as the coefficient of linear shrinking and it is assumed that the amount of shrinking is reversible. This assumption is true only in the range of wetness between wilting point and field capacity. In peat profiles, the value of  $\Omega$  of the lower layers is reduced by the load of the overlying material. For peat of medium decomposition (mesofibrous, von Post H4–H6),  $\Omega$ -values usually range from 0.42 to 0.63  $\text{mg m}^{-3}$  for  $\rho_b^*$  oven-dried and  $\rho_b^{**}$  at a matrix pressure of 0.33 bar.

#### 4.4.2 STRESS-STRAIN RELATIONSHIPS, STRENGTH, COMPACTION AND CONSOLIDATION OF PEAT

*The impressions of the steps of a single visitor to a mire will recover very quickly in a mire; the steps of a group of visitors, walking one after the other, will remain for many years (Eggelsmann, 1990).*

The elasticity, plasticity and stress-strain relationships in peat are dependent on the water content, composition of the plant residues, degree of decomposition, ash content, bulk density and plant cover. The *in situ* strength of peat or its ability to withstand mainly shear stresses or strains depends upon the structure of the peat and its water and ash content; it varies between 4.5 and 19.5  $\text{kN m}^{-2}$  over a depth of around 1.5 to 1.8 m below the ground surface. Anisotropy in peat strength is common, with vertical strengths often being up to twice as great as in the horizontal direction.

**Table 4.4** The variation with time of peat compression under load

Time	Load ( $\text{kN m}^{-2}$ )	Void ratio	Hydraulic conductivity ( $\text{m s}^{-1}$ )
0	0	12	$4 \times 10^{-6}$
2 days	60	7	$2 \times 10^{-8}$
7 months	60	4	$8 \times 10^{-11}$

Despite their high water content, mires have a relatively high shear strength owing to the fibrous nature of the peat deposits even when highly decomposed. Hobbs (1986) suggested that the physical stability of mires, and in particular, raised mires, is derived from their high cation exchange ability. This gives the mire a high liquid limit (the point at which peat under pressure begins to flow). The liquid limit decreases as the degree of decomposition increases (Lindsay *et al.*, 1988). Peat under load will be compressed or compacted and the amount of compression depends upon the botanical composition of the peat, its ash, water and gas content and permeability. The possible load for traffic upon drained peat ranges from approximately 20 to 40  $\text{kN m}^{-2}$ . The maximum load is much lower for undrained peat. Under load, peat compression is initially very fast and continues for a long time (Table 4.4). A change in the load may be induced by drainage, particularly as a result of the shrinking of the peat layers. The loss of height  $S$  of a peat body as a result of drainage may be calculated from the relationship:

$$S = a(0.08T + 0.066)$$

Table 4.5 Peat compaction and peat volume (where  $S = a(0.08T+0.066)$ )

$a$ factor	Volume of substance (%)	Compaction
4	< 3	Nearly floating
2.85	3-5	Loose
2.0	5-7.5	Rather loose
1.4	7.5-12	Rather compact
1.0	> 12	Compact

where  $T$  is the initial height of peat (m) and  $a$  is an empirical factor for volume of substance (Table 4.5).

#### 4.4.3 PEAT STRUCTURE AND AGGREGATION

Below the water table, undecomposed peat has a fibrous structure and highly decomposed peat has a massive or coherent structure. Drainage, and the resultant drying, will not change a fibrous peat matrix but will substantially alter a coherent peat matrix, which will break down into structural units of aggregates. For the upper peat layers, the biological activity is generally high as a result of plenty of organic matter, a high oxygen concentration and optimal humidity for organisms. Here, biotic activity results in the transformation of a physicochemical peat matrix structure to a biologically determined, usually crumb, structure. In a highly decomposed, drained peat, the structural arrangement of the peat matrix within 1 m of the ground surface is to some extent determined by land use. For example, under grass the structure is likely to be crumb, very fine granular, subangular blocky to blocky, prismatic and coherent. Alternatively, ploughed land may have a crumb structure which again is very fine granular, subangular blocky to blocky, but is platy rather than prismatic. Peat fibres or peat-derived aggregates are very stable and resist physically disruptive processes such as ploughing. They are, however, light in weight and are, therefore, very susceptible to wind erosion up to diameters of 0.5 to 2 mm (sand grains mainly up to 0.1 mm) (see Chapter 8 for further detail).

#### 4.4.4 PEAT AIR

The air-filled porosity ( $f_a$ ) in any soil is the difference between the total pore volume ( $V_t$ ) and volume wetness ( $\theta = V_w/V_t$ ). For peats at field capacity, the air-filled pores need to be at least 20% by volume to avoid  $\text{CO}_2$  toxicity of the roots of cultivated plants (with the exception of rice). This boundary value is double that of mineral soils and may be explained by the high production of  $\text{CO}_2$  (and  $\text{CH}_4$ ) from the decomposing peat. Atmospheric exchange of the high  $\text{CO}_2$  concentrations in the upper peat layers with oxygen may require double the cross-sectional area for diffusion. In the upper peat layers  $\text{N}_2$ ,  $\text{O}_2$  and  $\text{CO}_2$  dominate. In the peat subsoil, below the groundwater table, the volume of air-filled pores approaches zero. Here the soil environment is anaerobic and the soil air may be composed of  $\text{CO}_2$ ,  $\text{CH}_4$  and  $\text{H}_2\text{S}$ . Carbon dioxide concentrations greater than 3% are toxic.

## 4.4.5 PEAT TEMPERATURE AND HEAT FLOW

Soil temperature determines the rate at which soil physical processes and soil chemical reactions take place in peat. Temperature also determines the activity of organisms (including roots) in the soil. The soil temperature is regulated mainly by radiation emitted by the sun, but the volumetric heat capacities and thermal conductivities of the peat are also important (Table 4.6). These parameters are discussed in greater detail in Section 4.6.

**Table 4.6** The volumetric heat capacities and thermal conductivities of different soil constituents

Constituent	Heat capacity ( $10^6 \text{ W m}^{-3} \text{ K}$ )	Thermal conductivity ( $\text{W m}^{-1} \text{ K}$ )
Quartz	2.0	8.8
Other minerals	2.0	2.9
Peat	2.5	0.25
Water	4.2	0.57
Ice	1.9	2.2
Air	$1.25 \times 10^{-3}$	0.025

Bare peat, because it is dark in colour has a low albedo and absorbs most of the incoming atmospheric radiation during the day; conversely heat energy is readily emitted from peat during the night. Wet peat has a high heat capacity. This means that in comparison with a unit volume of wet mineral soil, an increase in the temperature of a unit volume of wet peat at  $1^\circ\text{C}$  requires *double* the amount of energy transfer. As a result, wet peat warms up very slowly in spring and cools down very slowly in autumn. Dry peat, on the other hand, has a low heat capacity and low thermal conductivity. Therefore, the surface of bare, dry peat may reach a noon temperature of about  $80^\circ\text{C}$  and a night temperature of about  $-10^\circ\text{C}$ . The wide temperature amplitude inhibits seedling emergence and growth (see Section 4.6).

## 4.4.6 PEAT WATER-HOLDING CHARACTERISTICS

**The 'wettability' of peat**

A drop of water placed upon *wet* peat spreads over the surface of the peat. The angle between the water droplet and the peat tends to zero because the wet peat is hydrophilic. On *dry* peat, water drops do not spread, but form contact angles between the water and the peat of up to  $85^\circ$ , especially at low pH values. Thus dry peat is water repellent or hydrophobic. The difference in the wetting behaviour of dry and wet peat influences the pattern of water movement in the peat and the extent to which precipitation infiltrates the peat surface.

### The capillarity and soil moisture characteristic curve of peats

A body of peat has a pore volume that is constructed of pores of different shapes and sizes. Three types of water are generally recognised as forming part of the peat matrix: (i) intracellular water, (ii) tightly bound intraparticle water, and (iii) loosely-bound interparticle (interstitial) water. The last of these is the only source of mobile water in mires under natural conditions. Only micromorphometric methods describe in detail the complicated form of pore systems; of greater relevance for the physics of peat soils are the functions of the pores. To understand the functions of peat pores it is convenient to treat the peat pore system as a bundle of capillaries with different radii, called equivalent pore radii. The coarser the pores, the lower the pressure ( $\Delta_p$ ) required to empty water-filled pores and vice versa. This may be expressed as follows:

$$\Delta_p = (2\tau \cos \alpha)/r$$

where  $\tau$  is the surface tension (at 0°C 75.6 g s<sup>-2</sup> and at 30°C 71.1 g s<sup>-2</sup>),  $\alpha$  is the contact angle, usually assumed to be 0°, and  $r$  is the equivalent pore radius.

Applying increasing pressures and successively evacuating the pore volume of water gives an idea of the pore size distribution or soil moisture characteristic of a body of peat (Figures 4.9 and 4.10). The relationship between pressure (or matric suction) and soil moisture primarily depends upon the degree of decomposition and the composition of the accumulated plant residues. The degree of compaction, or peat bulk density, is also important. The relationship will be influenced by the method of measurement used, that is, whether a sorption or desorption measurement is used. The equilibrium soil wetness at a given suction is greater in desorption than in sorption: this effect is known as hysteresis. In swelling and shrinking soils, each suction has its own pore size distribution. In shrinking soils, the volumes of coarse and fine pores increase and the volume of medium sized pores decreases (and vice versa for swelling soils).

Plants are unable to exploit all the water present in the soil matrix. In coarse pores ( $\Delta_p \leq 100$  mbar ( $10^4$  Pa);  $2r \geq 30$   $\mu$ m) water drains faster than plants can use it. This is known as the air-filled porosity at field capacity. In fine pores ( $\Delta_p \geq 15$  bar;  $2r \leq 0.2$   $\mu$ m) water is strongly held by the soil constituents or capillary action; this fraction is known as the non-available water capacity. As a result, at  $\Delta_p \geq 15$  bar ( $15 \times 10^5$  Pa), higher plants begin to wilt irreversibly (permanent wilting point) and die. Water held in the soil against gravity (assuming free drainage is possible) is known as the field capacity. Field capacity minus the non-available water capacity gives the available water capacity of the soil. The soil moisture tension or pressure at which a plant begins to wilt depends upon the plant species, the plant environment and the texture or pore size distribution of the soil which determines whether drainage will stop at  $\Delta_p = 33$  mbar (in sand) or 100 mbar (in loam and clay).

### The peat water potential

A plant using soil water has to use energy. This is calculated from the relationship:

$$\psi = \Delta_p \theta$$

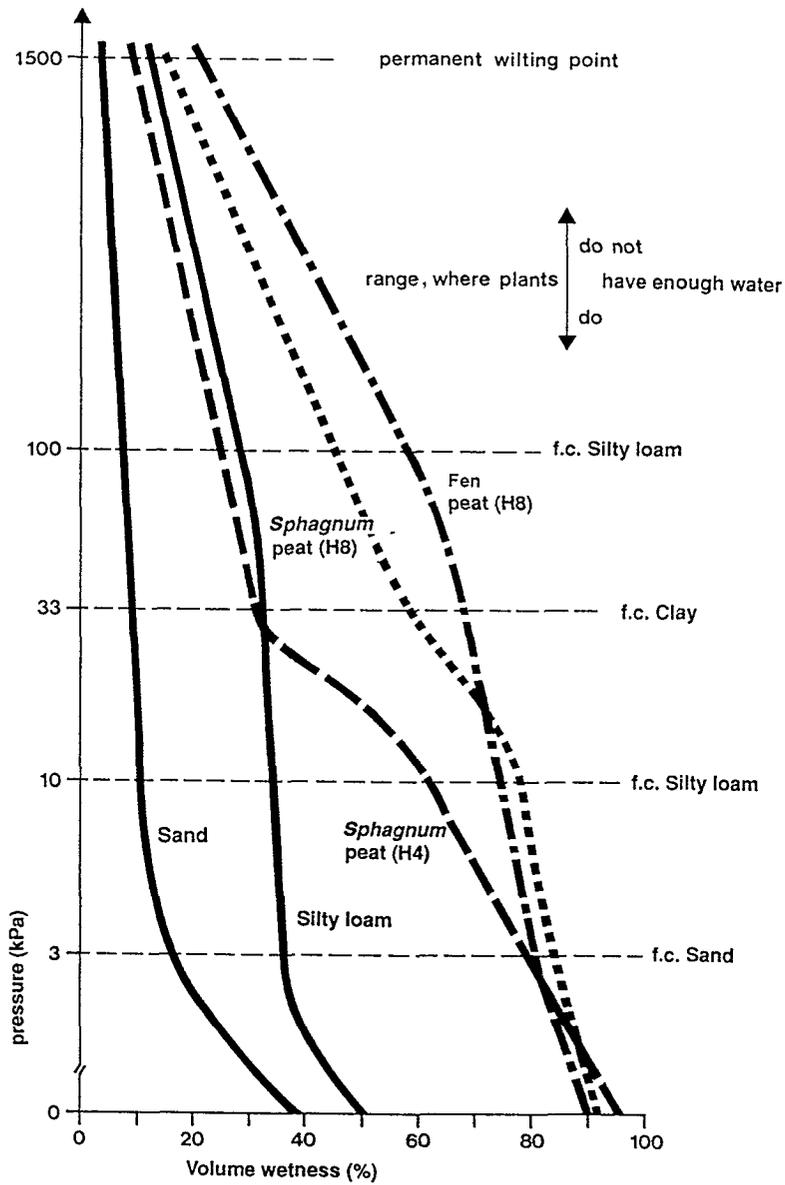


Figure 4.9 Summation curves of volume wetness against pressure for sand, silty loam, *Sphagnum* peat at H4 and H8 degrees of decomposition, and fen peat at H8 degree of decomposition (f.c. = equilibrium pressure at field capacity)

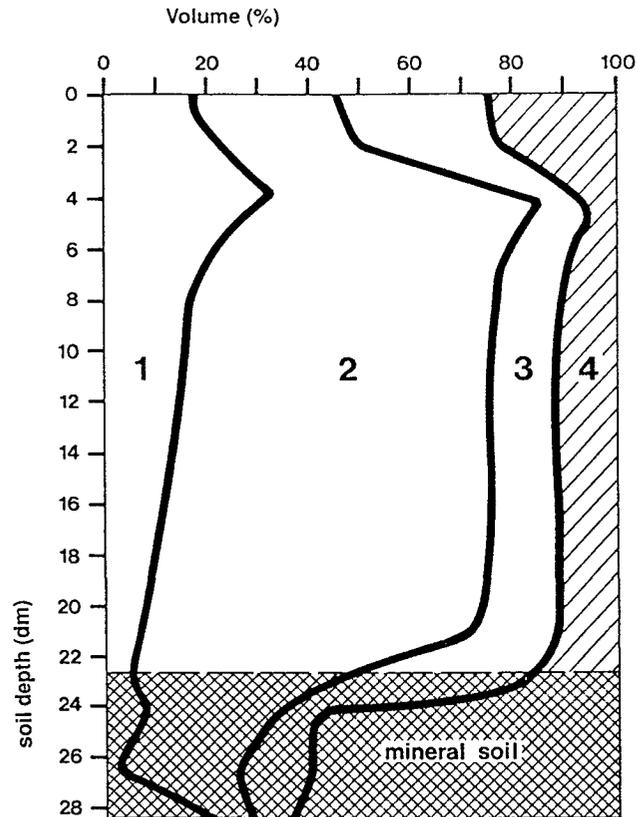


Figure 4.10 Volumes of solid material versus depth for *Sphagnum* peat over mineral soil: (1) pores  $>30 \mu\text{m}$ ; (2) and (3) pores  $0.2\text{--}30 \mu\text{m}$ ; (4) pores  $<0.2 \mu\text{m}$

Pressures (or suctions) may be initiated by: (i) the soil matrix ( $w_m$ ), (ii) gravity ( $w_g$ ), (iii) osmotic pressure ( $w_o$ ) determined by the salt content of the soil solution and a semipermeable membrane in the cell walls of the root, or (iv) volume changes (e.g. swelling pressures,  $w_s$ ).

These variables determine the direction of the pressure or suction gradient in the soil and hence the direction of flow of water. However, in the atmosphere-plant-soil system, it is usually more convenient to describe the flux of energy through the system. The energy flux is usually based upon the unit volume or unit mass of soil which exerts a 'specific energy' or 'potential' on a plant exploiting the available soil water. The overall potential  $\psi_t$  of a soil volume may be defined as:

$$\psi_t = \psi_m + \psi_g + \psi_o + \psi_s + \dots (\text{and others})$$

In swelling and shrinking soils such as peat, the unit volume is derived from the mean maximum volume of the swollen soil. In moderately decomposed peats, most of the water will be removed from water-filled pores between 1 and  $20 \mu\text{m}$  diameter—a pore size range commonly recorded in peats. Thus much of the peat water must be retained

by capillary forces, but, the wilting point ( $-20$  bar or  $-20 \times 10^5$  Pa) is well below the equilibrium water potential in most peats and is unlikely to be reached. In highly decomposed peats, the proportion of water with a water potential below the wilting point increases (Boelter, 1969).

### The flow of water in peat

Water flows through peat in pores that are not uniform and smooth but highly irregular, tortuous and intricate. The flow of fluids in a peat matrix may be described by a macroscopic flow velocity vector similar to that used in rivers where the overall flow is usually more important than the flow pattern in cross-section. The rate of horizontal flow (or flux)  $Q$  is defined, according to Darcy's Law, as:

$$Q = -k(\delta h/\delta l) \quad \text{or} \quad Q = V/ft \quad (\text{cm}^3 \text{ s}^{-1})$$

where  $\delta h/\delta l$  is the hydraulic gradient for head difference ( $h$ ) over the length of sample ( $l$ ),  $k$  is the hydraulic conductivity or coefficient of proportionality ( $\text{cm s}^{-1}$ ) and  $V$  is the volume of soil water moving across cross-sectional area  $f$  in time  $t$ .

The hydraulic conductivity depends mainly on the geometry and distribution of the water-filled pores. It is low when the water has to follow a tortuous path through fine pores. This is generally the case when the soil moisture content is low since, under these conditions, the soil water is mainly present in the finer pores which form irregular hydraulic continuity with many 'bottle-necks'. Under saturated conditions, the hydraulic conductivity ( $k_{\text{sat}}$ ) reflects differences in the geometry of the total pore space of the soil and is, therefore, well correlated with soil texture and structure. The presence of 'bio-pores' or macropores such as root channels and worm holes are also important. The hydraulic conductivity not only depends upon the soil but also on the characteristics of the fluid, including:

- (i) *Viscosity*—the more viscous, the lower the flux.
- (ii) *Fluid density*—the more dense, the lower the flux.
- (iii) *Polarity of the fluid particles and the density of the electrical charge on the matrix surfaces*—the higher the dielectric constant and the higher the density of charge (which is high in peat), the lower the flux due to adsorption.
- (iv) *Phase*—whether the fluid is liquid or gaseous. The velocity of the fluid flow on the surface of a matrix is zero for liquids and higher than zero for gases.

Both field and laboratory methodologies exist for evaluating the peat saturated hydraulic conductivity (Luthin, 1957; Boersma, 1965; Bouwer and Jackson, 1974). They are based on the principle that the hydraulic conductivity may be inferred from the measurement of the rate of change of hydraulic head ( $\delta h/\delta t$ ) under imposed conditions.

Laboratory measurements of the saturated hydraulic conductivity have the advantage of allowing the control of environmental parameters such as temperature and aeration. However, the problems of sample disturbance, sample size and the field applicability of

the results must be addressed. Furthermore, Boelter (1965), Irwin (1968) and Päivänen (1973) found that the laboratory evaluation of peat hydraulic conductivity yielded higher results than field evaluation, probably as a result of a non-constant rate of water flow (Sarasto, 1961) owing to leakage and soil disturbance. Waine, Brown and Ingram (1985), using *Sphagnum* peats of low decomposition, suggested that the discrepancy recorded in laboratory tests may be evidence of non-Darcian flow. These authors found that the saturated hydraulic conductivity decreased with time during the course of the experiment. They attributed this to the evolution of H<sub>2</sub>S in the outlet water and microbial pore-blocking. Mathur and Levesque (1985) and Galvin and Hanrahan (1967) made similar observations.

Field measurements of the saturated hydraulic conductivity of peats ensure minimum sample disturbance and have a larger effective sample size. However, the control of environmental variables is limited. Two basic field methodologies exist: the auger hole method (Kirkham and van Bavel, 1948) which is discussed further by Ernst (1950) and Boast and Kirkham (1971), and the seepage tube or piezometer method (Kirkham, 1946; Luthin and Kirkham, 1949). The auger hole method measures the saturated hydraulic conductivity mainly in a horizontal direction, whereas the seepage tube method may be used to determine the hydraulic conductivity in a primarily vertical direction. One of the key problems with the use of the auger hole technique in peats is that it averages the saturated hydraulic conductivity over the depth of the perforated well that is used to make the measurements. If the well penetrates different peat layers, for example the division between the acrotelm and the catotelm, unrealistic results will be obtained. Mathur and Levesque (1985) suggest that the length of the auger hole is probably more important in producing variable hydraulic conductivity readings than the degree of decomposition or the bulk density of the peat. The authors note that particular problems are likely to be encountered with the field measurement of the saturated hydraulic conductivity where anaerobic lower peat layers are included because gas bubbling from anaerobic zones and air introduction to these zones will affect the results. Alternatively, the seepage tube method by confining measurement to a single peat layer enables some evaluation of the influence of the degree of decomposition, bulk density and depth on the peat saturated hydraulic conductivity. Boelter (1965), modifying Luthin and Kirkham's (1949) piezometer technique for use in organic soils, found that it gave reasonable results, although a wide degree of variation was recorded. Päivänen (1973) found a similar wide variation in results obtained using this method. Irwin (1968), Dai and Sparling (1973), Päivänen (1973) and Rycroft, Williams and Ingram (1975b) all report difficulties in obtaining a satisfactory cavity in the peat, which is a requirement of this technique (Luthin and Kirkham, 1949). Päivänen (1973) and Heathwaite (1987) adapted the seepage tube method by incorporating a densely perforated plastic tube to achieve a more stable cavity shape. A stable cavity shape is essential in order to maintain constant hydraulic head throughout the course of the experiment. Rycroft, Williams and Ingram (1975b) suggest that seepage tube experiments should be conducted for more than 1000 minutes in order to achieve reproducible results. The techniques and their applicability to measurement of the saturated hydraulic conductivity in peat soils are reviewed in greater detail by Heathwaite (1987).

The hydraulic conductivity of peat deposits varies with the degree of decomposition of the plant remains (Rycroft, Williams and Ingram, 1975a; 1975b). Undecomposed peats have a high hydraulic conductivity which is of the order of  $10^{-1}$  to  $10^{-3}$  cm s<sup>-1</sup> and

the flow of water through such peats fairly closely approximates Darcy's Law (Ingram, Rycroft and Williams, 1974). In highly decomposed peats, the hydraulic conductivity is reduced to around  $10^{-6}$  cm s<sup>-1</sup> and the flow of water may deviate from Darcy's Law (Rycroft, Williams and Ingram, 1975b; Hemond and Goldman, 1985). The hydraulic conductivity decreases in highly humified peats because the proportion of physically bound water increases as the pore size decreases. This may result in non-linear behaviour or non-Darcian flow in amorphous peats as a result of (i) pore blocking, resulting in a diminished ability of the peat to transmit flow, and (ii) fluid mechanical effects, including compression and debris transport under experimental conditions (Hemond and Goldman, 1985).

The distinct hyperbolic relationship between the saturated hydraulic conductivity and degree of decomposition is shown in Figure 4.11 (after Baden and Eggelsmann, 1963) which gives typical hydraulic conductivities for peats composed of *Sphagnum*, *Carex* or *Phragmites* plant residues. The relationship is more pronounced for *Sphagnum* peat than

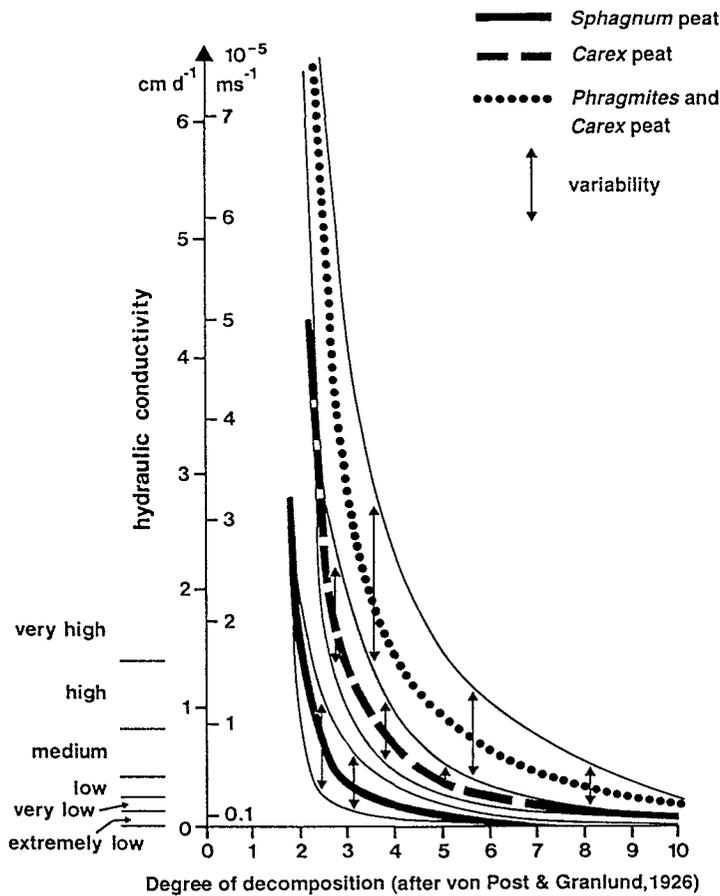


Figure 4.11 Relationship between hydraulic conductivity and degree of decomposition for different peat types

for *Phragmites* or *Carex* peat deposits. Ingram (1983) described a botanical sequence from high to low saturated hydraulic conductivity: *Phragmites* > *Carex* > Hypnoid mosses > *Sphagnum*.

Peat deposits usually accumulate as layers of plant residues which exhibit pronounced lamination with respect to the developmental sequence from fen through to raised mire (see Section 4.3); such layers are commonly anisotropic, hence the hydraulic conductivity is different for the vertical and horizontal direction. At the microscale, the horizontal orientation of, for example, *Sphagnum* leaves on decay may introduce marked anisotropy into the resultant peat medium. The flux of water in the vertical direction is:

$$Q = (k\Delta_p/l) + k$$

The flow in a composite column with different  $k$  values for two layers with lengths  $l_1$  and  $l_2$  and hydraulic conductivities  $k_1$  and  $k_2$  is:

$$Q = (\Delta_p/(l_1/k_1 + l_2/k_2))$$

The hydraulic conductivity of peat deposits decreases with increasing bulk density (Korpijaako and Radforth, 1972; Bloemen, 1983), largely as a result of an increase in peat bulk density that results from an increase in the degree of decomposition (Table 4.7, after Heathwaite, 1987). A number of techniques have been introduced to indirectly estimate the hydraulic conductivity of peat soils (see Section 4.2.2). However, Päivänen (1973) and Bloemen (1983) suggest that the indirect evaluation of peat hydraulic conductivity on the basis of definitive criteria such as bulk density and degree of decomposition is limited. Chason and Siegal (1986) conclude that 'hydraulic conductivity, bulk density and humicity all vary widely throughout the peat profile and in most cases are not mutually dependent'. Thus the direct evaluation of the saturated hydraulic conductivity in the field is more likely to yield representative results. Tables 4.8 and 4.9 indicate the variation in the physicochemical characteristics of the peats from two fen sites in West Sedgemoor, the Somerset Levels, England. According to Wheeler's classification of British Fens (Wheeler, 1984), the peat deposit is a soligenous valley fen. Both sites were drained; site A in 1979 and site B in 1972. An increase in the bulk density with increasing period of drainage is evident (Table 4.8); the site drained first had an average bulk density of  $0.35 \text{ g cm}^{-3}$  whereas the more recently drained site (drained for a period of 6 years at the time of measurement) had a bulk density of  $0.27 \text{ g cm}^{-3}$ . The two sites are only

**Table 4.7** The influence of bulk density on the hydraulic conductivity of fen peats (after Heathwaite, 1987; Bloemen, 1983)

Bulk density ( $\text{g cm}^{-3}$ )	Hydraulic conductivity ( $\times 10^{-6} \text{ cm s}^{-1}$ )
0.05	1680.0
0.15	26.7
0.25	3.8
0.35	1.1
0.45	0.4

**Table 4.8** Physico-chemical characteristics of West Sedgemoor fen peat soils (after Heathwaite, 1987)

Site	Depth (cm)	Texture	von Post	Bulk density (g cm <sup>-3</sup> )
<b>A:</b> drained 1979	0-20	Silty clay	n/a	0.99
	20-100	Mesofibrous	H6	0.20
	100-250	Amorphous	H10	0.27
<b>B:</b> drained 1972	0-30	Silty clay	n/a	1.09
	30-140	Amorphous	H9	0.31
	140-170	Amorphous	H9	0.32
	170-240	Amorphous	H9	0.35

**Table 4.9** Physico-chemical characteristics of West Sedgemoor fen peat soils (after Heathwaite, 1987)

Source	Method	Material	Depth (cm)	Hydraulic conductivity (× 10 <sup>-6</sup> cm s <sup>-1</sup> )
MAFF	Single auger hole	Silty clay over peat	80	160-750
Kellett (1975)	Laboratory core	Silty clay over peat	30-40	8-70
		Amorphous peat	30-40	0.1-0.6
Heathwaite (1987)	Single auger hole	Silty clay over peat	200	4.6-23.0 <sup>a</sup>
		Silty clay over peat	200	0.3-2.3 <sup>b</sup>

<sup>a</sup> Site A: drained 1979<sup>b</sup> Site B: drained 1972

300 m apart from one another. Drainage increased the bulk density of the peat as a result of the decrease in the pore size arising from an enhanced rate of decomposition in the drained, aerated peat. Table 4.9 indicates the hydraulic conductivity results for the two fen peat sites (after Heathwaite, 1987) in comparison with other data from West Sedgemoor (Kellett, 1975; MAFF, 1982, cited in Heathwaite, 1987). The results given by Heathwaite (1987) were obtained using a rising head pumping test, based on an auger hole method modified from Kirkham and van Bavel (1948). Kellett (1975) produced similar results using a laboratory core procedure. However, the MAFF results are considerably greater than those of either Heathwaite (1987) or Kellett (1975). This may be because the MAFF experiments were conducted for the upper 80 cm of the peat alone where the peat is mesofibrous to amorphous rather than wholly amorphous (Table 4.8). These results indicate some of the difficulties in obtaining reproducible results in the field. The hydraulic conductivity results for the West Sedgemoor peats show a close correlation with the results of Romanov (1968) shown in Table 4.10, although Päivänen (1973) and Baden and Eggelsmann (1963) give considerably higher values for the hydraulic conductivity of highly humified peat deposits.

**Table 4.10** The influence of degree of decomposition on the hydraulic conductivity of fen peats (after Heathwaite, 1987)

Degree of decomposition	von Post	Hydraulic conductivity ( $\times 10^{-6} \text{ cm s}^{-1}$ )		
		Päivänen (1973)	Baden and Eggelsmann (1963)	Romanov (1968)
Fibrous	H1-H3	2100	1620	5000
Mesofibrous	H4-H6	660	390	800
Amorphous	H7-H10	120	110	10

## 4.5 PEAT HYDROLOGY

### 4.5.1 THE ECOHYDROLOGY OF MIRIS

#### Mires in their original state

Undisturbed mires, from a geographical or hydrological viewpoint, occupy an intermediate position between land and open water; they are neither one nor the other. From a soil science viewpoint, Table 4.11 compares the volumetric percentage water content of a lake, three raised mire ecosystems and three mineral soils at field capacity. Despite having a water content as high as 97% by volume, one cannot traverse a mire by canoe and only with difficulty can one advance on foot from hummock to hummock while in the hollows one may sink to above the ankle or even knee-deep.

**Table 4.11** A comparison of the volumetric water content (%) of a lake, raised mire ecosystem and mineral soil

Lakes	Raised mires			Mineral soils at field capacity		
	Growing	<i>Calluna</i> stage	Grassland meadow	Clay	Loam	Sand
100	97	93	85-75	48	35	10

The ecosystems of mires with different flora and fauna all have one predominant characteristic: their close interrelationship with the water balance. The term 'ecohydrology' was first used by Göttlich (1977a). The ecohydrological aspects of mires belong to landscape ecological research which is concerned with the identification of

the interactive elements and functions of a system in terms of 'landscape units'. The same principles were laid down by Odum (1973) who maintained that 'the structure and function of an ecosystem can best be researched together'. Ellenberg (1973) also saw this as the focus of future ecological research. The term ecohydrology is used here to demonstrate that the ecosystem of a mire, or of any part of a mire, cannot be definitively evaluated unless account is also taken of its water balance. Ivanov (1981) emphasised the importance of hydrology in the stability of mires. He identified the link between the slope, surface patterns and vegetation in mires, and showed that the stability of the surface layer or 'acrotelm' (see below) of a mire determines the ability of the mire massif to exchange water and the intrinsic stability of the mire to adjust to changes in the water balance. The stability of a mire is, therefore, ensured by its 'microtopes' (after Ivanov, 1981) or its 'strip and ridge' pattern (Lindsay *et al.*, 1988). The vegetation both generates and then is controlled by the surface pattern. Such patterns are the main source of hydrological stability within a mire. Hence an understanding of the hydrology of a mire is essential in its conservation and management.

Ingram (1983) extended the work of Ivanov (1981) and Romanov (1968), and the earlier studies of Granlund (1932) and Wickman (1951) on mire hydromorphology, to relatively undisturbed raised mires in Scotland. He applied the general soil science concepts for hydromorphic soil types, having an oxidation and reduction horizon. From a pedological viewpoint, peat formation can be considered as a transformation process in which the upper and lower strata of the profile are treated as two completely separate soil horizons; the upper part of the profile is the active horizon, and the lower, the inert horizon. Since these terms are misleading in several respects—the 'inert' horizon has a hydrological function and is also the rhizosphere of many deep-rooted mire plants—it is better to substitute terminologically neutral terms. The artificial words 'acrotelm' and 'catotelm' suggested by Ingram (1983) are used here. The Ground Water Mound Theory developed by Ingram (1982), is essentially concerned with the lower layer of peat in a mire: the 'catotelm'. The catotelm gives the mire its overall shape and was described by Ivanov (1981) as the 'inert layer' because it has a constant or little changing water content, a slow exchange of water with the surrounding mineral strata and a low hydraulic conductivity (see Section 4.4) which may be up to five orders of magnitude lower than that of the upper peat layer. Furthermore, in the catotelm microbial activity is extremely low (see Chapter 6), largely as a result of the limited access of atmospheric oxygen. The upper surface layer of peat, or the 'acrotelm' (Ivanov, 1981; Ingram, 1982), is a shallow (10–15 cm) peat layer which includes the living surface vegetation of the mire. In this layer water movement is rapid as a result of the low degree of decomposition of the peat (commonly von Post H1–H3). Ivanov (1981) termed this layer the 'active layer' according to the intensive exchange of moisture with the atmosphere from this layer, the frequent fluctuation of the water table within this zone and the high hydraulic conductivity and water yield. In the acrotelm, microbial activity is usually high owing to a large population of aerobic bacteria relative to the catotelm (Figure 4.1). The upper limit of the acrotelm should be drawn where capillary and swelling forces become negligibly low on the surface of a coherent cover of root-fibre or dense moss carpet. The status and function of both these horizons are given in Table 4.12. The acrotelm–catotelm strata of most raised bogs in western Europe have been destroyed by peat removal (see Chapter 7) and drainage (Chapter 8). For growing (living) fens, the strata are not yet proved.

**Table 4.12** Status and function of the peat horizons of living mires (after Ingram, 1983)

Position of horizon	Upper	Lower
Designation	Acrotelm	Catotelm
Energy exchange	Rapid	Slow
Substance transformation	Rapid	Slow
Water table	Present	Absent
Water content (over time)	Variable	Constant
Water permeability (over depth)	Very variable, greatest at surface	Slight, relatively constant
Water movement (after Darcy)	Yes	No
Aeration	Periodic aerobic	Constant anaerobic
Peat forming activity (of aerobic bacteria)	High	None
Macroflora	Nutrient soil for living plants	Dead, except for roots

#### 4.5.2 THE HYDROLOGICAL PREREQUISITES FOR PEAT FORMATION

The decisive prerequisite for continuous peat deposition in a 'growing' or 'living' mire is that a milieu for decomposition processes of a certain intensity should have existed during a limited time period. When the dead and decomposing plant material finally enters the deep, permanently waterlogged, reducing zones the microbial transformations are largely brought to a halt and the stage of humification which has been reached is permanently preserved (Sections 4.1 and 4.2). Continuous peat deposition is possible only when the decomposition process is halted so that the lowest layer of the acrotelm becomes the uppermost layer of the catotelm. From this, it follows that a continuous rise of the (mire) water table is the decisive prerequisite for peat formation. In raised mires, such conditions are imparted by the water-holding capacity of the upper moss vegetation and the lower peat deposits. But even in sloping and spring-water mires, the plant cover and the resultant peat, which, relative to most mineral deposits, has a low hydraulic conductivity, have a profound effect on the water table; with increasing peat deposition, the upper limit of the catotelm also rises so there is a positive feedback between mire growth and water table rise. An increase in the height of the groundwater table can also result from external inputs. In this case, the growth rate of a mire is directly determined by the rate of water table rise. Examples of external influences are a water table rise in the vicinity of large bodies of water (including sea transgression), the effects of pumping or damming watercourses (see Koerselman, 1989a), the growth of a neighbouring raised, sloping or spring water mire, and the damming of outfalls. External hydrological factors may also operate when, for example, local subsidence (tectonic or caused by karst phenomena) takes place; here only a relative water table rise occurs. Subsidence effects can also occur where the increasing weight of newly formed peat results in the compression of the lower existing peat layers. In terrestrialised mires, this 'downward mire growth' may be important over long periods of time but it must also be important in all mires in which mire development began with the initial deposition of very loose 'floating' peats. At some stage in the mire development further loading must no longer increase the compression of the underlying peats. Once this occurs no further

decomposing plant material will be 'forced down' into the deeper, reducing layers of peat and the originally positive plant material balance will give way to an equilibrium between the formation of new organic matter and its decomposition. Mire growth has then reached its natural end (see Chapter 1 for discussion of some of the earlier theories of mire development). In ecological and pedological terms, this stage of stagnating mire growth, which in transitional mires and fens is characterised by swamp forest vegetation, is intermediate between drained and growing mires.

#### 4.5.3 THE HYDROPHYSICAL STRUCTURE OF MIRES

Ivanov (1981) identified a four-tier hierarchy of functional hydrology in mires: macrotope, mesotope, microtope and microform. These features, which are examined in more detail in Chapter 1, are essentially morphological, with the exception that, in Ivanov's view, they are active: they both control, and are controlled by, the hydrology of the mire. At the largest scale, macrotopes, such as the blanket mires of the South Pennines, England, and the raised mire/blanket mire complex of Silver Flowe, Galloway, Scotland, are intricate hydrological systems encompassing a series of mesotopes on which they depend for their stability. Mire mesotopes may represent a single raised mire or a spring-fed mire system, whereas the microtope describes, for example, the ridge-and-pool topography of the raised mire. Finally, the mire microform represents the smallest unit of functional hydrology such as a single hummock or hollow within the mire expanse. Although this approach is of value in identifying the role of hydrology at different mire scales, it is practically limited by the problems of identifying boundaries between, for example, mesotopes in the more or less continuous blanket mire expanse. Despite these limitations, the classification system used for mire units in Britain is broadly based on the mire mesotope (Lindsay *et al.*, 1988) and employs a hydromorphological basis (Goode and Ratcliffe, 1977; see also Chapter 1).

#### Hydrological mire types

Hydrological conditions are an important influence on the composition and stratigraphy of mires. Succow (1980), from a historical hydrological development perspective, classified mires as shown in Table 4.13. Two or more mire types frequently occur in combination.

**Table 4.13** Hydrological mire types in the former GDR (after Succow, 1980)

Classification number	Mire type	%
1	Paludified mire	35
2	Anmoor (mineral peat)	25
3	Flooded mire	5
4	Stream traversed mire	20
5	Spring water mire	1
6	Sloping mire	5
7	Kettle mire	6
8	Rainwater mire	3
Total		100

For example, a valley mire may be a complex of spring-water mires and flooded mires, a 'watery mire' may be a complex of terrestrialised and paludified mires, and a meadow mire may be a complex of flooded and terrestrialised mires in an ancient river bed. Models of the peat and plant communities and the water regime of four typical mires (after Kuntze and Eggelsmann, 1981) are presented in generalised form in Figures 4.12 to 4.15. The figures are based on the results of a large number of hydrological observations made in the lowlands of northern Germany. The vertical scale of Figures 4.12 to 4.15 is exaggerated about 100-fold in relation to the horizontal scale.

#### *Lowland mires*

The lowland raised mire depicted in Figure 4.12 has a uniform water regime. The high groundwater table was the main reason for the formation of the mire, and its importance continues to be demonstrated in the existence of the mire pool. The depth of the water table under the soil surface is affected by the drains and the stream, together with seasonal fluctuations in rainfall inputs. In winter, the water table is a few decimetres higher than in summer. The catena of hydromorphic soil types, gley and mire-gley together with terrestrialised mire-gley, podsol-gley and gley-podsol, has evolved as a result of the high water table. Furthermore, the plant communities and type of land use (arable or grassland) also depend on the depth of the water table. Koerselman (1989a) examined the water balance of a small quaking fen in The Netherlands. He found that the fen was a natural source of groundwater discharge. However, modification of the hydrology of the catchment through pumping resulted in the reversal of the natural flow pattern so that groundwater recharge from the catchment to the fen occurred. Such changes illustrate the sensitivity of mires to human modification (see Chapter 8) and highlight the risk of the nutrient enrichment of mires from contaminated groundwater sources (see Chapter 5).

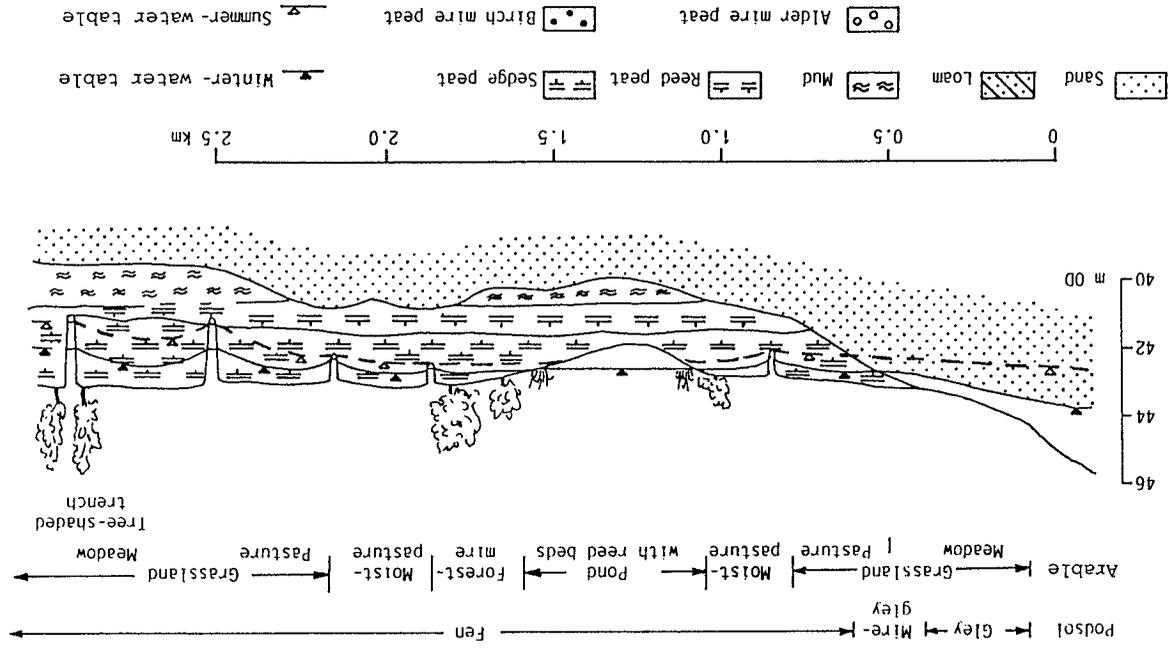
#### *Spring-water fens*

Figure 4.13 shows schematically the groundwater regime of a spring-water mire with its soils and plant communities. The overriding influence of groundwater on the lowland spring-water mire is evident. Similar research results from groundwater conditions in fens have been reported from Schleswig-Holstein, Mecklenburg and North Rhine-Westphalia (Göttlich, 1977a), and by Gilvear *et al.* (1992) for East Anglian fens. In general, the groundwater regime of fens is closely integrated with their topographic surroundings and in many cases has been the main cause of the original fen formation (Shaw and Wheeler, 1992).

#### *Raised mires*

Even where a raised mire is formed above a fen some inflow of groundwater may be expected. In northwest Germany, raised mires have evolved more frequently than is generally assumed, either wholly or partially over fens. For example, of 64 raised mires examined in Lower Saxony, two-thirds had formed over previously paludified mineral soils in which forest peat formed at the base of the mire (Eggelsmann, 1967). Groundwater from the mineral soil may be expected to penetrate the layers of forest peat (groundwater intrusion, Koerselman, 1989b). The effect on recent vegetation will of course be limited

Figure 4.12 Groundwater regime of a lowland raised mire with variable soil and vegetation cover (vertical scale exaggerated 100-fold)



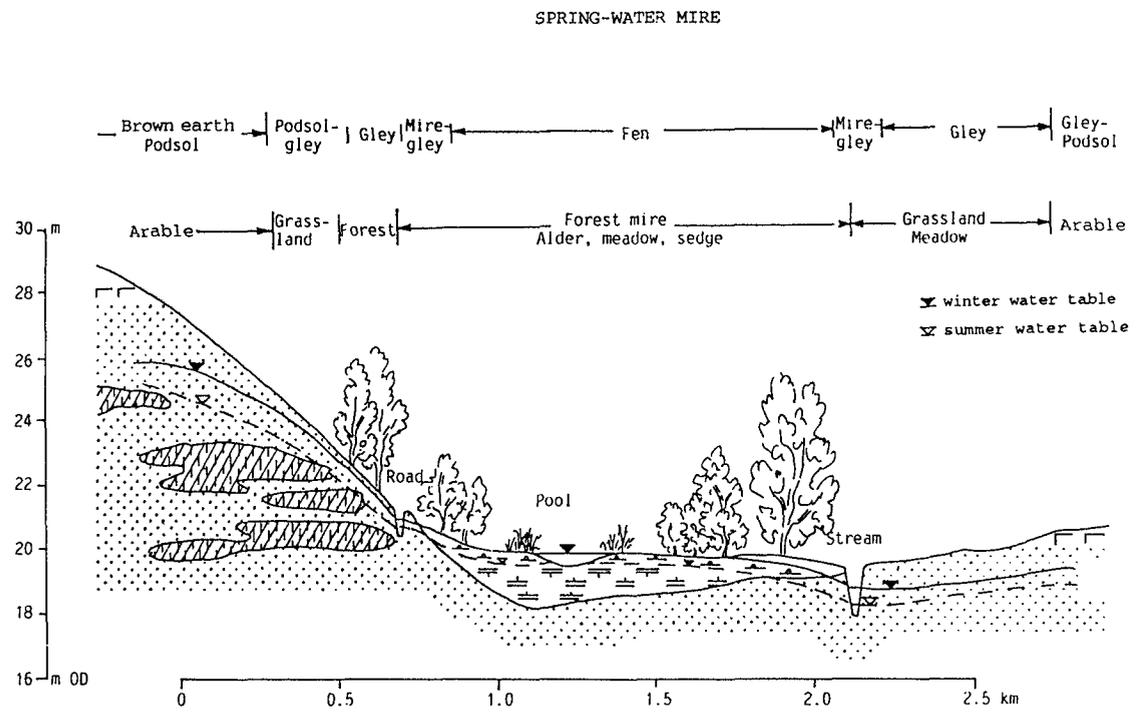


Figure 4.13 Groundwater regime of a spring-water mire with different soil and vegetative relations (vertical scale exaggerated 100-fold)

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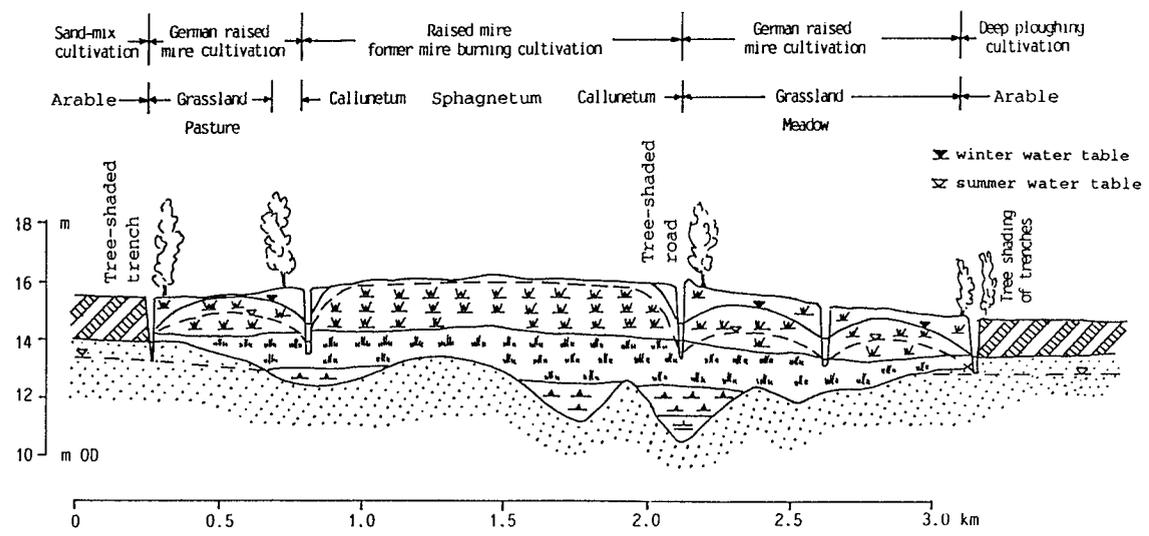


Figure 4.14 Groundwater regime of a typical northwest German raised mire where peat is not industrially exploited (vertical scale exaggerated 100-fold)

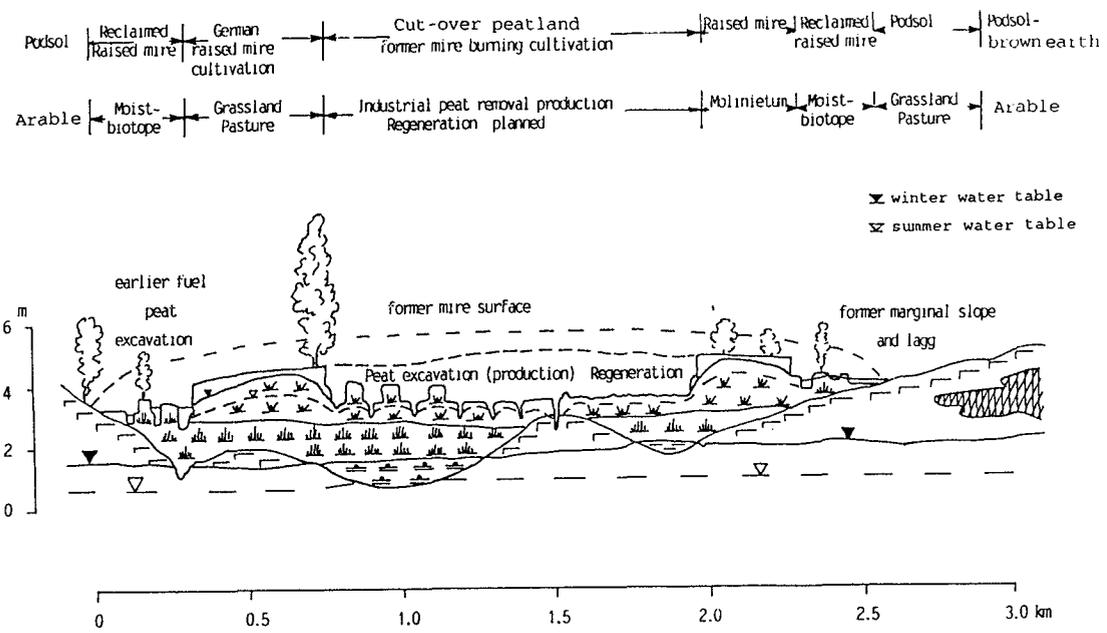


Figure 4.15 Groundwater regime of typical northwest German raised mire from which peat is being industrially extracted (vertical scale exaggerated 100-fold)

6 0 7 0 3 0 - D

if the thickness of (older) highly decomposed black peat, which is only very slightly water permeable, is greater than 50 cm. In Figure 4.14, which shows a section of a typical raised mire, there is probably an inflow of groundwater into the hollows in the mineral soil. Figure 4.15 shows the topographic and hydrological relationships for a raised mire from which the peat is being extracted.

The natural topographic gradients of raised mires in Germany are shown in Figure 4.16. In the upper half, the cross-section shown is based on average values for 64 raised mires in Lower Saxony before 1900; in the lower half it is based on average values for 28 characteristic raised mires in Bavaria. The typical domed surface of raised mires is in sharp contrast to the fens. The gradient of raised mires clearly distinguishes the high central expanse from the marginal slope. The raised mires of Bavaria are smaller in extent (length and breadth) than those of Lower Saxony and, in contrast to the latter, have steeper surface gradients. The morphology of the mires in Lower Saxony has been profoundly changed during the last 100 years by drainage, cultivation and peat removal. Many of the raised mires in southern Germany, because of their low economic significance and high precipitation amounts, are still relatively undisturbed and are now for the most part conserved. In the older mire literature (Eggelsmann, 1967), superficial erosion furrows or rills are described as a characteristic of the raised mires of the north German plains. Such rilling clearly shows that quite considerable quantities of water flow from raised mires during periods of heavy rainfall and snowmelt as a result of saturation-excess overland flow. This has been confirmed by hydrological investigation of the Esterweger Dose on the Coastal Canal (Uhden, 1967). Similar, although less extensive conditions, are found in raised mires in southern Germany. The runoff characteristics from mire catchments in Britain are examined by Burt, Heathwaite and Labadz (1990).

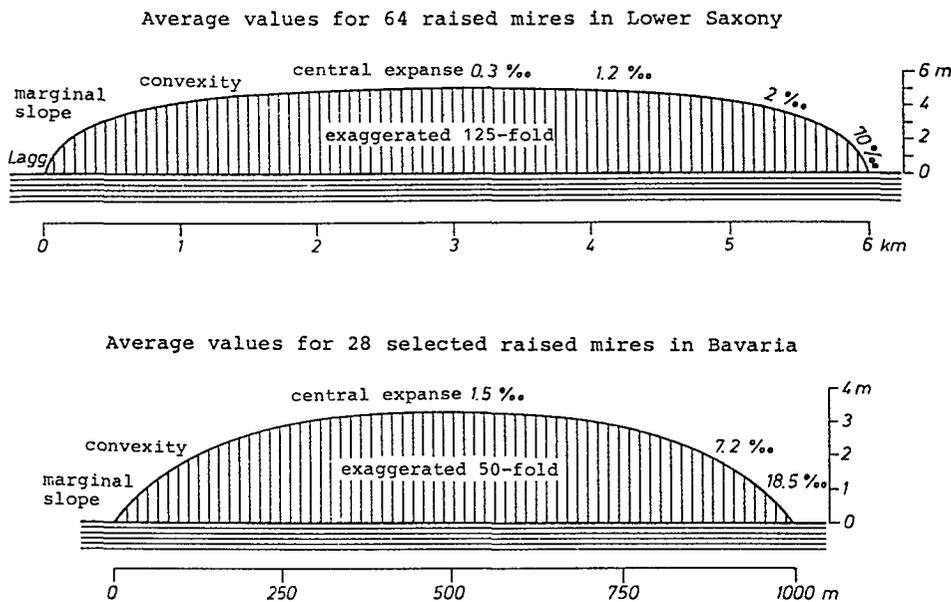


Figure 4.16 Surface gradients of raised mires in Lower Saxony and Bavaria (note the different vertical and horizontal scales)

*Mountain mires*

The surface gradients of mountain raised mires (for example, in the Harz, Solling, Hohen Venn, Schwarzwald, Rhon, Riesengebirge and Sudeten mountains), at 30% to 150%, are clearly steeper than those of the raised mires of the plains. Hydrological observations suggest that following heavy rainfall, mountain mires yield large volumes of runoff over a short period of time and, therefore, both surface and subsurface rills and soil pipes may form (Uhden, 1972; Ferda, 1973; Benne, 1977).

## 4.5.4 THE WATER BALANCE

The water balance of a mire may be expressed by:

$$P = D + E + (R - C) \text{ mm}$$

where  $P$  = precipitation,  $D$  = discharge,  $E$  = evaporation,  $R$  = reserve,  $C$  = consumption  $R - C$  storage.

Where there is an inflow of intrusive water ( $I$ ), the formula is expanded to:

$$P + I = D + E + (R - C)$$

More simply, the water balance can be expressed as:

$$\text{influx} - \text{efflux} - \text{change in storage} = 0$$

The water balance of a mire consists of four main compartments: (i) atmospheric inputs, (ii) the mire matrix, (iii) the adjacent mineral soil and parent material, and (iv) the hydrological network. Monitoring the flux of water between these different compartments is not easy. Evaporation and some components of water supply, for example groundwater, soil moisture and snow, are difficult to measure and are also influenced by a large number of environmental factors, including vegetation, soil and aspect, which are highly variable both within the catchment of the mire and the mire itself. Ingram (1983) suggests that the key water balance processes important in evaluating the complex pattern of water transfer in a mire are: precipitation, seepage, pipe (or fissure) flow, surface runoff, channel flow and evapotranspiration. These processes will be examined in more detail in Sections 4.5.5 to 4.5.8 below.

**The water balance of mire and mineral soils**

The monthly water balances for different catchments in Germany, with and without mire areas, are shown in Figure 4.17. The graphs comprise: precipitation, runoff, evaporation and water supply, according to the formula given above. These average monthly water balances for quite different German catchments, illustrate the opposing effects of precipitation and evaporation throughout the year on runoff and on the increase and decrease of the water supply in the soil and in the groundwater. They show in detail the climatic differences, for example, between central, western and southern Germany. These are far greater than the water balance differences between mire and mineral soils. The changes in water supply ( $R - C$ ) and in the groundwater are almost the same in the mineral soils of the Upper Ems, northwest Germany as in the drained and cultivated peats of Königsmoor, southwest of Hamburg; only the depth of groundwater under the cultivated soil is different. Similarly, the Upper Bavarian catchments of the Chiemsee

mires and Rote Traun have only slightly different water balances despite the difference in evaporation and groundwater depths. Thus, although there are large differences between the water storage ( $R - C$ ) of mires and that of mineral soils, their average annual water balances may be very similar.

#### 4.5.5 EVAPOTRANSPIRATION IN DIFFERENT MIRE ECOSYSTEMS

Evaporation is the sum of three processes: interception loss of evaporative water from plant surfaces, transpiration or evaporation of water from within the plant and direct evaporation from the non-living peat surface or plant litter. Transpiration and direct evaporation are difficult to distinguish separately; they are usually considered together as evapotranspiration. Ingram (1983) provides a detailed review of research on evapotranspiration from mires, including various techniques for its estimation; here only the key points will be discussed.

During the last three decades a large amount of hydrological data have been recorded for different mires in similar situations (see, for example, Eggelsmann, 1964; Baden and Eggelsmann, 1964; Bay, 1966; 1968; Bavina, 1967; Smid, 1975; Laine, 1984; Roulet and Woo, 1986; Koerselman and Beltman, 1988; Koerselman, 1989b). The results indicate that mires of high soil moisture content, in which the groundwater table is near the surface, are greatly affected by evapotranspiration (Table 4.14). At equal rates of precipitation, evapotranspiration is markedly higher from mires compared with mineral soils in agricultural or forestry use. The effect of altitude on evapotranspiration is important in distinguishing mountain mires from their lowland counterparts. If the average annual evaporation values for the various raised mires are ranked according to their height above sea level, similar evaporation values are obtained with respect to annual precipitation, but with an obvious gradation due to climate (Table 4.15).

The complex community structure of mires with its mosaic of hummocks and hollows, produces a distinctive pattern of mire evaporation and mire microclimate (see Section 4.6). This ranges from the permanent hollows and seasonal pools to dry hummocks with dwarf shrubs such as *Calluna vulgaris*. *Sphagnum* communities, which predominate in undisturbed raised mires, appear to lack water-conducting tissue. Water must be absorbed directly through the cells of the leaves and stem and be conducted by matric forces through the capillary spaces. In drought conditions, the larger hyaline cells empty of water and produce the characteristic whitish appearance on the upper *Sphagnum* tussocks (see Figure 1.19); this response lowers the albedo of the *Sphagnum*. In wet conditions, *Sphagnum* absorbs water rapidly, so the hyaline cells create a large storage capacity (Romanov, 1968). Different *Sphagnum* species appear to have differing abilities to retain water (Romanov, 1968; Overbeck and Happach, 1957; Päivänen, 1973) and hence have different evaporative characteristics. Unlike vascular plants, there is no sustained supply of water to the surface of a *Sphagnum* cushion under strongly evaporative conditions (Ingram, 1983). Neuhäusl (1975) found that dry atmospheres rapidly develop over *Sphagnum* lawns. Under strongly evaporative conditions on hot summer days, *Sphagnum recurvum* and *S. cuspidatum* were found to lose water even when their surfaces were only 20 mm above the water table. Seasonal contrasts between mire communities, and in particular between *Sphagnum* and vascular plants, could be explained by the drying out of the capitulata of *Sphagnum* owing to limited upward transport of soil water, which therefore lowered the overall rate of water loss.

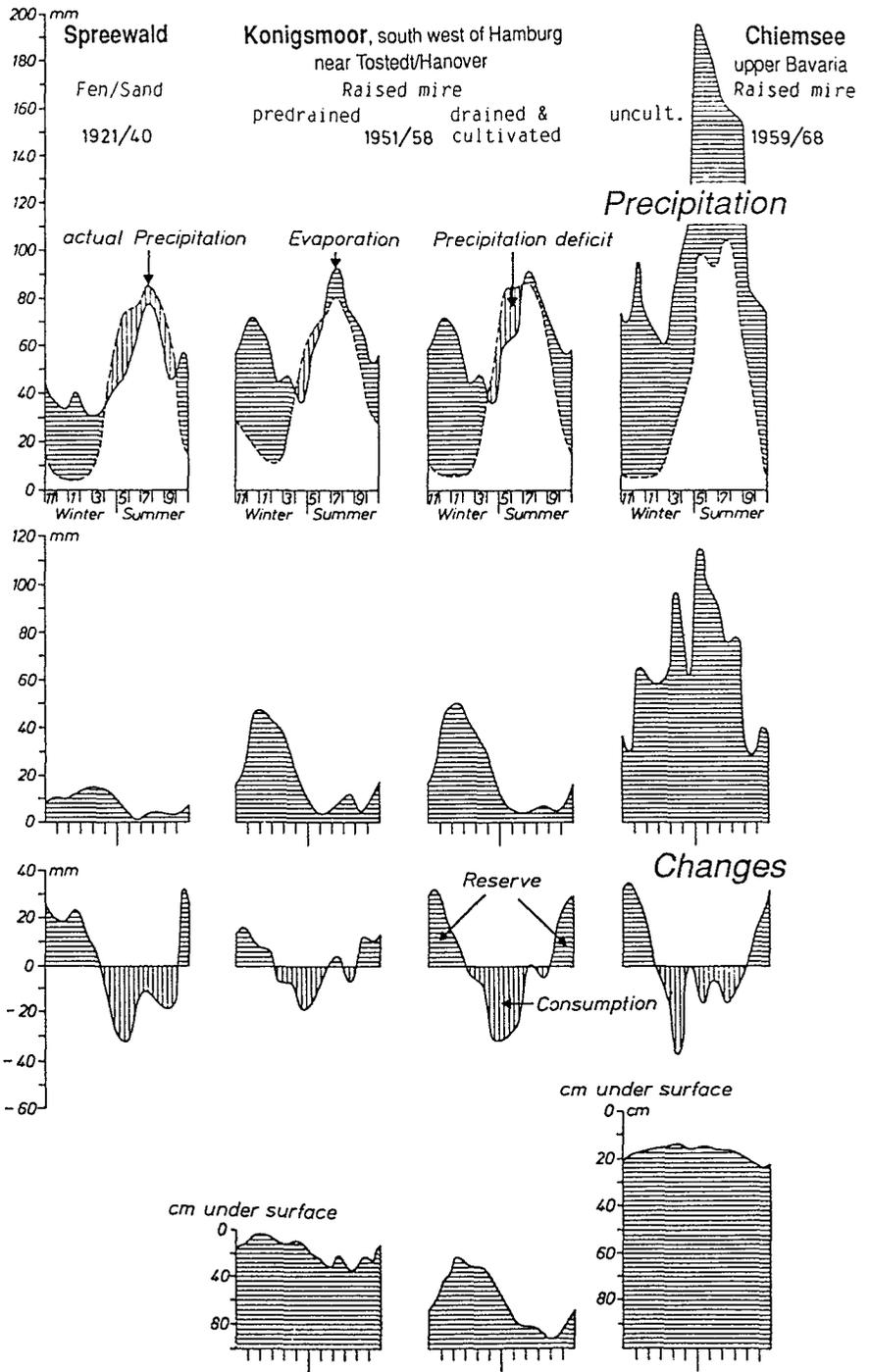
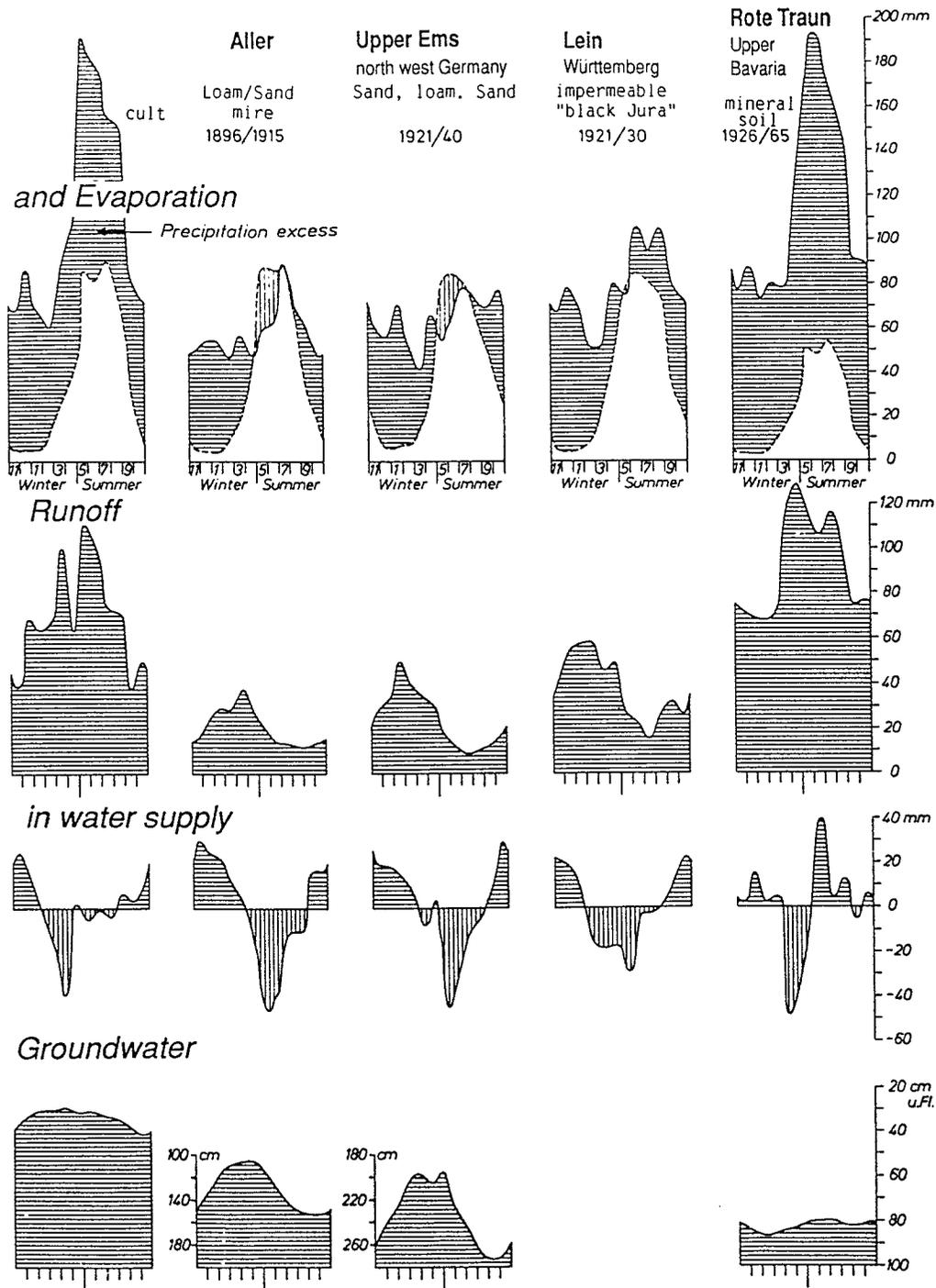


Figure 4.17 Mean monthly water balances of mire and mineral soil catchments in Germany



**Table 4.14** Average annual evaporation (mm) from mires in comparison with that from mineral soils in the lowlands of Germany

Province	River catchment	Soil/mire type	Vegetation	Evaporation
Schleswig-Holstein	Eider	Fen	Swampy meadow	550
			Pasture	520
Lower Saxony	Wümme	Raised mire	Sphagnetum	532
		Raised mire	Callunetum	506
		Raised mire	Mown meadow	491
Bavaria	Alz	Raised mire	Sphagnetum	547
		Raised mire	Mown meadow	476
		Raised mire	Coniferous forest	914
North Rhine/Westphalia	Upper Ems	Sand/loam	Arable, forest, grassland	479
Lower Saxony	Aller	Sand/loam	Arable, forest, grassland	455

**Table 4.15** Evaporation from raised mires related to height above sea level

Mire location	Height above sea level (m)	Evaporation (mm)	Precipitation (% of evap.)	Period
Königsmoor/Tostedt	39	506	67	1950-1951
Solling	460	512	48	1975
Chiemsee/Alps border	530	525	39	1959-1968
Upper Harz	800	510	36	1958-1970

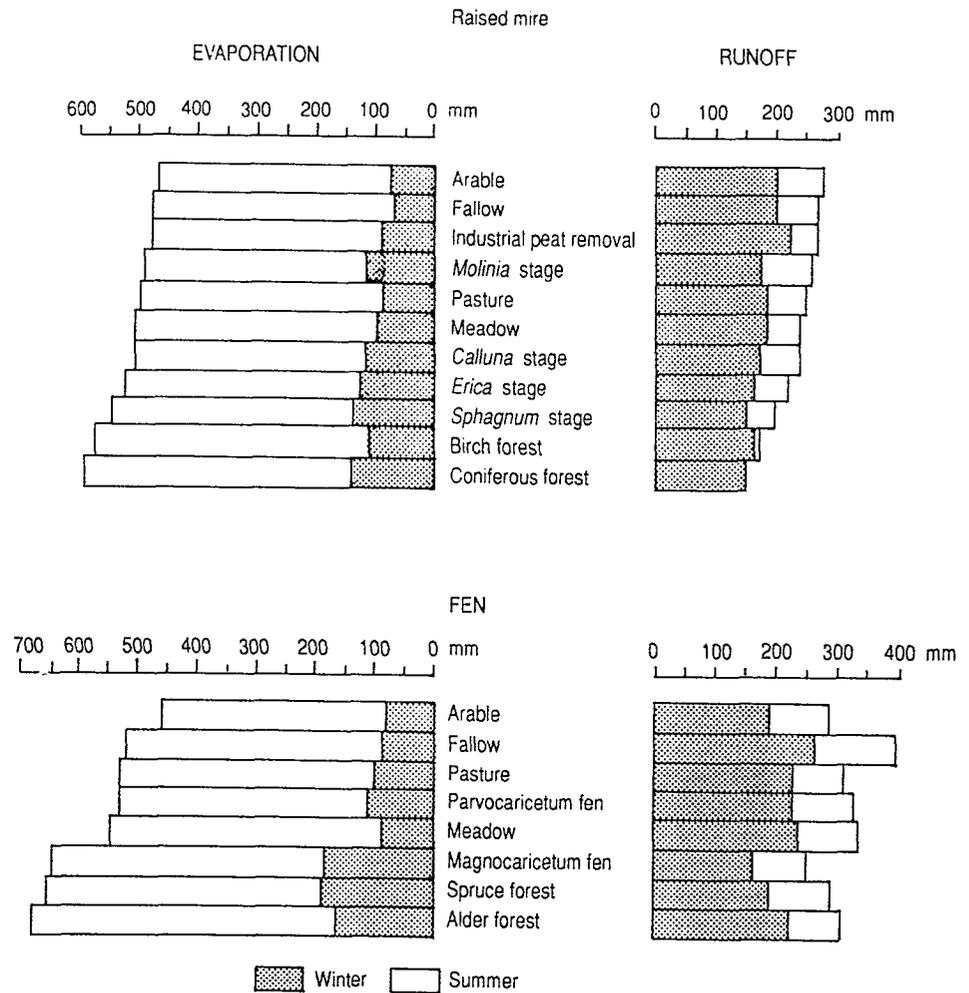
Dwarf shrub communities, containing characteristic mire species such as *Calluna vulgaris*, *Erica tetralix*, *Vaccinium myrtillus* and *Empetrum nigrum* are generally shallow-rooted, although the depth of rooting depends on the degree of waterlogging. This means that they are largely confined to the acrotelm in undisturbed mires. The dwarf shrub community appears to have a high level of resistance to drought conditions (Bannister, 1964; Firbas, 1931) and an ability to control the rate of transpiration from mires. *Erica tetralix*, which is commonly found in wetter sites than *Calluna* is thought to be less tolerant of desiccation. Bannister (1964) and Ashmore (1975) showed that *Calluna* can regulate water loss through stomatal closure, although there are some uncertainties as to the water potential at which stomatal closure occurs. In a similar manner to the dwarf shrub community, some of the cyperaceous graminoids such as *Eriophorum vaginatum* display xeromorphism. The work of Firbas (1931) and Miller, Stoner and Ehleringer (1978), however, suggests that *Eriophorum* has little ability to regulate evaporative losses.

Comparative observations of the effects of vegetation and land use on evaporation were carried out on eight fens and eleven raised mires in Germany (Eggelsmann, 1964; 1990).

Similar approximate evaporative limits for mire communities have been determined by Huikari (1963) in Finland, Tinbergen (1940) in Belgium and Neuhäusl (1975) in Czechoslovakia. Ingram (1983) using the results of the authors indicated above, suggests the following groupings for mires stands:

- (1) *Negligible transpiration* (around 0 mm per day), but high evaporation from open water: *Sphagnum cuspidatum* and *S. recurvum* in old peat cuttings.
- (2) *Low transpiration* (< 2 mm per day): *Sphagnetum magellanicum* in undisturbed mires and *Eriophorum vaginatum*—*Sphagnum recurvum* in old peat cuttings.
- (3) *Moderate transpiration* (2–4 mm per day): *Caricetum fuscae*, *Caricetum dioicae*, *Carici-Festucetum rubrae caricetosum paniceae* in fens and *Betula pubescens*, *Pinus sylvestris* and *Pinus mugo* on the mire expanse.
- (4) *High transpiration* (> 4 mm per day): *Carici-Festucetum rubrae* meadows with *Carex rostrata* together with meadows and pastures with *Trifolium-Festucetum rubrae* and *Nardo-Festucetum capillatae*. Also on drained and deforested mire expanse *Vaccino uliginosi-Pinetum*.

The effects of vegetation and land use on evaporation from fens and raised mires in Germany are shown in Figure 4.18 which presents the yearly and six-monthly evaporation and runoff values, ranked by increasing evaporation rates (after Eggelsmann, 1990). The results illustrate the profound effect of evapotranspiration on the water balance of the raised mire and fen ecosystems investigated. For both raised mires and fens, the arable habitat had the lowest evaporation rate, followed by fallow and industrial peat removal (in raised mires). The highest evaporation values were recorded in coniferous forest (forestry) closely followed by birch swamp forest; in both cases, the evaporation values were affected by interception. Similar trends were recorded by Heikurainen (1963) in a pilot study of mires with *Betula*, *Picea* and *Pinus* near Helsinki. He concluded that *Betula* transpired as much as the conifers even though the standing crop and rate of growth of *Betula* were lower. In raised mires in Germany, the *Sphagnum* stage exhibited a lower evaporation rate than the two forest ecosystems, and was closely followed by the *Erica* and *Calluna* stages. The fen ecosystems which have a higher water table because of intrusive water have, as a consequence, a higher rate of evaporation compared with raised mires. The arable fen habitat is the exception. The alder swamp forest has the highest evaporation for the fen ecosystems studied, and is closely followed by pine forest. In the forest ecosystems, the evaporation rate is affected by evapotranspiration and interception; this probably also applies to the Magnocaricetum mire. In both coniferous forest habitats, interception also increases the evaporation losses during winter; a similar phenomenon was also noted in the Magnocaricetum mire during the winter period. The winter evaporation values for the *Sphagnum-Erica* and *Calluna* stages of the raised mire ecosystems are also relatively high, a phenomenon closely connected with the assimilation of these plants during the autumn and early winter months. Baden and Eggelsmann (1966) concluded that in general, catchments with mire development display a higher rate of evapotranspiration than those without. Koerselman and Beltman (1988) examined the evapotranspiration from fens using a lysimeter system. They found that evapotranspiration from vegetated lysimeters exceeded evaporation from water-filled lysimeters by a factor of 1.7 to 1.9. They developed a single equation to explain the evapotranspiration losses from the groups of fens they studied in the Vechrplassen area north of Utrecht. On a



**Figure 4.18** Annual and six-monthly runoff and evaporation from raised mire and fen ecosystems

monthly basis:  $E = 0.73E_0 + 0.16$  mm per day ( $r = 0.97$ ) where  $E$  is the actual evapotranspiration and  $E_0$  the Penman potential evaporation.

Baden and Eggelsmann (1964) compared the evaporation from an intact raised mire at Königsmoor in northwestern Germany with that of a neighbouring reclaimed mire which had been tile-drained and supported a grass sward. They found that under conditions of low evaporative demand, the intact raised mire lost water more slowly than the reclaimed mire but that the reverse was true under high evaporative demand. However, when averaged over a long (eight-year) time period (Eggelsmann, 1964), the differences between the intact and the reclaimed mire were small.

Where there is no inflow of intrusive water, as in all raised mire ecosystems and in cultivated fens, the high evaporation rates also reduce the levels of discharge or runoff. The inflow rates of intrusive water increase both evaporation and, especially in winter, discharge (see Section 4.5.6).

In summary, published evidence suggests that the rate of evapotranspiration from mires depends strongly on the vegetation structure of the mire community, with the presence or absence of trees being particularly important. Ingram (1983) concluded that the actual evapotranspiration from raised mires probably approaches the potential evapotranspiration but that actual evapotranspiration from fens is greater than the potential (see Koerselman and Beltman, 1988). These generalisations are subject to seasonal variations, usually with actual evapotranspiration greater than potential in winter and the reverse pattern in summer—at least in treeless mires. The summer trend is the result of the ability of the mire to regulate its water loss to a limited extent. This may be achieved by a change in the albedo of the surface layers of the mire through, for example, the drying out and consequent ‘whitening’ of *Sphagnum* communities. Alternatively, vascular plants may control transpiration through stomatal closure.

4.5.6 GROUNDWATER AND PERCHED WATER IN MIRES

Groundwater

Groundwater is found only in those mires whose peats have an adequate volume of macro- and mesopores (see Section 4.4), that is, in structured peats of low to medium decomposition ( $H \leq 6$ ). Numerous measurements of groundwater levels in raised mires and fens have shown their well-defined seasonality, with maxima in winter and minima towards the end of summer. In spring and summer, evaporation depletes the stored water, whilst in autumn and winter precipitation augments the groundwater in the mire which lies mainly near its surface. The effect of water table oscillation on the storage of water in mires is discussed in more detail in Section 4.5.8.

The annual pattern of water table movement may be masked to some extent by changes in the weather. Figure 4.19 shows the annual groundwater position (based on

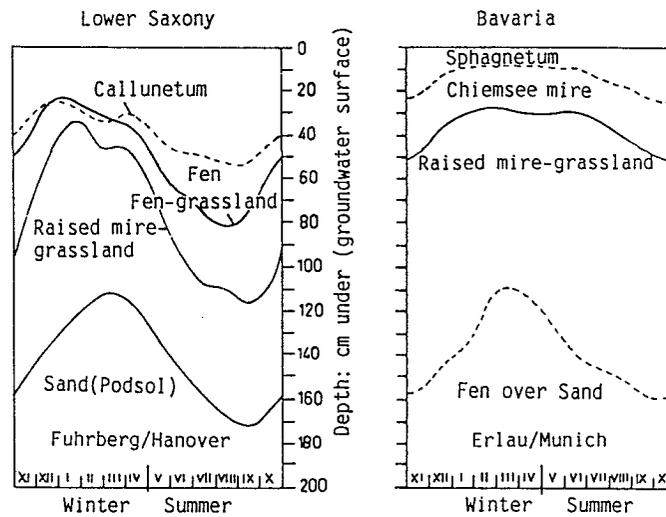


Figure 4.19 Average annual groundwater curves for various mire and sandy soils in Lower Saxony and Bavaria, Germany

monthly groundwater averages) for several mires and mineral soil systems in northern and southern Germany. The patterns shown reflect the effects of climate and vegetation, and in particular the heavy precipitation (> 1300 mm per year) of the Chiemsee mires near Bernau, Bavaria. Here, about 60% of total annual precipitation falls in April to August, and about 64% between May and October. Although during this period, the main water requirement of plants decreases and evaporation is a maximum, the groundwater table is *highest* in spring and summer and *lowest* in autumn and winter months. This is primarily because most of the total winter precipitation is retained as snow and ice, generally for 100 days and more, which does not melt until spring, and frequently not until April or May. When snowmelt occurs, it brings about a rise in the water table.

In fens, the groundwater supply is frequently related directly to the water of neighbouring lakes or rivers (Kassas, 1951). This applies particularly to those fens that have evolved by terrestrialisation. In fens, the movement of the water table is complicated by the variety of water supply sources, as was shown by Godwin (1931), and updated by Gilman (1988), for Wicken Fen in Cambridgeshire. It is necessary, therefore, to understand the relationship of the fen with its catchment in order to interpret that pattern of water table movement (Gilvear *et al.*, 1992). Kulczynski (1949) for the Poles'ye mires suggested that the main control on fen water table oscillations is the size of the catchment in relation to the mire. Large catchments with long water-retention times produce a slowly oscillating water table in the fen and sustained water supply from the catchment often ensures that a high water table is maintained for long periods. By contrast, fens with small catchments are far more 'flashy' in their response to water inputs from the catchment and produce sharp and rapid changes in the position of the water table. In such fens, the water table is likely to be lower on average because the water supply from the catchment is not sustained (Burt, Heathwaite and Labadz, 1990).

#### Perched water

In mires where thin layers (<130 cm) of weakly decomposed (highly permeable) peats overlie highly decomposed (almost impermeable) peats, the groundwater may be regarded as *perched* water. Since, except in sloping mires, there is no inflow of perched water, the presence of a perched water table occurs mainly in the winter and spring months whilst in summer it is depleted by evapotranspiration. This applies particularly to raised mires (see Figures 4.14 and 4.15) where the water table in the centre of the mire expanse may be several metres above the regional groundwater table. Bay (1967) studied raised mires in Minnesota which were formed in depressions in glaciofluvial sands, and found that the presence of a perched water table in the mires was clearly related to the water regime of the surrounding sands and that the sands largely controlled the oscillations of the water table in the mire. Water recharge from the mire catchment reduced the amplitude of water table oscillations in the raised mire by supplementing losses from evapotranspiration. Ingram (1983) suggested that raised mires with distinct hydrological connectivity with the regional groundwater table are perhaps best regarded as transitional mires rather than true raised mires.

The groundwater or perched water table, which is usually found near the mire surface is a good guide to the water balance. It can be measured and monitored relatively easily

using simple equipment (for example, PVC drain-pipes) and should be thoroughly studied in the evaluation of mire ecosystems (see also Ingram, 1983).

#### Groundwater and perched water oscillation

The oscillation of the mire surface, like the rise and fall of the water table in a lake or pond, is a direct measure of the changes in the water supply (see Section 4.5.8). This oscillation was noted in the then undisturbed Store Vildmose raised mire near Aalborg/Jutland by Prytz (1932), on areas mainly carrying *Sphagnum* and heather. Further measurement data are available from the Esterweger Dose, from Königsmoor near Tostedt/Hanover, and from several small raised mires (Eggelsmann, 1981). At Thorne Moors in South Yorkshire, England, prior to industrial peat extraction it was claimed that the oscillation of the raised mire water table was so extensive that during winter months the view across the mire of the church spire 8 miles away at Goole was concealed by the rise of the peat surface. At this time, the peat was thought to be up to 8 m deep in places (Limbert, 1987); today the maximum depth of peat is around 2.5 m. This phenomenon has been recorded in other raised mires such as Cors Fochno in Wales (Fox, 1984). Kulczynski (1949) suggests that the phenomenon of *Mooratmung* or 'mire-breathing' reduces both the depth and oscillation of the water table in the mire expanse. The differences in the water table oscillations between central and peripheral mire zones are important in influencing the structure of the vegetation community. Dwarf shrubs tend to dominate in the better drained and seasonally fluctuating water table zones of the margins of the mire whereas *Sphagnum* communities are concentrated where the water table is consistently high in the centre of the mire (Section 1.4).

The oscillation for various raised mire stages in German mires is shown in Figure 4.20. During the summer, when evapotranspiration exceeds precipitation, the surface of the mire sinks, whilst with the positive climatic water balance in autumn, the mire surface rises again. Average amplitudes are between 10 and 15 mm for *Erica* and *Calluna* stands and from 30 mm to over 50 mm in mire hollow stands. Oscillation also occurs in raised mire grassland. Although no data are available on oscillation in fens it is assumed that it occurs. It should be greater in 'floating' to 'loosely layered' (slightly to moderately decomposed) fen peat than in the 'rather dense' to 'dense' layers of fen peats. Oscillation does not occur where layers of silt are either incorporated within the fen layers or have been deposited on the fen surface.

#### 4.5.7 RUNOFF AND INFLOW IN MIRES

Ivanov (1981) provides a detailed classification of recharge, throughflow and discharge in mire mesotopes based on Russian examples. This he links to the mire development process so that the initial phase of mire development, derived from a concave surface relief pattern with recharge from intrusive water sources, shifts eventually to a convex final stage in which meteorological water is the main source of recharge. The shifts in the source of recharge water produce corresponding shifts in the trophic status of the mire communities from eutrophic to oligotrophic. The classification scheme is developed further by Ingram (1983) and the runoff component from mires is covered in some detail in this section.

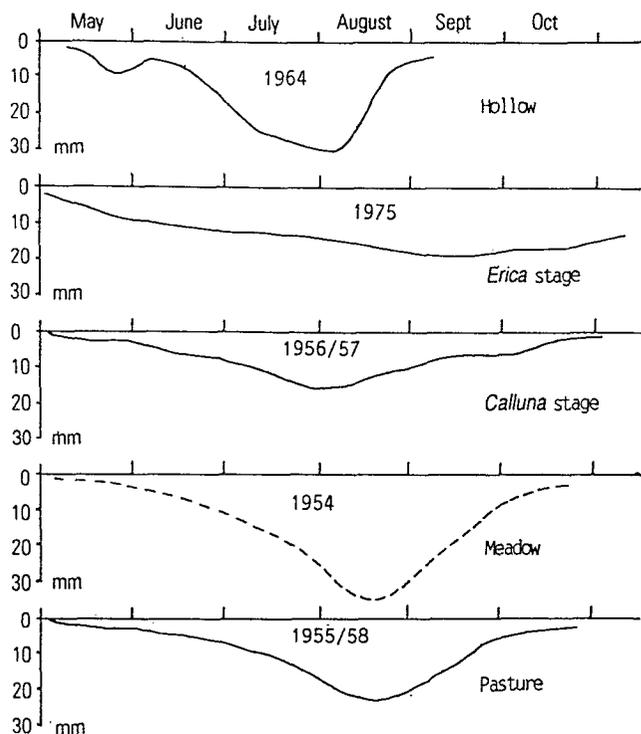


Figure 4.20 Groundwater oscillation between May and October for different stages in the development of raised mire (after Eggelsmann, 1981)

### Runoff

Discharge or runoff is the hydrological term for the fraction of precipitation input which reaches streams or rivers. Discharge ( $Q$ ) may be given in volumetric units of  $\text{m}^3 \text{s}^{-1}$  or related to the catchment area as runoff yield or load in  $\text{m}^3 \text{s}^{-1} \text{km}^{-2}$  (or ha). For defined periods of time, integrated discharge may be expressed in  $\text{m}^3 \text{km}^{-2}$  or runoff in millimetres of water height. Runoff in connection to the specific yield of a mire is discussed in more detail in Section 4.5.8.

The key hydrological pathways of runoff from mires are: seepage, pipe flow, open channel flow, groundwater flow and surface runoff or overland flow. A distinction is usually made between overland flow ( $A_o$ ) and subsurface or groundwater flow ( $A_u$ ). However, in lowland soils, where gradients are generally shallow, and which are drained by a network of channels with or without pipe drainage into outfalls, the overland flow component ( $A_o$ ) is taken to include both overland flow and subsurface lateral throughflow. Seepage is determined by differences in water potential within a mire and in relation to its surrounding catchment. Water moves from areas of high potential to areas of low potential at a rate which is determined by the steepness of the hydraulic gradient and the hydraulic conductivity of the peat. The pattern of water movement is explained by Darcy's Law (see Section 4.4). Seepage takes place mainly in the saturated zone of the peat where discharge in a horizontal direction is possible. In the unsaturated zone,

water potential gradients occur in a vertical direction in response to gravity. Rapid water seepage is usually recorded in the acrotelm. Romanov (1968) quotes velocities as great as  $2.5 \text{ cm s}^{-1}$ . In the catotelm, where rates of flow are much lower because the potential gradients are low, there is some doubt that Darcy's Law can be satisfactorily applied (Galvin and Hanrahan, 1967; Rycroft, Williams and Ingram, 1975a; 1975b; Heathwaite, 1987). This is discussed further in Section 4.4.

Pipe flow in British mires is a well-known feature (see for example, Gilman and Newson, 1980; Jones, 1981; Newson, 1976; Taylor and Tucker, 1970), and has also been recorded in Germany (Eggelsmann, 1960). Pipe flow in mires is thought to develop from shrinkage cracks formed during drought conditions which are then enlarged by water flow. Ingram (1983) suggests that a combination of steep potential gradients and a widely variable water content is necessary for pipe formation. As a result, they are often recorded at the margins of mires. Open channel flow in mires may take the form of rills, streams or even rivers. In mires, the measurement of channel flow using the standard techniques of hydrograph separation to distinguish surface runoff from subsurface flow is complicated by the problems of catchment delineation (Burt, Heathwaite and Labadz, 1990) and the definition of contributing areas. Ivanov (1981) regarded mire development as being counter-erosive. There is evidence in mires for a biologically driven constrictive type of channel formation, for example the shift in the lagg associated with a raised mire as the mire spreads outwards (Ingram, 1983). Snow-melt and heavy rain are thought to be the main agents of water loss from upland mires in the form of rills and erosion channels. Tallis (1973) suggests that heather burning, a traditional management practice in the southern Pennines, may have initiated the development of extensive erosion gullies in the blanket peat. Mire burning can destroy the acrotelm and often results in an upper surface layer of low permeability which encourages surface runoff during heavy rain. Tallis (1973) suggests that around 20% of the average annual precipitation in the southern Pennines is dispersed as surface runoff.

Groundwater flow is discussed in some detail in Section 4.5.6. Its relationship to the permeability of the acrotelm and catotelm is examined in Section 4.4. The differences in the permeability, and hence rates of groundwater flow, between the acrotelm and catotelm may be of a single order of magnitude in some fens, but up to eight orders of magnitude in raised mires with a highly humified catotelm (Ingram, 1983). Water discharge from raised mires in Lower Saxony in relation to the surface gradient was examined by Eggelsmann (1967) and Eggelsmann and Schuch (1976); their results are shown in Figure 4.16 and discussed in detail in Section 4.5.3. Groundwater runoff from mires is examined below.

#### Runoff from different mire ecosystems

Figure 4.18 indicates the annual runoff and evaporation for a number of different raised mire and fen ecosystems. The highest runoff from both mire types is from the arable habitat which has the lowest evaporation. The lowest runoff occurs in the forested ecosystems where evaporation and interception are both high. Runoff from fen ecosystems is considerably higher than that from raised mires owing to the input of intrusive water which alters the water balance.

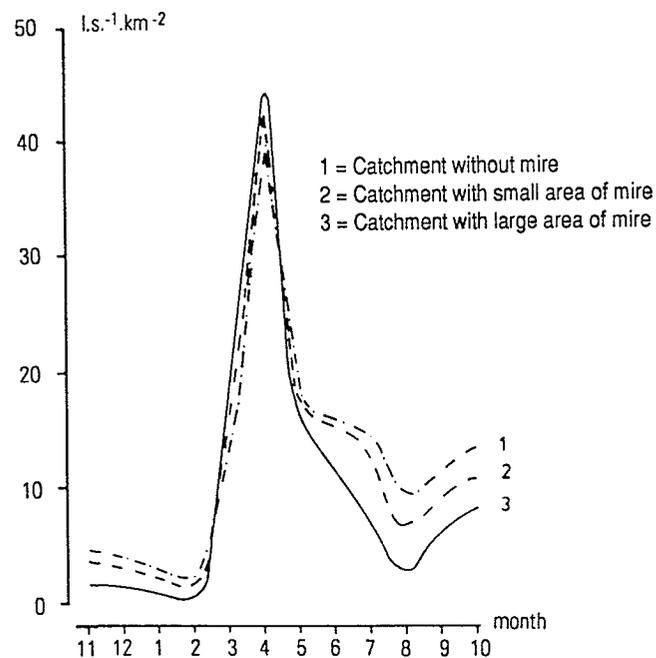
Lowland mires, where the groundwater table is usually close to the ground surface, have 10 to 15% higher evaporation than mineral soils (Table 4.14). As a result, runoff from lowland mires is usually lower than from mineral soils, although the water balance

**Table 4.16** Average annual precipitation, discharge and evaporation (mm), for mire (Königsmoor) and non-mire (Ems) areas in Germany

Annual average	Upper Ems (non-mire) 1921-1940	Königsmoor (mire) 1951-1958
Precipitation ( <i>P</i> )	762	742
Discharge ( <i>Q</i> )	286	243
Evaporation ( <i>E</i> )	476	499

is roughly equal. This is illustrated in Table 4.16, where data from the Upper Ems, where there are no mires, are compared with those from the mire-rich area of Königsmoor in Lower Saxony.

Mires are characterised by high evaporation and correspondingly low runoff relative to mineral soils (see Section 4.5.6). Mires also have a lower retention capacity (Section 4.5.8), as shown by the runoff curves for catchments with varying proportions of mires in Bohemia and Moravia (Figure 4.21). The average annual discharge from the various raised mires of Germany increases sharply with increasing altitude (Table 4.17). This is due to climatic influences, since evaporation scarcely varies (Table 4.16). Mountain mires commonly have little compensating effect on the runoff from streams and rivers.



**Figure 4.21** Runoff regimes for catchments in Bohemia and Moravia, with different proportions of mire (after Ferda, 1973)

Table 4.17 Runoff from German raised mires in relation to altitude

Mire/location	Height above sea level (mm)	Precipitation (mm)	Runoff	
			mm	% of pptn.
Königsmoor/Tostedt	39	742	236	32
Mecklenbruch/Solling	460	1066	554	52
Chiemsee/Alpenrand	530	1345	820	61
Brockenfeld/Harz	800	1434	924	64

Uhden (1972), investigating the Brockenfeld mire in Upper Harz, Germany, found that mountain mires are almost always saturated with water and may be covered with ice or snow for long periods during the winter. On steep slopes, runoff from snowmelt or heavy rain is high (Figure 4.22), although during low precipitation input, runoff is slight (Ferda, 1973; Benne, 1977). Mountain mires do not act in the same manner as glaciers, which melt slowly and produce their maximum runoff at high summer temperatures; mountain mires do not occur at such high altitudes and produce their maximum runoff in spring when they may cause flooding.

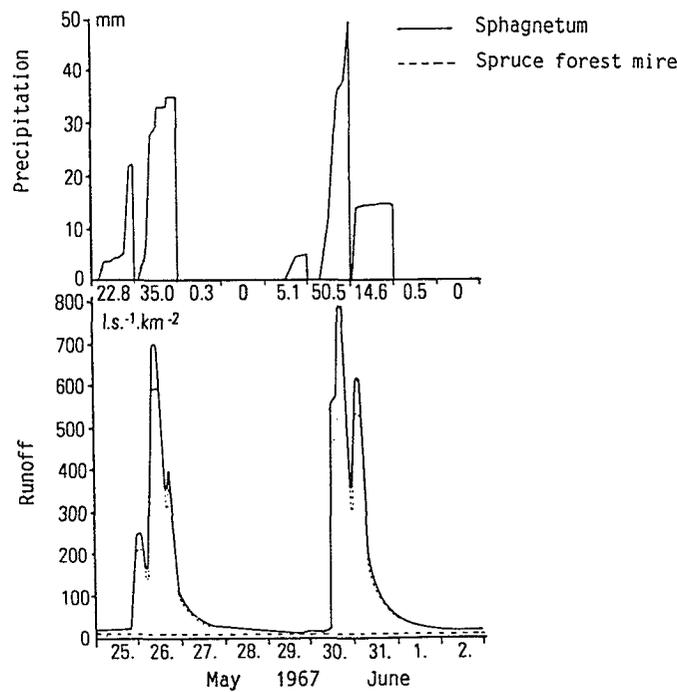


Figure 4.22 Precipitation and runoff in Brockenfeldmoor, Upper Harz, under different mire vegetation covers (after Uhden, 1972)

### Groundwater runoff from mires

Mires, as a consequence of their high evapotranspiration, are water consumers. They are not, therefore, important in the regeneration of groundwater (Section 4.5.8). Eggelsmann (1973) compared the groundwater regeneration from mires with that of sandy soils. He found, for an equal precipitation (750 mm), the infiltration or seepage rate from mires to deep groundwater was 80 to 50% lower in mires than in sandy soils. Furthermore, as a result of the different permeabilities of peats, this rate diminished from forested mires through to fens and raised bogs (Table 4.18).

**Table 4.18** Regeneration of groundwater in northwest Germany (after Eggelsmann, 1973)

Soil/mire	Regeneration of groundwater	
	Infiltration rate (l s <sup>-1</sup> km <sup>-2</sup> )	Runoff (mm year <sup>-1</sup> )
Sand	3-6	100-200
Forest mire	> 2	> 60
Fen	1-2	30-60
Raised mire	< 1	< 30

### Intrusive water input

Many fens, particularly flood- or stream-traversed mires, had, or continue to have, an overground input of water, for example runoff from upland areas or flooding from rivers. An intrusive, groundwater input may also be important in many fens (Koerselman, 1989b). Groundwater influx is difficult to measure and is commonly estimated (Gilvear *et al.*, 1992). It depends, according to Darcy's Law (1856), on the hydraulic gradient, which is to some extent determined by topography, and on the permeability of the peat. Groundwater influx may be classified according to Table 4.19.

**Table 4.19** Intrusive water input

Class	Intrusive water estimate	Input (mm year <sup>-1</sup> )
1	Very low	<20
2	Low	20-50
3	Moderate	50-100
4	High	100-200
5	Very high	>200

Along the embankments of rivers or lakes, intrusive water inflow may occur, especially when the surrounding water levels are high. Where highly permeable soil layers are

interlayered within the peat, for example gravel or forest peats, intrusive water inflow may be high (Koerselman, 1989a).

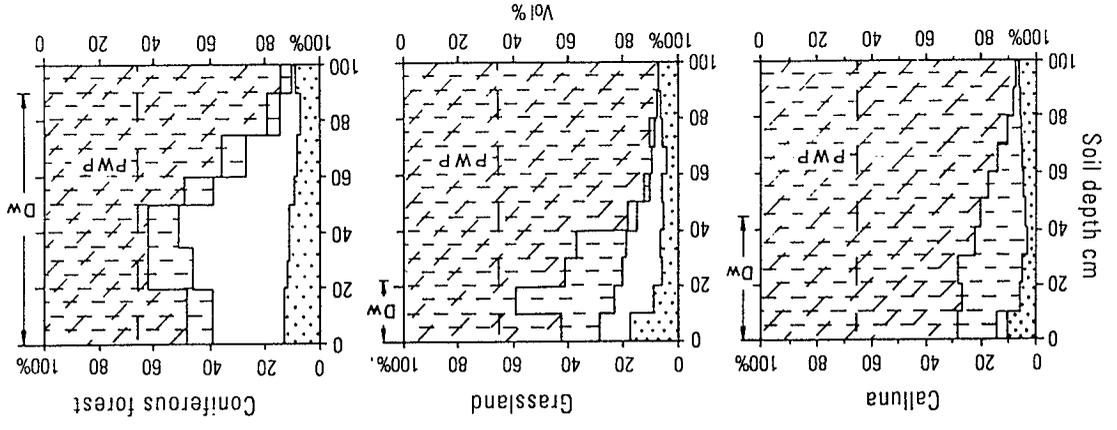
#### 4.5.8 MIRES AS WATER RESERVOIRS IN THE LANDSCAPE

The peats of which mires are composed contain very large quantities of bound water, amounting to 70 to 95% on a volume basis, depending on peat type, decomposition and mire utilisation. Only a very small proportion of this large quantity of stored water is involved in the seasonal exchange of water (see Section 4.4). In contrast to, for example, rivers which store precipitation for a short period and thereafter release it slowly, mires retain large quantities of water for long periods. The amount of water stored in mires varies seasonally owing to an effect known in Germany as *Mooratmung* ('mire breathing') which is discussed in more detail in Section 4.5.6. Changes in mire water storage or the capacity of mires to act as 'reservoirs' are reflected in changes in the position of the peat water table throughout the year. Indeed Ingram (1983) goes as far as to state that a high water table is the single most distinctive hydrological and ecological feature of the mire landscape. For fens, the early work of Godwin (1931; 1932) is still of relevance. His study of Wicken Fen, Cambridgeshire identified the pattern of a falling water table during summer months superimposed upon which was a diurnal water table cycle in response to transpiration losses. Godwin was able to discern these trends despite the fact that in many fens, including Wicken Fen and the Norfolk Broads of East Anglia, England, the movement of the water table is complicated by the supply of intrusive water or groundwater from the fen catchment. Heathwaite (1990) identified a similar pattern of water table decline at Thorne Moors, a cut-over raised mire in South Yorkshire. The diurnal cycle, which could be of the order of a few centimetres, and was recorded in drainage ditches, dry peat baulks and wet peat baulks, was more pronounced under specific weather conditions, notably high temperature, low cloud-cover periods. As with Wicken Fen, at Thorne precipitation was the main source of recharge, although an irregular response to storm events was recorded.

In mires, the water table need not necessarily be flat, even though the water table position is determined by gravity and not the different matric forces of the mire vegetation community. Ingram (1983) suggests that where the acrotelm has a high permeability, homogeneous water table movement will occur in response to changing storage conditions, and the water table will remain flat. Where the permeability of the acrotelm is low, an undulating water table may result between the hummocks and hollows of the mire. Bragg (1978), for example, found that the water table associated with the highly permeable *Sphagnum magellanicum* was flat but, because the permeability of *Sphagnum capillifolium* was lower, a concave water table was found below hummocks of this species during summer months. Figure 4.23 shows the volume of water, air and solids, to a depth of 1 m, in raised mires in Germany with different vegetation covers. The highest water content is that of the *Calluna* vegetation cover, the lowest that of 35-year-old coniferous forest; grassland has an intermediate position. In addition to evaporation, interception is also significant in the case of coniferous forest (see Section 4.5.5). With the exception of mires of the *Schwingmoor* type with floating peat rafts, the amount of water stored in the mire acrotelm depends on the depth of the water table. The capacity of the acrotelm to act as a temporary water storage reservoir depends on the porosity, pore

Figure 4.23 The volume of water, air and solids in the upper 1 m of three raised mire ecosystems: *Calluna*, mire grassland and afforested mire

Air volume  
 Min. water volume (summer)  
 Max. water volume (winter)  
 Solids volume  
 PWP = Permanent wilting point  
 Dw = Root penetration depth



size distribution and pore architecture, which determine the proportion of pores which drain at a given water potential (see Section 4.4).

Runoff from mires comprises surface water and (free) gravitational water (groundwater or pressure water). In mires containing weakly decomposed peats, this water fraction amounts to about 8 to 10%; in highly decomposed peat, the runoff volume is reduced to around 1 to 3% by volume (see Section 4.4). Quantification of the relationship between storage and the water table depth involves the concept of specific yield. The specific yield is defined as the quantity of water discharged from the peat when the water table is lowered by a unit depth. It is difficult to monitor owing to the large numbers of hydrological pathways by which water may be discharged from peat. These include, for example, surface runoff, pipe flow and discharge via drainage ditches. A further problem is that, as the water table falls, not all pores drain completely in the capillary fringe and the unsaturated zone (Childs, 1969). Boelter (1964; 1970) examined the specific yield of Minnesota peats using laboratory techniques. His 'water yield coefficient' for *Sphagnum* peats was 0.85 for surface layers, decreasing with depth to around 0.50 and down to 0.08 in highly humified peat material. Similarly, Päivänen (1973) found that the specific yield decreases with increasing degree of decomposition, and that this could be related to the changing bulk density of the peat (see Section 4.4).

Most of the water in mire ecosystems is stored in the catotelm. The general assumption is that this permanently waterlogged layer has a more or less constant water storage capacity. Heikurainen, Päivänen and Sarasto (1964), however, found some evidence that the water content below the water table was not constant over short time periods and appeared to depend on local hydrostatic pressure. Thus, short-term changes in the water storage capacity of the catotelm are possible. However, most of the changes in the water storage of mires are linked to water table oscillation in the acrotelm—at least in intact mires. Eggelsmann (1990) suggests that the storage changes accompanying movements of the water table are small, and are of the order 3 to 10% by volume. In effect, this means that mires, by virtue of the small volume of peat in the acrotelm, have a limited capacity to store or release water on a short timescale (see above). Drained mires are better storage reservoirs than intact mires (see Figure 4.23) and mineral soil systems are better still. The conservation of mires as a means of storing water in the catchment is, therefore, a misguided argument, although hydrological arguments, such as the role of mires in water quality modification, still hold (see Chapter 8).

### Mires and springs

Where springs and the tributaries of rivers rise from mires they can usually be classified as valley, spring or sloping mires. The peat deposits are commonly raised mires that are underlain by a paludified (usually swamp forest) mire and their genesis is related to specific morphological and hydrographic conditions. These mires often have a relatively large and continuous output of groundwater which arises not from the mire itself, but from mostly sandy, gravelly aquifers that have come to the surface and brought about mire formation. There is, therefore, no causative connection between the streams flowing from such mires and the mires themselves, even though they may seem to act as water reservoirs. The outflow from such springs would probably be greater if they had a direct hydrological connection with the river or stream because, as a result of the high rate

of evapotranspiration from mires, some spring outflow will be lost before it enters the drainage network.

### Standing water in mires

In many mires small, shallow pools exist; in exceptional cases they may form lakes with depths over 10 m. In Germany such pools and lakes must by law be conserved (see Chapter 8). In the context of this chapter, the term 'lake' (German: *See*) refers to a large, deep body of open water, while the term 'pool' (*Welher*) is used for one that is smaller and shallow and can be drained easily. The term 'pont' (*Tumpel*) is used for small bodies of water that may dry up periodically as, for instance, on heaths.

Most of the open mire waters in northwest Germany are extremely shallow and generally not more than 1–2 m deep. Their genesis varies greatly and only a few large bodies of mire water have been limnologically investigated, for example the Dümmer (Dahms, 1972; Poltz, 1979) and the Federsee in Upper Swabia (Göttlich, 1961). Most German mire waters, because they are shallow, must be termed pools but they are variously termed 'lake' or 'sea'. Some German terms have included: *Kolle* or *Kuhle*, *Moor-* or *Seeauge*, *Blänke* or *Bleek*, *Pool*, *Pohl* or *Schlatt*, *Blindsee* or even '*Unergründliches Meer*' (bottomless sea). This last term for raised mire pools was derived from the (dark) brown colour of the water, the bottom was not visible and the layer of mud was difficult to sound. Limnologically these are classified as brown-water (dystrophic) lakes.

### Standing water types in mires

The standard limnological classification shown in Table 4.20 is of limited value for many mire waters such as those of northwest Germany because they are so shallow (Poltz, 1979). Whereas in deep lakes organic (and mineral) sediments are deposited in the hypolimnion, and are thus withdrawn from the cycle of material in the epilimnion during the summer and winter, the situation in shallow lakes and ponds is totally different. Here, even slight currents disturb and continuously displace the light organic sediments. Stratification is possible, however, in calm weather with intensive solar radiation but it is short-lived and usually dispersed during the night.

Table 4.20 Limnological classification of mire waters in their natural state

Mire water	Colour of water	Characteristic trophic status and name	Summer pH	Autumn	
				NO <sub>3</sub> -N (mg l <sup>-1</sup> )	PO <sub>4</sub> -P (mg l <sup>-1</sup> )
Raised mire pool	Yellow-brown	Dystrophic, brown water	<6	Trace	—
Excavated lake in mire	Yellowish	Oligotrophic	6–7	Trace	—
Mire lake	Greenish	Eutrophic, mire pool	7	<1	1–0.2
Fen pool	Green	Eutrophic, mire pool	>8	>2	0.5

Therefore, in contrast to lakes, the sediments in mire pools participate constantly and directly in the material balance of the total body of water, resulting in continuous re-fertilising of the water by the nutrients released from the sediment, especially phosphate (Poltz, 1979). Fluctuations in the water table also have a considerable effect in shallow waters.

The hydrology of mire pools is essential for their preservation, especially the relationship between precipitation and input on the one hand and between evaporation and output on the other, as well as their hydrogeological situation.

#### The water balance of standing water in mires

There are few hydrological data for areas of open water in mires. Recent hydrological investigations on the Steinhuder Meer and of lakes without input and output in the northern German lowlands have confirmed their high rates of evaporation. The annual values of precipitation and evaporation for a body of water of this kind are given in Table 4.21. In a normal year, evaporation equals precipitation and the water balance is in equilibrium; however, in a dry, warm year there is a deficit of about 300 mm. If the deficit is not compensated by a greater influx of water, the water table sinks by about 30 cm (Eggelsmann, 1990).

**Table 4.21** Annual totals (in mm) of precipitation and evaporation of shallow water in mires in northwest Germany

Annual total	Dry, warm year	Normal year	Wet, cold year
Precipitation	550	750	950
Evaporation	850	750	650
Difference	-300	0	+300

In shallow water in mires the evaporation rate, owing to the transpiration from vigorous vegetation, may be increased by 25 to 30%. This observation is supported by measurements on the common reed (*Phragmites australis*) in Neusiedler Lake, Austria (Eggelsmann, 1990). Even the evapotranspiration from a *Sphagnum* mat can be greater than the evaporation from an open water surface.

#### Mire pools

Mire pools often have no surface runoff inflow although groundwater flux may be important, especially where the bottom of the lake or pool is deeper than the mire or where the mineral subsoil is sandy. In the raised mire pool shown in Figure 4.24, there is no surface runoff inflow and only a small groundwater input derived from the mire itself. The high water (HW) and low water (LW) positions in the mire pool in relation to the groundwater table are shown. As the water levels in the pool fluctuate, the position of the (mainly floating) pool margins also rise and fall. The water levels in the artificial pool of oligotrophic water shown in Figure 4.24 were observed over a period of 8 years (1977-1985). The amplitude between maximum high water (MHW) and maximum low

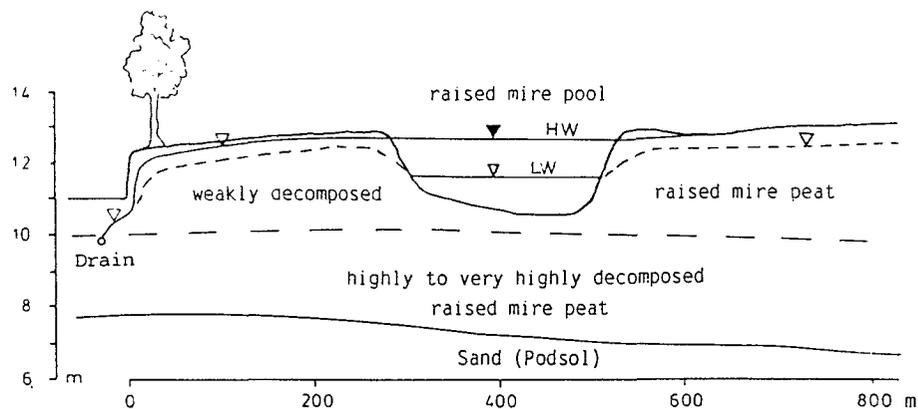


Figure 4.24 Relationship between groundwater and the water table of a raised mire pool at Kolk, Moorage (vertical scale exaggerated 40-fold, HW = maximum water table position, LW = minimum water table position)

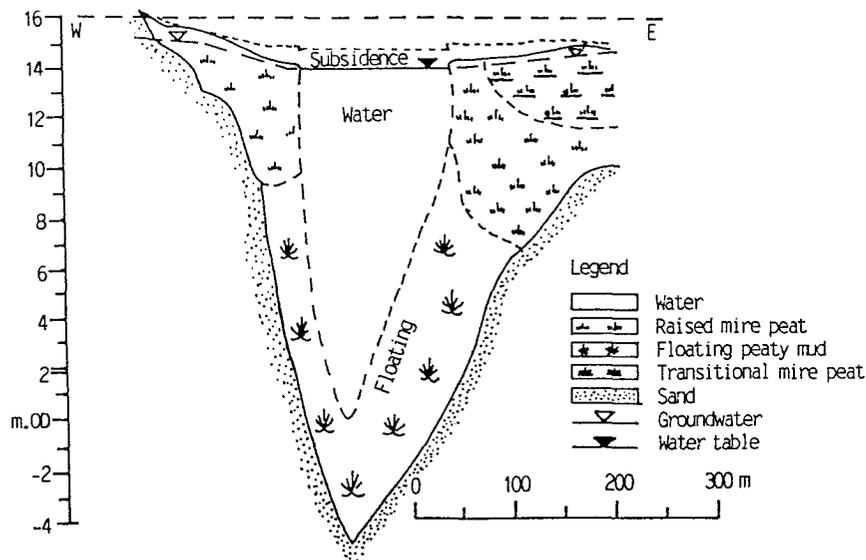
water (MLW) amounted to more than 100 cm. During three dry, warm summers the pool dried out owing to the unusually high evaporation. Heath pools are well known to dry out completely and hence they are termed 'heavenly pools' colloquially, because they are fed only by precipitation.

#### Mire lakes

Natural mire lakes often evolved in kettle holes which remained following the retreat of the ice during the Holocene. The mire lake known as the 'Grosse Tate-Meer' formed as a result of underground erosion above the 'Salzstock' of Gehlenberg. Figure 4.25 shows a section (W-E) of this body of water which is about 20 m deep, 1.16 ha in area and has a mainly sandy catchment area of over 120 ha. Only the immediate surroundings of the Tate-Meer are terrestrialised by a floating mat of vegetation; its margin consists of floating peat. The Meer subsided by more than 1 m following drain deepening operations three decades ago and for the past 15 years the water table has been maintained by a wooden weir. Although regular water table observations are not available, local observers assert that, even during the extremely warm and dry years of 1975 to 1977, the water table in the Grosse Tate-Meer did not fall. It is assumed that the high evaporation losses were compensated by groundwater input (Eggelsmann, 1977).

#### Excavated lakes in mires

In many of the raised mires and fens of the northern German plain and in the fens of the Alpine foreland numerous lakes have been formed as a result of sand and gravel excavation. The excavated lakes are commonly 12 to 30 m deep and have open water areas of 5 to 10 ha. The water table in the excavated lakes are usually at the same height as the groundwater table of the mires. Observations of water levels in excavated lakes indicate that locally no groundwater input or output takes place owing to a minimal hydraulic gradient between the lake and its catchment and the deposition of a layer of silt and clay



**Figure 4.25** Cross section through the deep lake Grosse Tate-Meer. The water area is about 1.3 ha (vertical scale exaggerated 25-fold)

on the bottom and sides of the excavated lake during sand jetting operations. Although excavated lakes are well suited to aquatic fauna including fish, the lack of water flow increases the risk of eutrophication.

#### 4.5.9 THE EFFECT OF DRAINAGE ON THE HYDROPHYSICAL STRUCTURE OF MIRES

Drainage activities are the greatest threat to the 'ecohydrology' of mires. The mechanisms involved in mire 'cultivation' are discussed in greater detail in Chapter 7 and the nature and implications of mire drainage for mire conservation and management are examined in detail in Chapter 8. Here, it is important to note the effect of drainage on the hydrological integrity of mires, particularly the stability of the acrotelm and catotelm.

Drainage, by lowering the water table and accelerating the rate of decomposition of the peat, results in irreversible changes in the hydrology, morphology and ecology of a mire (see Section 4.4). Interpreting the impact of drainage on mire systems is complicated by their 'diplotelmic', or two-layered, structure (Ingram, 1983; Ingram and Bragg, 1984) and its role in maintaining the stability of the mire. Under natural, undrained conditions, the acrotelm buffers the catotelm from external influences. Thus the aerated layer does not move into the waterlogged catotelm in undrained mires. Eggelsmann (1990) suggests that where drainage has lowered the peat water table, both the acrotelm and the upper limit of the catotelm is displaced downwards; if the profile is shallow or the drainage deep, the acrotelm may disappear entirely. For example, where a mire is drained for forestry

purposes, site preparation disrupts the surface hydrology and encourages extensive peat wastage, whilst as the trees mature, deep oxidation of the peat, together with increasing compression from the timber overburden, will produce irreversible changes in the peat.

Drainage results in primary consolidation, followed by shrinkage, secondary compression and finally wastage or subsidence of the mire surface (Hobbs, 1986). Primary consolidation occurs as the aerated upper peat layers compress the waterlogged lower peat. This decreases the void space as water is expelled. Primary compression can result in the subsidence of the peat surface by 1.5 m in a peat depth of 10 m within 12 months of drainage, if the water table is maintained at 1 m depth (Hobbs, 1986). Weakly decomposed peats tends to undergo greater primary consolidation than amorphous peats owing to their larger void spaces (see Section 4.4). The reverse is true for shrinkage: amorphous peats shrink more because their fibres do not have a strong alignment. Weakly decomposed peats may shrink considerably in a lateral direction but there is less capacity for vertical shrinkage where, for example, *Sphagnum* leaves remain upright in unhumified peat (see Sections 8.2 and 8.3). In such peats, cracking rather than shrinkage often results when the peat is drained. Clear examples of cracking as a result of drainage are shown in Figures 4.26 and 4.27 for Blantyre Muir, Scotland. Here pump drainage of the raised mire to prevent the flooding of an adjacent opencast mine resulted in extensive cracking and slumping of the peat surface (Heathwaite, 1988; Bragg, Brown and Ingram, 1991).



Figure 4.26 Crack formation in the upper peat layers as a result of drainage, Blantyre Muir, Scotland (after Heathwaite, 1988; photograph: A. L. Heathwaite)

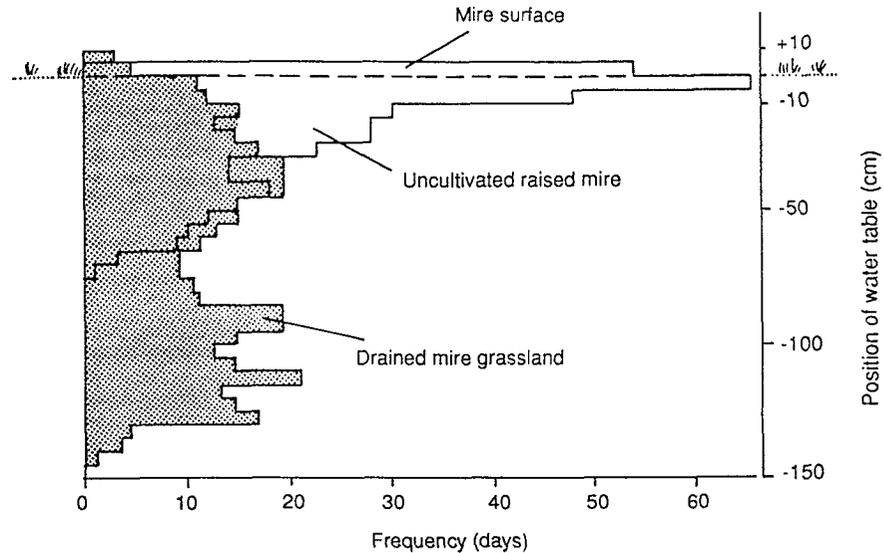


Figure 4.27 Extensive cracking and slumping of the peat surface as a result of mining at the mire periphery and pump action to alleviate flooding of the opencast site, Blantyre Muir, Scotland (photograph: A. L. Heathwaite)

Secondary compression occurs as the gradual rearrangement of peat fibres takes place and more tightly bound water is excluded from the peat micropores. Secondary compression is much slower than primary compression. The final stage in the chain of events initiated by drainage is that of subsidence which arises as a result of the oxidation of the aerated, upper peat layers. Subsidence is difficult to distinguish from the effects of shrinkage and secondary compression.

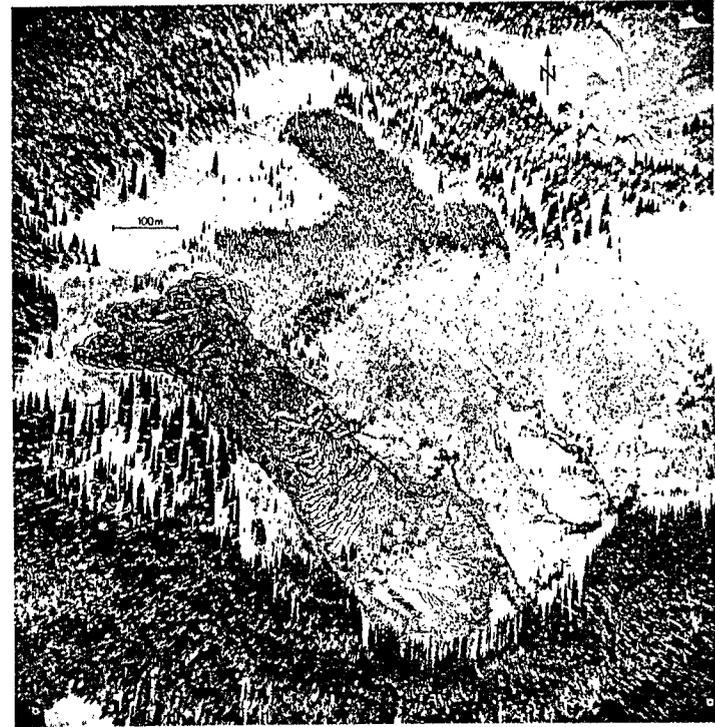
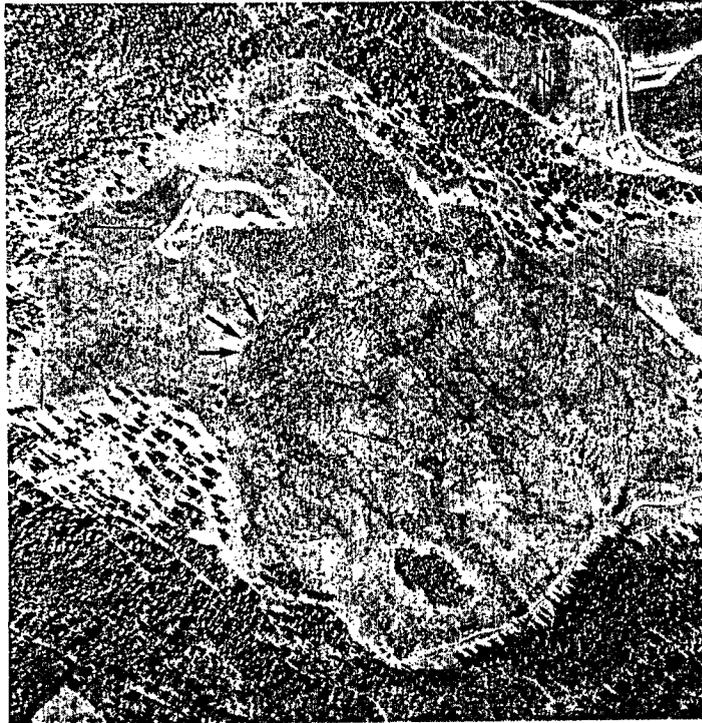
Drainage may, therefore, result in irreversible changes in the surface layer of a mire because groundwater is more or less permanently excluded, so the originally high water content of this layer is regained only briefly, if at all. This means that the access of air to the peat is much greater than in the undrained state. In such conditions, peat deposition no longer takes place, and, on the contrary, there may be increased decomposition of the surface peat layer and the positive balance of organic matter may become negative. Ivanov (1981) suggests that where a mire has had its surface vegetation replaced by a non-peat-forming community and the natural drainage system is disrupted, a gradual loss of peat will result until eventually all trace of organic soil will be lost. The rate of decomposition and hence the rate of peat wastage depends on the acidity of the peat. In raised mires and acidic transitional mires, the rate of consumption of the organic material may be small; in drained fens on the other hand, a considerable decrease in the height of the mire profile may occur, particularly in calcareous peats. As a result of the changes brought about by peat drainage, the term 'acrotelm' does not apply to the upper strata of drained mires.

Contrary to the effects described above, a number of authors have suggested that the effect of drainage on mire hydrology is confined to a few metres either side of the drainage ditch (Boelter, 1972; Galvin and Hanrahan, 1967; Stewart and Lance, 1983, 1991). Lindsay *et al.* (1988) suggest that such a limited impact on mire hydrology only occurs where an acrotelm is no longer present at the mire surface; where a well-developed *Sphagnum*-rich acrotelm is drained, the hydrological and ecological impact of drainage is large (Ingram and Bragg, 1984; Hobbs, 1986). Figure 4.28 illustrates the change in the 'residence time', or time during which the water table stands at a given depth in the peat, for undrained and drained raised mire peats. In an undrained raised mire, the water table lies within a few centimetres of the ground surface for more than 90% of the year; drainage alters the pattern of residence time in the peat.



**Figure 4.28** The change in the residence time (proportion of time the water table is at the peat surface) for undrained and drained raised mire peats (after Lindsay *et al.*, 1988; reproduced by permission of the Nature Conservancy Council)

The impact of peat drainage is not restricted to changes in the composition of the plant community alone. Ivanov (1981) suggests that the relationship between hydrological stability and the surface patterning in mires may also change. Drainage decreases the rate of surface seepage of water through the acrotelm as a result of the increasingly dry conditions (Lindsay *et al.*, 1988). This leads to a mire surface which is dominated by ridge and hummock communities of low hydraulic conductivity, rather than the hollows and pools which are present in the undrained mire. Drainage, therefore, imposes a new set of gradients on the mire hydromorphology to which the acrotelm must adapt, if it can. The most extreme examples of an acrotelm which cannot adapt to the changes such as drainage are bog bursts and the development of erosion complexes in the mire (Figure 4.29).



**Figure 4.29** Catastrophic bog burst in the Mouille de la Vraconne National Park in the Swiss Folded Jura range close to the French frontier, at 110 m above sea level. The bog burst occurred during the night of 25/26 September 1987, and was initiated by 180 mm of rain falling in 8 hours (an intensity of  $22.5 \text{ mm h}^{-1}$ ). From the mire type and geomorphological situation it appears that this burst occurred in a soligenous blanket mire of about 50 ha overlying a layer of impermeable marl on a 1% slope of stratified Jura limestone. There is a gravity water outfall at the higher northern end of the mire and a chain of dolinas at its lower southern margin. The burst affected an area of 9–10 ha and the flow is 600 m long and about 150 m wide.

## 4.6 THE MICROCLIMATE OF MIRIS

In general, mires have a specific microclimate, which is often markedly different from that of their immediate surroundings and evident, for example, from night frosts in spring and autumn or from ground haze in summer. To a certain extent, the microclimate of mires depends on topography. For example, the microclimate of the many mires found in valleys or depressions is affected by the influx of cold air. However, as discussed below, the microclimate of mires is primarily soil dependent.

### 4.6.1 THERMAL CONSTANTS

In the absence of plant cover, heat transfer to a mire depends on molecular or physical thermal conductivity, mass exchange or thermal radiation, and on heat transfer through water in its various forms.

The microclimate of any mire is strongly influenced by the thermal conductivity and thermal capacity of the upper 20 to 30 cm of peat because it is only to this depth that daily thermal radiation penetrates. Thermal conductivity and capacity depend, to some extent, on the peat type and bulk density, but are mainly influenced by the volumetric proportions of mineral and organic material in the soil and, hence, by the volume of water and air in it. If a dry and wet peat and sandy soil are compared, the soil-dependent differences in the thermal constants become obvious (Table 4.22). An increase in the soil water content improves the thermal conductivity and also increases the heat capacity and, as a result, more heat is stored in the soil. The temperature conductivity can be determined mathematically from the delay and attenuation in the daily or annual progress of a heat wave in the soil. The amplitude of temperature fluctuations is rapidly damped in peat soils. The damping depth (the depth at which the sinusoidal oscillation has been reduced to  $1/e = 0.37$  of that at the surface) is approximately 5 cm for the daily cycle and 1 m for the annual cycle in peat. This means that at a depth of only 15 cm, the amplitude is  $e^{-3} = 0.05$ , so daily temperature fluctuations will be small even though they may be at least twenty times this figure at the peat surface. Such variations in the temperature characteristics of the upper peat layers have a significant impact on the rate at which organic material is decomposed (Clymo, 1983).

Table 4.22 Thermal properties of peat and sand (after Geiger, 1961; Oke, 1978)

Soil	Thermal capacity ( $\text{J m}^{-3} \text{K}^{-1} \times 10^6$ )		Thermal conductivity ( $\text{W m}^{-1} \text{K}^{-1}$ )		Temperature conductivity ( $\text{m}^2 \text{s}^{-1} \times 10^{-6}$ )	
	Dry	Wet	Dry	Wet	Dry	Wet
Mire	0.6	4.0	0.07	0.5	0.1	0.2
Sand	1.2	2.9	0.20	2.0	0.2	0.8

4.6.2 SOIL TEMPERATURE

The better the thermal conductivity of a soil the more uniform is its temperature at ground level and vice versa. Soil colour or albedo is also important; dark coloured peat soils will have a different temperature distribution to light-coloured sandy and loamy soils. Figure 4.30 illustrates the geotherms (isotherms) for a cultivated fen (Donaumoos) and a mineral soil (Ingolstadt) in Bavaria. The patterns shown illustrate the varied seasonal warming and cooling that take place during the vegetative period in both ecosystems. The experimental areas are 12 km apart and at the same height above sea level (Kern, 1952). The loam which is the colder in winter, warms up faster in spring and to a higher temperature and a greater depth than the fen. The behaviour of the geotherms show that the cooling and warming of the upper soil layers take place in individual waves which from time to time are interrupted by counter-phases of inertia. Layers more than 15 cm under the soil surface are not affected by short-term temperature fluctuations.

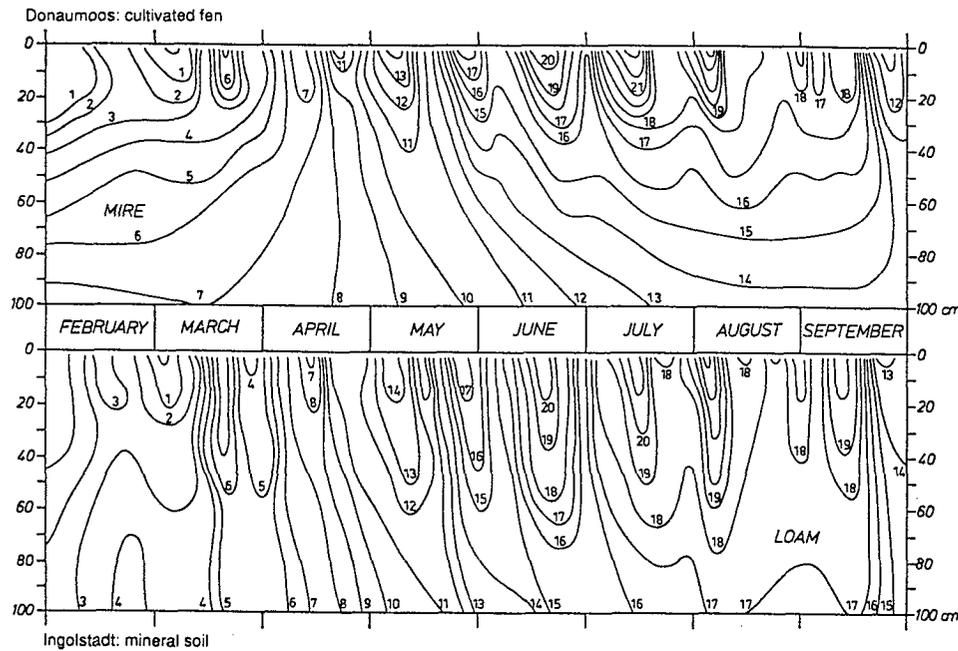


Figure 4.30 Geotherms for a cultivated fen (Donaumoos) and a mineral soil (Ingolstadt), Bavaria

Figure 4.31 compares the depths to which mire and mineral soils at Königsmoor Experimental Farm near Tostedt, Hanover, froze during the winter of 1952/53. The depth of freezing is illustrated by 0°C isotherms. The pattern and depth of freezing indicate that sandy soils not only freeze to greater depths but also thaw out faster than mire soils.

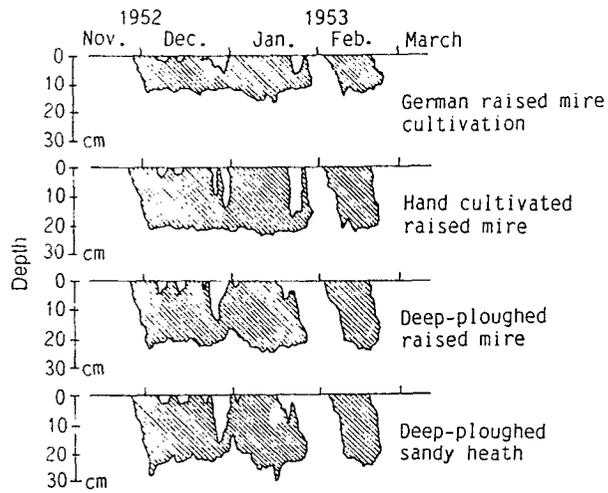


Figure 4.31 Soil frost depths at Königsmoor near Tostedt, Hanover (after Baden and Eggelsmann, 1958)

4.6.3 THE MICROCLIMATE OF THE SOIL SURFACE LAYER

The soil microclimate of a habitat occupies the zone between the soil surface and roughly 2 m above it. It is affected firstly by the soil itself and secondly by its plant cover. In order to quantify the microclimate of a habitat, comparable periods of windless, cloudless weather with undisturbed radiation are needed. In general, during the day the air layers nearest the soil surface warm up to a greater extent than those higher up: at night the reverse takes place.

The heat balance of three mire habitats in Teufelsmoor, north of Bremen was examined (Miess, 1968). The meteorological measuring stations used on Teufelsmoor are shown in Figure 4.32 and the air and soil surface temperature differences at various heights

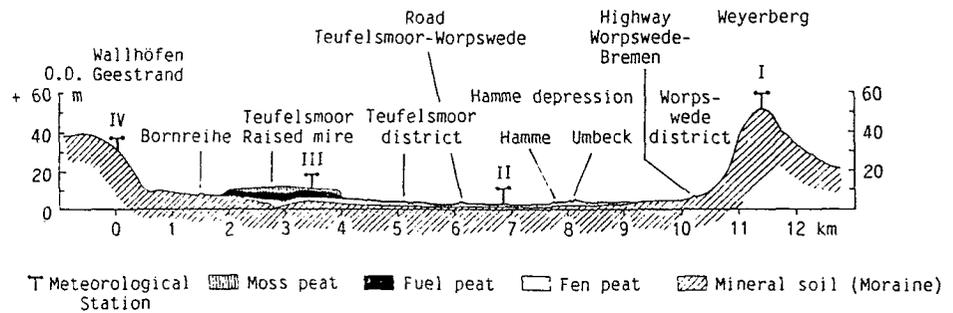


Figure 4.32 Meteorological measuring stations on Teufelsmoor (1944-1966) showing the section of the Hamme depression between Wallhöfen and Worswede (after Miess, 1968) (Vertical scale exaggerated 30-fold)

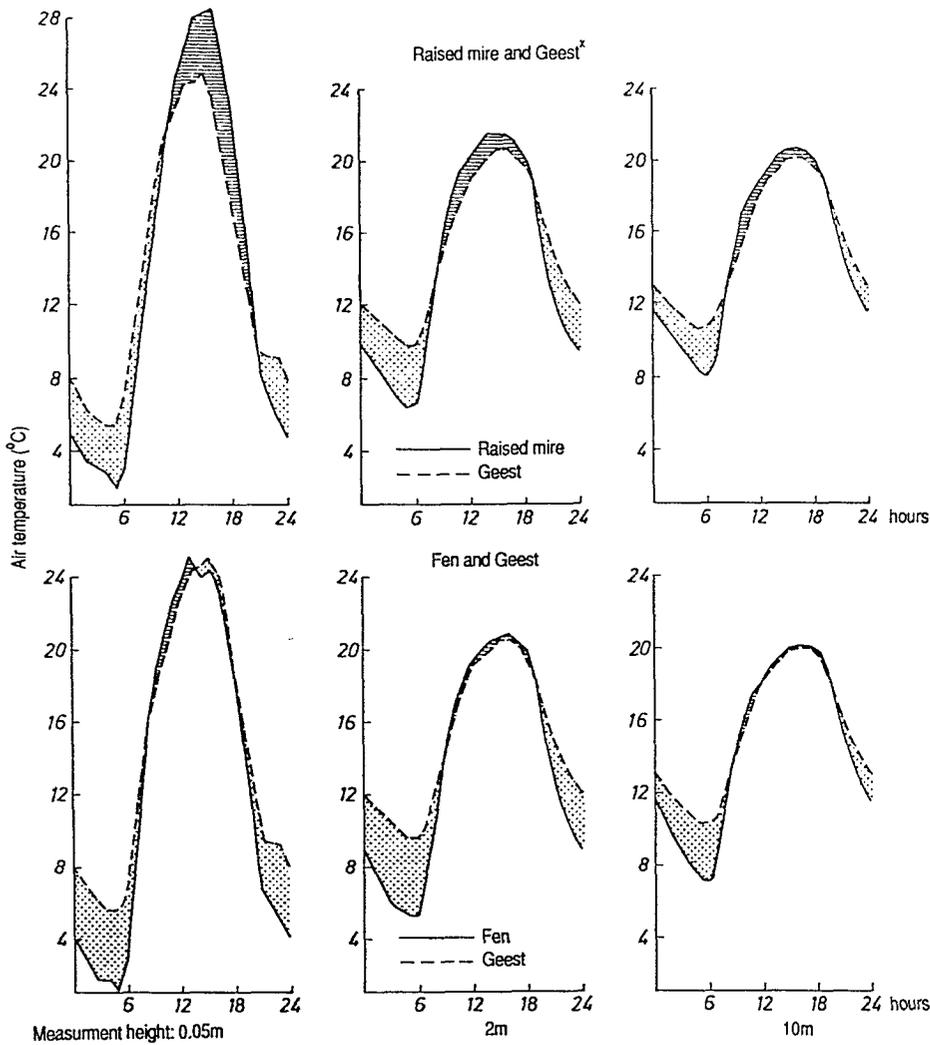


Figure 4.33 Air temperature differences on Teufelsmoor at various heights between the mire and Geest habitats (average values 9-18 August 1965) (after Miess, 1968) (Geest\* = sandy soil)

recorded over a 24-hour period are shown in Figures 4.33 and 4.34, respectively. The raised mire temperature variations have a wide amplitude relative to the sandy soil (Geest\*) which shows a more level temperature curve at its surface. Air humidity values are often similarly differentiated between the microclimates of such habitats. This is because the greater evaporation from mire surfaces (see Section 4.5) results in the air layer near the mire surface having a higher moisture content than in a mineral soil.

\* Geest habitats are found in the northwest German coastal region and consist of poor sandy soils in an elevated position above the fertile marsh.

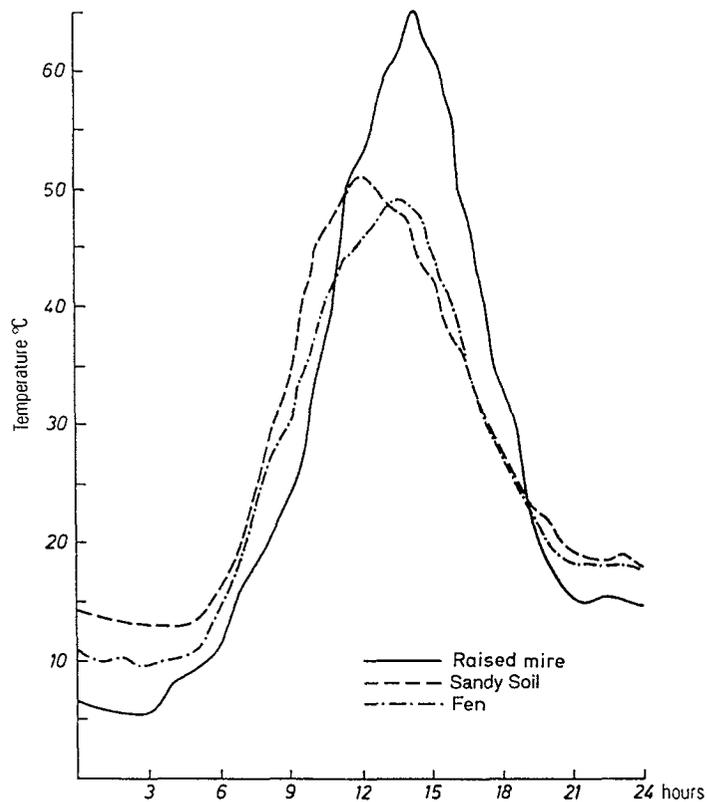


Figure 4.34 Maximum temperatures at the soil surface on July 18, 1964 at Teufelsmoor (after Miess, 1968)

#### 4.6.4 THE EFFECT OF PLANT COVER ON MIRE MICROCLIMATE

Plants modify the microclimate of a habitat by altering the heat and water balance of the soil in which they grow. Plant cover moderates the extremes of soil temperature and can, therefore, compensate for the thermal effect of soil type. For German mires, the highest noon temperatures (45 to 65°C) were measured in living, but dried-out, cushions of *Sphagnum* and *Polytrichum* on a raised mire (Eggelsmann, 1990). Similar values have been obtained for lichens, but because of the lower thermal capacity and conductivity of the dry plants, an accumulation of heat at the surface occurs during the day which changes to supercooling by night (frost hazard).

The air temperature and humidity values recorded in summer at a height of 5 cm above (i) raised mire with grassland cover and (ii) raised mire overgrown with heather demonstrate the effect of plant cover on microclimate (Table 4.23). The heather-covered raised mire has a lower evaporation intensity which results in less humid air above the soil surface which warms up by day, but by night it cools down to a greater extent than the more humid air recorded close to the soil surface of the raised mire grassland.

Table 4.23 Monthly mean air temperature (°C) and humidity at a height of 5 cm above the mire surface

Month	<i>Calluna</i>						Raised mire grassland					
	Vapour pressure (kPa)	Relative air humidity (%)	Air temperature				Vapour pressure (kPa)	Relative air humidity (%)	Air temperature			
			Max.	Min.	Amplitude	Mean			Max.	Min.	Amplitude	Mean
May	8.4	65	23.6	2.9	20.7	13.3	10.3	79	21.4	3.4	18.0	12.4
June	12.8	63	22.4	5.6	16.8	14.0	14.2	77	20.8	6.2	14.6	13.5
July	14.8	71	23.5	8.0	15.5	15.8	15.3	84	20.5	8.2	12.3	14.4

The soil climate of the grassland cover is less extreme; the lower maximum and higher minimum temperatures are a direct result of higher evapotranspiration.

#### 4.6.5 THE REGIONAL MIRE CLIMATE

On a regional scale, the microclimate of mires, in comparison with that of mineral soils, is characterised by higher air humidity, greater fog frequency, and a greater risk of night frosts. For example, over a 10-year period (1951–1960) at Königsmoor near Tostedt, Hanover, at least one night frost was recorded, at a height of 5 cm above the soil surface in all months (even in June and July) and the number of foggy days was two to three times greater than the average in Lower Saxony. Figure 4.35 shows the number of hours per day of high (>97%) relative humidity, measured at 0.7 m above the plant-covered soil surface, for a Geest habitat, consisting of poor sandy soils in an elevated position above the fertile marsh of the northwest German coastal plain, and a fen (Duvenstedter Brook) habitat in Schleswig-Holstein. It is clear that the air humidity is much higher over the mire than over the mineral soil. The slight differences between the maximum temperatures, together with the pronounced difference in the minimum temperatures between a fen (Duvenstedter Brook), a cut-over mire (Ahrensburg) and the city of Hamburg (Figure 4.36), are typical temperature profiles for this form of surface cover. On a clear night in July 1976, a temperature of 13.4°C was recorded within the city and 7.0°C on its outskirts on the sandy soils, whilst on the mire, a slight frost was recorded (Figure 4.36). The large differences in the minimum temperatures and the small differences in the maximum temperatures of a fen in comparison with a neighbouring Geest habitat are shown in Figure 4.37.

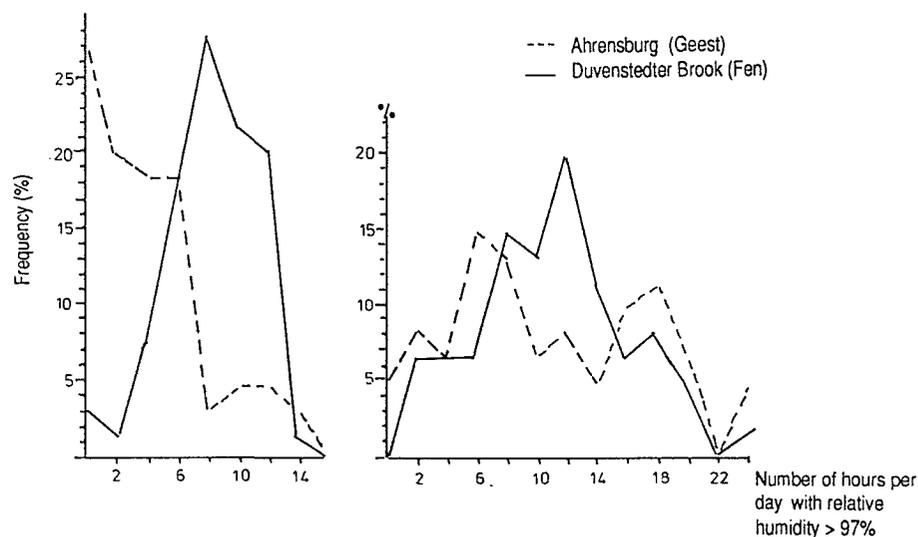


Figure 4.35 Percentage frequency and number of hours per day with greater than 97% relative air humidity for Geest (---) and fen habitat (—) near Tlamburg (1976). Measurement height 0.7 m

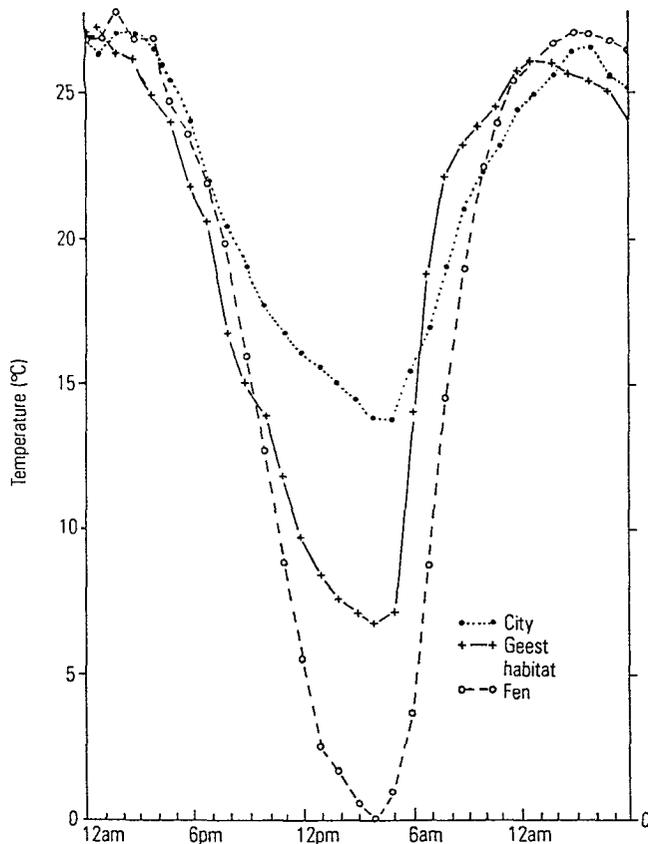


Figure 4.36 Daily curve of air temperature at 70 cm above a fen (Duvenstedter Brook near Hamburg), a Geest habitat (Ahrensburg) and a city (Hamburg). All habitats have a short grass cover

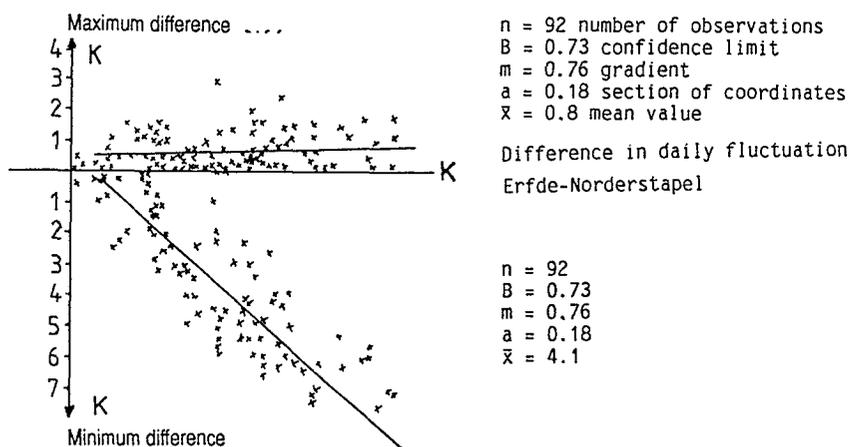


Figure 4.37 Minimum-maximum differences in air temperature between Norderstapel (fen, Treen-Eider-Gebiet) and Erfde (Geest habitat) at 0.7 m reference height. Both sites have grass cover; 1976-1977; data in °K

#### 4.6.6 THE EFFECTS OF DRAINAGE AND CULTIVATION ON MIRE MICROCLIMATE

In general, deep drainage has little effect on the microclimate of a mire. However, if a raised mire is drained and not subsequently used, for example, for peat production, then its microclimate may be expected to become locally more extreme, with an increased risk of night frosts and, in dry summers, increased heating leading to fire risk. Any cultivation, such as reseedling with grass or tillage over sand-mix cultivation (see Chapter 7), leads to 'microclimate improvement' (see Section 4.6.7).

#### 4.6.7 THE EFFECTS OF REWETTING AND FALLOWING ON MIRE MICROCLIMATE

If an area of grazed mire is abandoned or fallowed, the soil water balance, vegetation and the heat balance will alter (see Table 4.24). Most significantly, the incidence of frost increases by at least 30%, shortening the vegetative period of the fallow by about two weeks in both spring and autumn in comparison with its previous use as grassland.

**Table 4.24** Differences between surface temperatures and standard air temperatures (at 2 m height) on abandoned (fallow) raised mire and grazed grassland at Königsmoor near Tostedt, Hanover. Radiation days are given for the period 1976–1977; data in K (after Beinhauer and Klose, 1981)

Type of material	Fallow	Grassland
Dead plants, sedges	up to +7	—
Thistles, sedges	up to +3.5	—
Grassland	—	–2 to +2
Mire, overgrown 4 m <sup>2</sup> area	+5 to +7	+3 to +5
Mire, overgrown 1 m <sup>2</sup> area	+11 to +14	+6 to +12
Mire, bare	+30 to +35	—

During a five-year experiment on fallow at Königsmoor near Tostedt (Hamburg district) the elements of the heat balance were recorded (Figure 4.38). The greater the heat intake and the better the thermal conductivity, the higher the soil temperature rises and the more active the various forms of life in the soil become. It seems likely that in an abandoned mire habitat, the average soil temperature at 10 cm depth regresses by about one degree per ten years, as has been found on other fen habitats (Beinhauer and Klose, 1981). Abandoned (fallowed) areas have a higher radiation balance and a higher latent heat flux than grassland as a result of the lower albedo of the abandoned area (0.18) compared with that of grassland (0.22). These values apply to dry conditions. In abandoned mires, the increasing growth of birch and shrubs, together with the lower albedo and higher latent heat flux, results in an increase in the evapotranspiration from fallow to about 10% higher than that from grassland. The higher sensible heat flux (compared with the latent heat flux) from abandoned mires

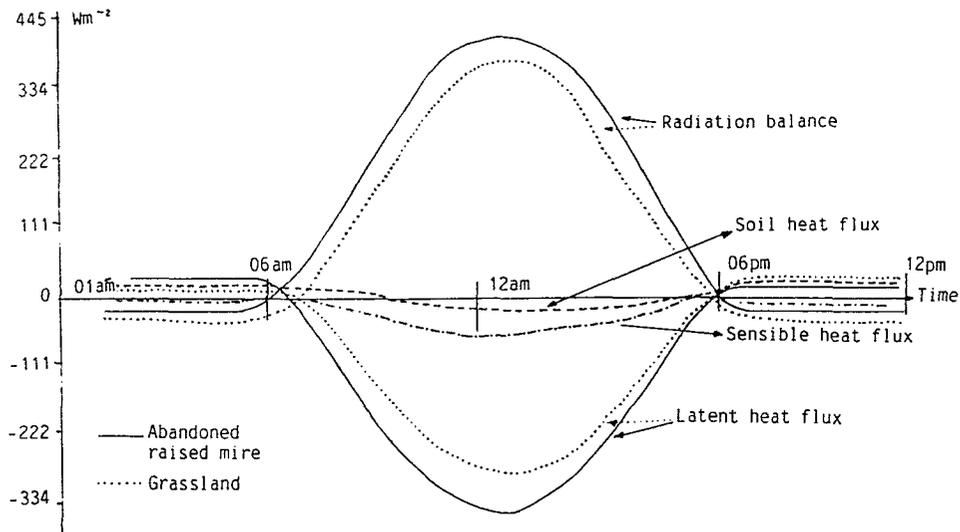


Figure 4.38 Radiation balance of sensible, latent and soil heat flux of an abandoned raised mire (—) and a raised mire used for grass production (- - -), Königsmoor (Tostedt/Hanover) for radiation days in 1980

resulted from the ample supply of water during the test period so that more of the radiated energy went to evaporation than to warming the layer near the soil. It was also found that the soil temperatures at depths of 5 and 10 cm in the fallow were about 0.5 K lower than in the neighbouring grassland. Similar values were obtained in a test of fallow on fen at Ritterhude near Bremen. The air temperature differences during radiation nights at 5 cm above the soil surface and between fallow and grassland were on average about 1 K higher on the latter than on the former, and in exceptional cases as much as 5 K (Table 4.25). Beinhauer (1977) suggests that, during the first few years after the flooding and resaturation of abandoned raised mires, the thermal conductivity worsens.

Table 4.25 Average minimum temperatures in °C during radiation nights in spring and autumn of various habitats; 1977-1979; scatter 0.8 K

	Geest mineral soil	Königsmoor raised mire	Ritterhude fen
<b>Spring:</b>			
2 m height	2.94	1.13	1.38
Fallow, 0.7 m height		-0.20	0.54
Grassland, 0.7 m height		0.50	0.93
<b>Autumn:</b>			
2 m height	3.30	1.55	1.42
Fallow, 0.7 m height		0.43	0.12
Grassland, 0.77 m height		0.99	0.93

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