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Staatsbosbeheer

THE HYDROLOGY OF BOG ECOSYSTEMS

Guidelines for management

J.G. Streefkerk and W.A.Casparie

T H E   H Y D R O L O G Y   O F   B O G   E C O S Y S T E M S

GUIDELINES FOR MANAGEMENT

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PREFACE

Directions for the reader

This report is concerned with the hydrological aspects of peat bog growth. Part I gives the setting for the formation of peat while part II discusses mainly questions of management.
It is primarily intended to aid managers of peat reserves in identifying possibilities for the regeneration of peat growth, so that these options may be included in management plans for the conservation of bog lands.

The report consists of two parts. Part I contains chapters 1 to 6, in which fundamental information is given on the spatial, historical and hydrological aspects of peat formation. Point of departure for this part of the report is the question:
Can the formation of peat, which took place over large areas of Western Europe in the past, be explained with the aid of knowledge of the hydrology and stratigraphy of bogs in the Netherlands?
The extensive hydrological knowledge of peat-lands is analysed and this information is tested against up to date stratigraphical opinion, the specific ecological characteristics of peat formation is also discussed. For a division of the types of peatland from an ecological and landscape point of view see e.g. Succow (1980, 1982) id.
A description of the present status of knowledge with regard to the types of peat-land is not included, although this would be a refinement. In fact the emphasis of this part of the report lies on the general understanding of the formation of peat.

Part II contains chapters 7 to 9 and discusses the possibilities for management, using the information of part I. The central question here is: Is it possible to create conditions suitable for the formation or the maintenance of ombrotrophic and actively growing bog ecosystems, in the nature reserve areas of the Netherlands?
The two disciplines hydrology and palaeobotanical peat research are integrated in this report. The conclusions of both parts of the report are not directly intended as a manual for the manager of a reserve, but the conclusions indicate possibilities for management.

Incentive

The incentive for this report came from a meeting of Dutch managers and researchers in the Netherlands in October 1985, which was concerned with the hydrological management of bog reserves. It became apparent that background information about the how and why of certain management measures was often lacking. To fill the gap the division Hydrology, Soils and Air of the State Forestry Service compiled this report.

Awknowledgement

The original Dutch version of this report was commissioned by the Management team of the State Forestry Service. The authors were supervised by Ir. W.P.C. Zeeman and Drs. H.H. Joosten, both of the State Forestry Service. Extensive discussions took place between both of these and the authors.

The draft report was commented upon by the following:

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PART I - THE HYDROLOGY OF BOG ECOSYSTEMS

1. INTRODUCTION

1.1. RAISED BOG IN THE NETHERLANDS AND ITS GENERAL SIGNIFICANCE

Raised bogs in the Netherlands developed in places where accumulation of organic material took place above the original level of drainage. At the same time the groundwater table rose. Finally the supply of water and nutrients originated almost entirely from precipitation. In 1823 the Danish geologist Dau put this in the form of a riddle: "Vom Regen nur und Thau des Himmels aufgewachsen", in which he compared bogs to trees without roots, with a very short trunk and a large flat crown. A living raised bog can be defined as a system derived from and build up by peat producing communities, which depend for their nutrition almost entirely on the atmosphere, and with a water table which is maintained by the system itself (ombrogenous peat growth). The latter distinguishes it from other systems which accumulate peat.

In the definition above the word "almost" is used in connection with nutrition, because in many cases the underlying material influences the vegetation on the surface to some extent and this leads to the development of different bog types. The isolation from the sub-soil is never complete, this is so not only at the edges, but also in the centre of raised bog complexes. Furthermore, within a bog a re-division takes place of water and nutrients originating from an even atmospheric supply, so that differentiation results through the action of flow of material and energy.
The different parts of raised bog complexes which can be distinguished are as follows: hummocks and hollows, lagg zones (the borders with other systems), contact zones, bog streams and flushes and pools. These differences give rise to different vegetation types.
In the Netherlands ombrogenous peat formation started from around 5000 B.C., and from about 3000 B.C. the bogs were well developed.
Bogs which developed in the Netherlands and which are characterised by the above definitions, belong to the raised bogs. It is estimated that 1,000,000 ha of raised bog existed in The Netherlands; three-quarters disappeared because it was eroded away by the sea or covered over by clay. At present less than 1% of the original surface remains, because of cultivation of the areas (e.g. drainage and fertilisation of the bog and cut away) and through the influence of the sea, giving rise to a halting of bog growth and a further decrease in the bog's domain.
About 8000 ha of mostly seriously drained bog lands still exists on the higher grounds of the Netherlands, of which almost 6000 ha are owned and/or managed by nature conservation organizations. These remnants are important from a historical and biological point of view. Therefore it makes sense that these fragments are protected and maintained as best as possible, with their vegetation and fauna typical of the bogs of the past. A good example of a totally intact bog landscape, with its typical plant and animal communities, does not really exist any more in the Netherlands. Smaller systems, (e.g. small fens and boglets) with some of the characteristics of raised bogs, do still exist, but these are so small that the essential characteristics of the large systems are missing, like the typical bog flushes and pools. Forces must be put into motion to regain large scale bog landscapes, with their typical communities.
Hydrological knowledge is of the utmost importance to achieve this. This leads us to discuss the hydrological problems of the existing bog remnants.

1.2. THE HYDROLOGICAL PROBLEMS OF THE EXISTING BOG REMNANTS

Because practically all bog remnants in The Netherlands are drained or partly dug away, optimum hydrological protection and management of these fragments is a complicated matter. Hydrological research on living bogs was not carried out. In the past in the Netherlands fundamental research did not start until the latter half of the 20th Century. The Dutch bogs were already mostly dug-away at that time, and their hydrological status drastically changed. The Dutch nature conservation organizations have, attempted to reconstruct the bog landscape over the last 15 years with some success, mostly as a result of an experimental approach, rather than on the basis of fundamental knowledge.
To deduce essential conditions under which bog regeneration would become possible, specific hydrological knowledge was applied more and more.
In general managers are little aware of the specific hydrological characteristics of bogs. The relevant literature is generally not easily accessable. This report aims to supply managers of bogs and planners of land reconstruction projects with this information, which is highly relevant to the possibilities for redevelopment and maintenance of the unique bog lands. Knowledge of the original bog ecosystems is fundamental.

In the following chapter is discussed the formation and development of peat bogs in general and of raised bog in particular, including the spatial aspects of bog formation.

2. SPATIAL AND TEMPORAL ASPECTS AND CONDITIONS FOR THE INITIATION OF THE FORMATION OF BOG

2.1. GENERAL

The huge surface area of the peat bogs of the past was without a doubt their most typical feature. In the North-East of the Netherlands more than half of the inhabitable area had disappeared under peat. Before that, in the coastal areas of Northern and Western parts of the Netherlands, enormous peatlands had developed, which disappeared again as a result of the rising water level of the sea. Prehistoric man too was confronted with expanding peat growth. The inhabitable area decreased, and he had to traverse peat barriers, often several kilometres in width, which were difficult to cross and compartimentalised the landscape. It was not until the Middle Ages that man succeeded to reverse this threat, by drainage of the peat bogs.
An other important characteristic of bogs is their significance as a stock pile of fossil energy. Prehistoric man must have been aware of this also, but the effective development of this source of energy by peat cutting did not start until the 16th century A.D.

In the present day raised bog is mainly of importance for its particular vegetations and the remarkable nutrient supply thereof: the ombrotrophy, i.e. the sole manor of feeding by precipitation.

The rarety of this ecosystem today indicates its sensitivity to human interference. Its value with respect to the landscape is usually considered as moderate, the recreational value as minor, and the scientific value is often considered very high. The latter is especially the case when the measure of interference with the peat producing vegetations is small. Intact bogs do not exist any longer in the Netherlands; in North-West Europe they are - if still present - very rare.
Prehistoric man attempted repeatedly to gain access to the bogs; this is witnessed by the existance of wooden trackways (toghers) in the bog.
These trackways could cross a whole raised bog, in which case we can speak of transport arteries, or perhaps these roads were mend to reach a destination in the bog itself. A valuable commodity was iron ore, which can be present in deposits of fen peat originated through seepage, or in fen peat underneath the ombrogenous peat layers. Prehistoric access to the bog is evident from objects left behind in the bog, usually called bog finds. Some of these objects would presumably have been lost or forgotten; some were almost certainly sacraficial. Bog must therefore have had a sacred or ritual significance. In the Middle Ages bog which was saturated with sea water showed to be excellently suited to the production of salt. The "selnering", digging and burning of peat sods, saturated with salt, caused large changes in various coastal areas.

Peat was, and is, usefull for various applications, apart from its use as a fuel; for campshedding of banks, for horticulture, for the preparation of active carbon, as a substance for insolation and even for construction of dwellings. A few industrial uses are also known.
Coastal peat bogs played an important role in the creation of the landscape since the last ice age, from about 10,000 years ago. As part of increasingly upward growing coastal barriers they kept a sizeable proportion of the hinterland free from regular or periodical flooding by the sea. Large deltoid estuaries remained habitable and exploitable for prehistoric man for an

extended period. Eventually the sea took posession of these areas; new coastal barriers were formed further inland at a higher level, these gave protection against the sea in turn.
This process repeated itself many times up to the 10th to 12th century A.D., after which time man started to protect himself from the sea by the construction of dykes.
As a consequence of peat digging for the winning of salt the coastal peat lands could not keep the sea from flooding the land any longer.
The peat lands, bog as well as fen, have significant scientific value as an archive of botanical and zoological material.
Vegetation history of the late Pleistocene and the Holocene are firmly rooted in the research of peat deposits.

2.2. ORIGIN AND DEVELOPMENT; ASPECTS OF TIME AND SPACE

2.2.1 General

Insight into the formation and accumulation of peats and into the mechanism of bog growth is mainly founded on the results of paleobotanical and stratigraphical research on bogs. The aims of this research are mostly the recording of bog accumulation and vegetation development, explanation of the biological processes, explanation of the prehistoric activities of man, description of vegetation and landscape development, the understanding of the processes involved in bog growth, and the recording of the development of climate.
Paleobotanical research, with the primary aim of insight into the hydrology of bog systems, has sofar hardly been undertaken.
However, a lot of information of a hydrological nature can be derived from this type of peat research (Casparie 1972, 1980, 1984, Casparie, Van Geel en Teunissen 1981, Dupont 1985, Van Geel 1976 en 1978, Van Zeist 1955).
This is specially so in the case of bogs investigated in detail in a number of areas, i.e. the Southerly part of the Bourtangerveen East of Emmen, between Emmererfscheidenveen and Klazienaveen and in the present day nature reserve Bargerveen.
Although a description of the development of this peat bog and of the processes involved is not given, the results from research in this specific place determines to a large extent the contents of what follows below. However, the statements have wider application than just to apply to the Bourtangerveen.
The areas of research are situated in the Hunzelaagte, a remnant of the icemarginal valley of the Hunze (better: the Ems). The oldest deposits are of Late Glacial times, even before the Allerød-Interstadial, around 11,000 B.C. (see Table 1).

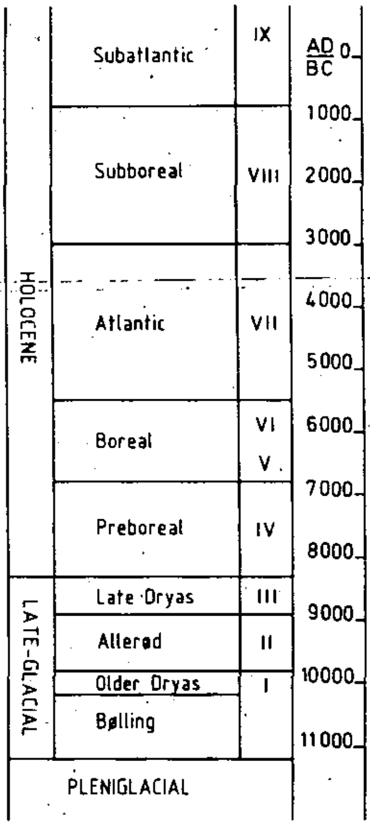


Table 1.
Time table for the bio-geological periods after the Weichsel-Pleniglacial. The division in roman numerals was developed for North-West Germany by F. Overbeck and S. Schneider, and is still used frequently. This division and time table appears also in fig. 7.

The formation of peat development continued, with many serious and less serious interruptions, until the final drainage of the Bourtangerveen for peat extraction. This last process started already in the 16th century A.D., near Groningen. Generally it can be stated that the drainage occured against the gradient of sub-soil relief/bog surface relief.
With the creation of a number of large drainage channels in the area East of Emmen, the most important drainage works were set in motion mostly in the 19th century. It is almost certain that the formation of peat was strongly reduced at least, if it had not altogether ceased, by the 17th century.
In the Bargerveen, situated to the South, these processes took place somewhat later, here bog formation had all but stopped by the end of the 19th century.
A schematic cross section is presented of the peat stratigraphy of the Bourtangerveen East of Emmen, in appendix 1.

2.2.2. The earliest peat deposits

The earliest peat deposits of the Late-Glacial period consist in many cases of Hypnaceae peat, its species combination indicates that it must have been formed under very moist conditions (see Table 2). Many gully-shaped depressions filled with fen peat and also bowl shaped depressions (e.g. remains of pingo) contain Hypnaceae peat deposits at the base with a thickness of 10-30 cm.
This peat formation often started in the Early Dryas time, the second last cold phase of the Weichsel Glacial. Peat formation often ends during the next warm period, the Allerød time, and usually coincides with the end of the Betula phase of this period.

Table 2. Botanical remains (seeds, fruits, leaves, pollen grains), found in the Late Glacial Hypnaceae peat (Braunmoostorf) in the valley of the Hunze, East of Emmen.

Species/type	Abundance	Species/type	Abundance
Betula pubescens	abundant	Myriophyllum spec.	frequent
Potentilla anserina	occasional	Potamogeton spec.	frequent
Comarum palustre	frequent	cf. Puccinella	frequent
Menyanthes trifoliata	frequent	Scorpidium scorpioides	occasional
Typha latifolia	occasional	(= Hypnum scorpioides L.)	
Carex cf. trinervis	frequent	Calliergon sarmentosum	abundant
Carex cf. paniculata	abundant	(= Hypnum sarmentosum Wahl.)	
cf. Scirpus fluitans	abundant	Drepanoclades indet.	abundant

Hypnaceae peat started to form as a result of a slight improvement in climate which made the permafrost thaw at the surface, and resulted in a surplus of water which could not drain away into the soil. It is possible that precipitation increased somewhat at the same time.
The end of the growth of the Hypnaceae peat, which usually occurred suddenly, is contributed to the melting away of the permafrost. This made drainage possible to a greater depth and because of this a steep decrease in water table appeared, which dried out the Hypnaceae vegetations.
In the Pinus phase of the Allerød peat formation occured more sparingly, probably because of a lack of precipitation.
In the Late Dryas, the last period of the last ice age, permafrost was present again in many places, which functioned as a water impermeable layer promoting new growth of Hypnaceae peat, which ended once more because of the thaw of the permafrost. This layer of younger "Braunmoostorf" is usually thinner than the layer that was formed earlier.
In places were an impermeable sub-soil remained, as in areas of boulder-clay and in pingo remains, the drying out is mostly absent, but a decrease in water table, and therefore a decrease in water supply to lowerlying areas, is recognisable none the less: a different type of peat is present or a certain slowing down of peat growth can be noted. In some places sufficient water was present to maintain an area of open water, in which gyttja could be deposited. Alternations of Braunmoostorf and gyttja deposits occur also.

2.2.3. The formation of fen peat

Often only after considerable time since the disappearance of the permafrost in the Late Dryas, are conditions wet enough to facilitate the development of fen peat. It is usually a very compact peat, which is composed of mainly Betula, various sedge species and Phragmites, as well as aquatic species like Menyanthes and Doepanoeladus (table 2) species. This type of peat can in general develop from the beginning of the improvement in climate after the glacial period; this is the transition to the Preboreal.
Although the presence of aquatic species indicates very wet conditions favourable for peat formation, the accumulation of organic material is in general small. In addition thin charcoal layers point to several interruptions in peat formation as a result of drying and fire. Apparently precipitation was sufficient to create wet conditions; on the other hand a surplus of precipitation was not always present. The precipitation and not the temperature is almost certainly the limiting factor.
Damp to wet conditions existed in cut-off valleys of brooks and rivers, in depressions like pingo-remnants and in gully shaped low lying ground, in which Braunmoostorf had already developed. These peat deposits functioned like a dam in the drainage system, obstructing the drainage to a great extent.
Overall the ground water table was rising gradually, with the result that conditions favourable for fen peat formation were maintained for a long time, resulting in fen peat deposits which were sometimes several meters thick.
During the Boreal the precipitation must have increased somewhat.
Pinus established itself several times on dryed-out peat. Towards the end of the Boreal period Alnus appears on the scene. This tree is well adapted to the conditions of the fen peat deposits, so that during the transition to the Atlantic period the formation of Alnus peat was initiated. The increase of the ground water table ended gradually in various places; in many cases the depression was completely filled with fen peat. The mineral subsoil was in almost all cases saturated with water and a large amount of water was held in the peat deposit, in which flow was practically absent. The influence of direct precipitation on the environment, in which peat formation took place, became more important.
The earlier eutrophic to mesotrophic vegetations of the fen peat were replaced by vegetations of a mesotrophic or slightly mesotrophic nature. In the tree layer Betula and Pinus were common, as well as Alnus; Scheuchzeria and Carex limosa could form extensive stands in very wet areas. The system was becoming more oligotrophic and appreciably more acid. The substrate was now colonised by several species belonging to the Ericaceae, e.g. Calluna vulgaris, Andromeda polifolia, Vaccinium vitis-idaea and V. oxycoccus, and Empetrum nigrum, as well as by the first Sphagna, for example the peat-forming species Sphagnum rubellum and S. fuscum. The influence of ground water on the system is now very minor; instead of fen peat we are dealing with transitional peat. This lies in many cases at the base of raised bog peat. The development of the system towards more oligotrophic and more acid conditions is not tied to any particular time period. In general the climate was suitable for ombrotrophic peat formation since the beginning of the Atlanticum.

2.2.4. <u>The marginal zone of a fen and the lagg zone of a bog</u>

A fen is usually surrounded by a special zone, which can be on the one hand more wet and on the other hand more sensitive to drying out than the fen peat system itself. During periods of high discharge of water from the fen when the sub-soil is saturated a system of pools develops around the fen, and locally gyttja formation can take place in these pools. The depth of water in these places is usually small and this marginal area can become appreciably drier rather quickly when the discharge from the fen decreases or the surrounding ground water table lowers temporarily. The area can become wooded with Alnus and Betula. If the water table increases again these woods can still survive for a longer time. The trees are than often submerged at the base. Fen-wood peat, specific of this vegetation, is formed in that case.

A zone of peat producing vegetation can be present around a bog complex, which has characteristics of both fen and bog. Such a lagg zone is an area where mixing of ground water and precipitation takes place. Scheuchzeria palustris and Carex limosa can occur here massively. Pools with Sphagnum cuspidatum and S. recurvum occur, as well as Alnus and Betula and areas with Sphagnum rubellum can develop. This lagg zone is very sensitive to drying out, just like the marginal zones of fen described above.
The development of lagg zones is favoured by a rather flat sub-soil. The peat deposit has usually a thickness of one to four dm and remains of Scheuchzeria palustris and Sphagnum cuspidatum are often clearly recognisable in the peat. A supply of oligotrophic acid water, rich in humic remains and flowing from the adjacent bog complexes, stimulates the development of a lagg zone. The humic acids flocculate out on the sandy sub soil and this promotes waterproofing of the substrate.
Lagg zones grow upwards slowly, in tandem with the extension of the bog complexes along the slight slopes around the bog. They are not restricted by a time period. Geomorphological and hydrological conditions were suitable for their development since the end of the Borial period. The substrate of the lagg zone is often a sand, which can be strongly podsolised, especially if it is a young lagg (Subboreal, Subatlantic). The growth of raised bog can often take place on lagg deposits.

2.2.5. <u>Seepage peat</u>

Seepage is present in some places from the beginning of the Atlanticum; and here extensive peat formation can take place during many centuries, and sometimes during thousands of years.
In the seepage fens Hypnaceae are the main peat formers. Where the flows of ground-water in the mineral subsoil, which feed the seepage, pass over deposits rich in iron or rich in phosphates, like boulder-clay and marine sediments, the resulting seepage peat is rich in these compounds. Infiltration areas can often be hundreds of hectares in extent. These can be peat complexes present at a relatively higher altitude, the water appears as seepage elsewhere; in the Northeastern Netherlands the Odoornerveen and the Bargerveen are examples of this.
Seepage fens are usually also hundreds of hectares in extent, or even bigger. The resulting peat deposits can be more than a metre in thickness, dependent on the amount of seepage and the relief of the sub-soil.
The surface relief of seepage fen reflects in the first instance the intensity

of the seepage. The peat shows little layering, which differs clearly from the situation in fen peat deposits.
In a number of cases it was calculated that a difference of 2 or 3 meters in altitude between the infiltration area and the seepage area is sufficient to maintain seepage at a distance of 2 to 8 km for a long time; up to approximately 2000 years.
As the difference in height between the two areas decreases (as is usually the case when seepage peat is formed) the share of direct precipitation increases and becomes more important for peat formation. Finally an environment can develop in which ombrotrophic species play an important role. Fluctuations in seepage supply are often difficult to observe in seepage peat deposits, except where this gives rise to the transition to ombrogenous peat formation. In practice this is usually a matter of a decrease in the seepage level until it is somewhat below the level of peat formation. In these cases the seepage still exists and the sub-soil remains saturated. In a few cases drainage of the area of infiltration has resulted in a dramatic decrease in seepage level. In that case a sharp transition from seepage peat to fen peat or even to ombrogenous bog can result. The mineral sub-soil was almost certainly not saturated with water for a definite span of time, when this occurs.

2.2.6. The start of ombrogenous peat formation

As a rule the transition between the production of non-ombrotrophic peat and bog peat is easily seen in peat profiles. Not only do peat forming Sphagna appear but also companion species like various Ericaceae and Eriophorum vaginatum are present when the transition to raised bog occurs. The transition is, as already mentioned, not tied to a particular time period.

In general it can be said that the climatic conditions for ombrogenous bog formation have been present for a minimum of 7000 years. The duration of the transition can vary from a few years to about 5 centuries. The peat accumulation also shows great differences. The thickness of the peat deposit, in which the transition takes place, is sometimes only a few centimetres, in other cases 3/4 of a metre. The micro-topography of the peat sections shows that the transition was not a uniform process. In a few cases it is evident that temporary drying out is the cause for the transition; the level of the transition can consist of wood peat and sometimes there is a clear break in the peat development.

The transition indicates that the trophic status of the water (i.e. the ionic loading), the pH and the availability of water are such that over a long period of time Sphagnum-rich peat forming vegetations can establish and maintain themself.
Many different initial conditions and substrates, mineral as well as organic, exists under which or in which raised bog formation can start off. These can include situations and substrates created by man.
Paragraph 2.3. gives further details.

2.2.7. Highly humified Sphagnum peat

The most important peat producers in most bogs are Sphagnum rubellum and/or Sphagnum fuscum. The number of companion species is generally large; large differences in space and time are present. The highly humified nature of the

peat profile makes for difficulties in interpretation; however a uniform peat accumulation is not present.
From the first half of the Atlanticum on the peat producing vegetation cover shows clear patterns of wetting and drying, hollows with Sphagnum cuspidatum and Scheucheria palustris and hummocks rich in Eriophorum vaginatum and Calluna vulgaris are present (see 2.2.8.). Most of the hollows will only have had open water to a small extent; the fact of the matter is that the growth of Sphagnum rubellum, a hummock builder is slowed down almost completely in open water.
In some well researched bogs (Bargerveen) large concentrations of hollows with open water were clearly present in the past; these consisted of shallow accumulations of water, which could maintain the peat formation.
The vegetation cover of strongly decomposed peat supported also large areas of predominantly Eriophorum vaginatum without hummocks and hollows; probably rather large fluctuations in water table took place here.
Since the beginning of the Atlantic precipitation has yielded enough water to maintain the formation of ombrotrophic peat (3.3.). Many bog surfaces show slight relief, which causes flow of water at the bog surface. The quality of the water changes a little during its course (pH, trophic level, oxygen content). As a result different systems which produce highly humified Sphagnum peat can co-exist at the bog surface, these are characterised by differences in the manner of layering, in the accumulation of organic material, in botanical composition of the peat and possibly also in the hummock - hollow systems. For example, in the bogs of Southeast Drenthe one can distinguish a complex of brown-black highly humified Sphagnum peat deposited down between approximately 4,000 and 2,000 B.C., which is different in the above characteristics from a blue-black highly humified peat (formed between 3,100 and 1,500 B.C.). The cause of the differences can be found in the local bog hydrology. The brown-black deposit was fed by water, which had flowed over the bog surface; for a relatively long course this water had become more acid, which resulted in peat formation in a more oxydising environment than in the case of the blue-black deposit, which had formed to the side of this main hydrological system.
The longer peat accumulation takes place, the more water is contained in the increasing deposit, and therefore sensitivity to short lived water shortages decreases. Gradually conditions can arise which cause the formation of poorly humified Sphagnum peat. Climatologically the conditions for this, were present since around 2,000 B.C. The substratum for this was supplied by the well developed hummock/hollow patterns: the conditions were very moist to wet, oligotrophic and of a low pH (2.2.8.).

2.2.8. Hummock - hollow systems and dome shaped complexes

The slight change in climate around 2,000 B.C. consisted of a slight increase in precipitation and air humidity and probably also of slightly lower mean temperatures. Conditions for the formation of ombrotrophic bog generally improved. This expresses itself in different ways according to local conditions. On soils already moist and with a thin basal layer of fen peat ombrogenic bog may start to grow; the establishment of an apparent water table, which manifests itself because of an impermeable layer in the mineral sub-soil (iron pan of heathland podsol), stimulates this process. In a number of depressions the water table increases, so that fen peat starts to grow. Some bogs extent considerably in a lateral direction; for example the Smildervenen and the Fochterloërveen in the Northern Netherlands. Clay deposits are becoming so wet in various places of Northern and Western regions of the Netherlands

that peat growth is beginning; sometimes after a short period of fen peat production ombrogenic bog is formed, see also 2.2.6. and 2.3.
Bogs with well developed hummock and hollow systems are becoming appreciably wetter at the surface, which results amongst others in the presence of permanent open water in the hollows. Without a doubt this resulted also in new drainage patterns; often it is not clear what these may have been. This is also so for the well researched part of the Bourtangerveen East of Emmen. For example the production of blue-black highly humified peat (2.2.7.) appears to continue without change. The hollows do become wetter, but the water surplus evidently drains away relatively quickly. The structure of the drainage pattern is not known. In the brown-black highly humified peat complex (2.2.7.) water discharge is stagnated. In a short time the hollows fill up with water, caused by increased precipitation and a decrease in mean temperature (3.3.).
Apparently an efficient drainage system was lacking or possibly it became inoperative because of the increase in water. In the hollows, which had a water depth of about 10 cm, the growth of highly humified Sphagnum rubellum is replaced by the production of less humified peat of Sphagnum cuspidatum and S. papillosum. On the slopes of the hummocks, just above the water table, poor to moderate humified S. imbricatum peat is formed. Both large-leaved Sphagna appear around 2,000 B.C., they can establish on the rather acid, very moist to wet, and oligotrophic bog surfaces.
On the hummocks the production of highly humified peat continues, with S. rubellum, Eriophorum vaginatum and Calluna vulgaris, under somewhat more moist conditions.
Around 1,500 B.C. the open water disappears from the hollows; the formation of peat however continues under very moist conditions (papillosum peat). This indicates the development of a new drainage system: periferal drainage of the domed complexes to the contact zones by means of a network of hollows, which are the places of water accumulation on the bog surface. The diameter of these domed complexes is approximately 3 to 5 km (fig. 1).

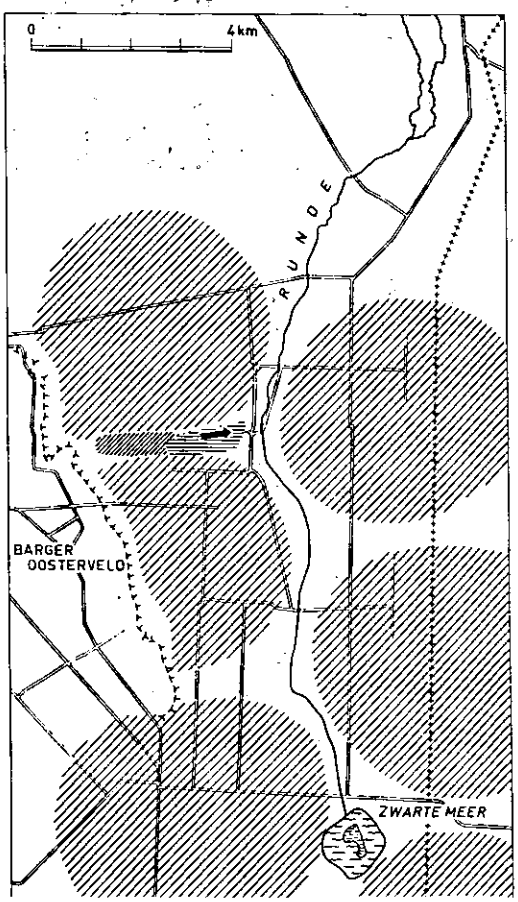
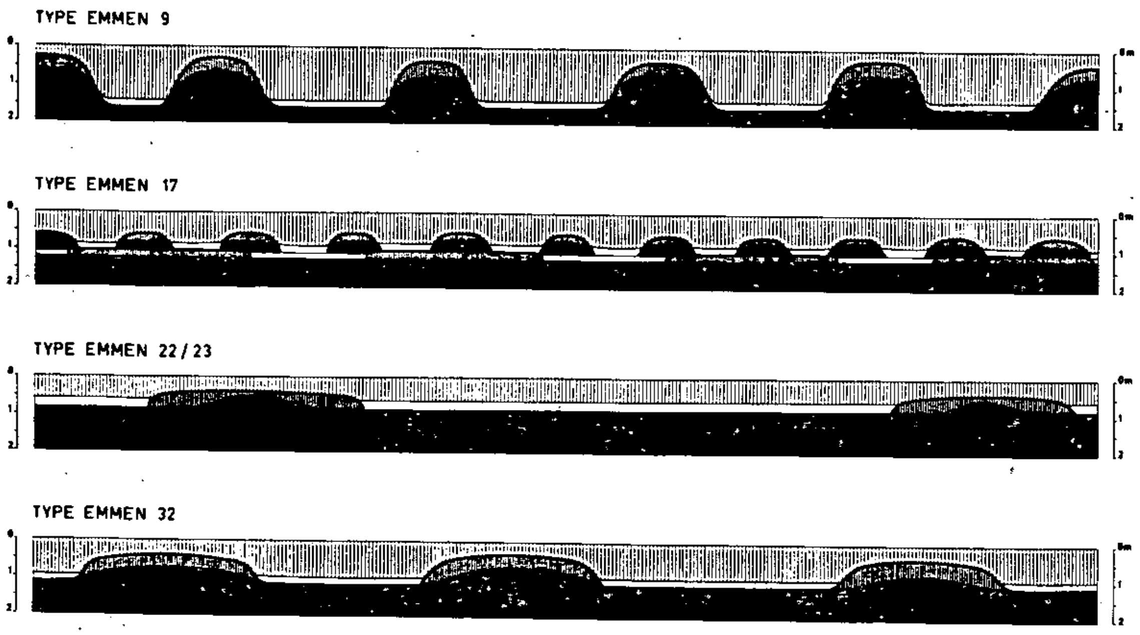


Figure 1.
The location of some domed complexes in the raised bog of Southeast Drenthe established by paleobotanical and stratigraphical research. The domed complexes started to develop about 2,000 B.C. The most common hummock - hollow system is type "Emmen 9" (see fig. 2). Contact zones, lagg zones etc. are not indicated separately. For an extensive description see Casparie, 1972.

The centre is probably 2 or 3 meters higher than the edge. The surface water flows very slowly, hampered by the vegetation of the hollows, in a centrifugal direction and thus feeds the ombrotrophic bog. In the domed complexes highly humified peat formation takes place in round and oval hummocks of a diameter of 3-6 m, which are surrounded by areas of poorly humified peat produced in the hollows, which vary in width from less than 1 m to 10 m.
The whole system is slowly growing upwards. Peat accumulation amounts to 10 to 15 cm per century (in the original situations, before shrinkage occurred of the peat deposits by drainage). This development can be clearly seen from the peat sections, see fig. 2.

Figure 2.
Four types of hummock and hollow systems can be distinguished in the raised bog of Southeast Drenthe, which characterises the transition from highly humified to poorly humified Sphagnum peat. These types are represented schematically, leaving out details like the companion vegetation e.g. Eriophorum vaginatum, Calluna vulgaris, Scheuzeria palustris etc.
Black: highly humified Sphagnum peat; narrow hatching: moderately humified Sphagnum peat; wide hatching: poorly humified Sphagnum peat; white: cuspidatum peat. The peat production pictured covers roughly the period of 3,000 B.C. to the first few centuries A.D. For detailed descriptions see Casparie, 1972.



Type Emmen 9: This is the most common type of the domed complexes.
Type Emmen 17: This is from a West-East contact zone. In fact this represents two different systems; the older, lower one with large, moderately humified hummocks, which changes around 1,500 B.C. into a much more pronounced form again with initially highly humified hummocks.
Type Emmen 22/23: This represents the marginal zone of a bog lake, which will not be discussed further here.
Type Emmen 32: This is from a South-North contact zone, in which took place already around 1,500 B.C. a slight permanent flow of water.

Large bog lakes developed in places were water collected, which flowed from the domed complexes (2.2.10). In the marginal zones of these lakes, patterns of hummocks and hollows developed, which are of a different scale than those of the domed complexes.
Part of the water that discharged from the domed complexes on the "brown-black" peat deposits, formed a lake on the deposit of "blue-black" peat. Here poorly humified cuspidatum peat deposits developed in the hollows from 1,500 to 1,300 B.C., which often contains many Scheuzeria palustris remains.
The latter indicates some influx of nutrients (caused by the blowing-in or flowing-in of nutrients from outside the bog area) or in other words an eutrophication of the water, which remains however very acid.
Although contact zones and bog lakes did certainly discharge some water, the supply of water from the domed complexes was much larger in comparison. This results on the one hand in good conditions for a very moist, poorly humified peat production and on the other hand it increases the sensitivity of the bog surface to erosion (2.2.10.).
Poorly humified peat production in the hollows is interrupted several times by the expansion of more humified peat formed by the hummock vegetations. This points to fluctuations in the amount of water which is stored at the bog surface. It is often not clear if these short interruptions in the very moist peat production are primarily due to fluctuations in climate (a dry phase of for example a few dry summers) or to a change in the system of discharge, which causes parts of the domed complexes to discharge water more quickly and therefore to dry out more.
The formation of poorly humified peat in the hollows of highly humified hummock-hollow systems is associated mainly with the relatively high humidity of a rather wet climate with almost certainly more than 700 mm precipitation per year, see chapter 3. This condition was present from at least 2,000 B.C. In many bogs the production of poorly humified peat started much later, probably because the acidity, the trophic level or the retention time of the water, in which peat formation took place, were not, or less, suitable. Sometimes poorly humified peat formation was not present, although for example Sphagnum imbricatum was present anyway.

2.2.9. Poorly humified Sphagnum peat and bog pools

Poorly humified Sphagnum papillosum peat and Sphagnum imbricatum peat only forms in the presence of acid oligotrophic water at a very high level in the bog profile. Sphagnum papillosum needs wet to very wet substrates and S. imbricatum grows primarily on moist to very moist sites. Since about 2,000 B.C. climatological conditions were suitable for this. Some centuries later the spacial structures in the form of domed complexes were also present (2.2.8.). The poorly humified moss peat, which was at first limited to the hollows, grew gradually over the strongly humified slopes of the hummocks. Finally the

hummocks were completely covered, but the hummock-hollow pattern remained Sphagnum imbricatum, which is a hummock former producing poorly humified peat, had taken over from S. rubellum; Eriophorum vaginatum and Calluna vulgaris played usually a less important role in the hummock vegetations than before. In the hollows Sphagnum papillosum was the most important peat producer; after inundation S. cuspidatum usually expanded strongly for a relatively short period. The process of growth of the less humified peat over the more humified hummocks, which had started in the bog of Southeast Drenthe between 2,000 and 1,800 B.C., was for the greater part completed between 500 B.C. and the beginning of the Christian period. During this development a catastrophic draw-off of water took place in the form of a bog burst (2.2.10). The supply of a sufficient amount of water to allow this poorly humified peat production to take place was associated with the formation of water basins on the higher central part of the domed complexes: i.e. the bog pools.
These probably originated because of the expansion of wet hollows during the growth of the hummock-hollow system, from about 2,500 to 2,000 B.C., in those parts of the bog surface where because of only small differences in level these basins could be filled with water for longer periods. The diameter of bog pools can be up to several tens of metres. The water depth is usually a few decimetres.
Present in the water are mostly floating mats of Sphagnum cuspidatum, Scheuchzeria palustris is sometimes also present.
Because of the generally homogeneous nature of the poorly humified peat deposits it can be assumed that also in the vegetation period, when water evaporated strongly from the Sphagna, enough water was still available to ensure contineous growth, even if precipitation ceased for longer periods. Moreover the quality of the water must have remained much the same. The water which disappeared through evaporation is compensated for by the subsidence of the peat surface, and so the level of the water table stays relatively high (in German: "Mooratmung" = bog respiration).

2.2.10 Contact zones and bog lakes

As a result of the surplus of precipitation, which usually occurs yearly, bogs build up a tremendous store of water; because of this and even given that the amount of precipitation remains the same, the bog surface becomes continually wetter. This is expressed by a growing amount of surface water, which typically discharges very slowly.
The greatest collections of water occur at the contact zones, where the surplus of water accumulates. The speed with which the waterlevel rises is naturally directly correlated with the size of the surplus of water from precipitation. The more this level increases - which results in the appearance of a real lake - and the more the pressure on the discharge system (the bog flushes) increases, the more the capacity of discharge increases also. Despite the increase in discharge capacity such large lakes did originate and were perhaps at least 10 ha in size and remained in existence for many centuries. For example a bog lake originated in Southeast Drenthe between 1,500 and 1,200 B.C., which catastrophical pushed out its lowest shore around 500 B.C. and emptied in a very short time (bog burst). Almost certainly a few wet years preceeded this. The erosion gullies which developed downstream functioned for many centuries as a system of discharge. After the speeding up of the discharge of the surplus of water from the bog, the bog surface became considerably more oligotrophic. This stimulated the growth of fresh to poorly humified Sphagnum peat. Such bog lakes are known from various large bogs; the former "Zwarte

Meer" in Southeast Drenthe was such a lake.
The occurrence of very extensive peat erosion (bog burst) has been documented more than once, partly on the basis of stratigraphical peat-bog research.

2.3. INITIAL CONDITIONS FOR THE FORMATION OF OMBROGENOUS PEAT

In 2.2.6. it was already mentioned that various substrates and various initial conditions can serve as a start for ombrotrophic peat growth.
We can distinguish (A) initial characteristics of the (mineral) subsoil; (B) peat producing substrates, which (can) change into raised bog; (C) conditions or substrates derived at by cultural-technical means, which are suitable for the development of ombrotrophic peat producing vegetations.
Borders between these three categories are not distinct; the differences between the distinguished substrates and conditions are not always absolute.

2.3.1. Initial conditions of the (mineral) subsoil, which can result in the development of Sphagnum peat

Sand

Considerable lateral extension of bog is sometimes induced by the growing up of peat deposits in areas with very slight relief. Often the sand is over-grown directly by Sphagnum vegetations (encroaching bog, "wurzelechtes Hochmoor"). The sandy subsoil which was at that time saturated with water, shows in the present day a thick peaty podsol, in which the "gliede" layer (amorphous humic material with many charcoal particles) is still present.
Water-impermeable layers, which caused apparant water tables to exist, did play at the most a minor role. These extensions of the bog dated mostly from the Subboreal and Subatlantic period; possibly this process started already in the later part of the Atlanticum on favourable sites. The extensions can be quite considerable; the most easterly border of the Smildervenen and parts of the Bargerveen originated in this fasion.

Clay

In the clay areas of the Northern Netherlands Sphagnum peat deposits are present on transgression sediments (mostly Calais IV, Duinkerke 0 and 1) sometimes up to a thickness of an ample 50 cm. After sedimentation of the clay in a salty environment the salt was apparently washed out in a relatively short time or the high salt content prevented other plants from establishing. The low permeability of the clay impeded the supply of nutrients and helped to retain water from precipitation sufficiently long to create conditions favourable for the growth of ombrotrophic peat. Part of these peatlands developed as true coastal bogs.

Boulder clay

Parts of the Bourtangerveen (east of Weiteveen), of the Fochteloërveen and of the easterly edge of the Smildervenen are situated on such a thin layer of sand over boulder clay, that one can consider that the peat formation started on the boulder clay itself.
Below the true ombrotrophic peat a thin layer of gliede is sometimes present, usually a thin peat layer with the characteristics of a lagg zone, developed

before the Sphagnum vegetations took over. The boulder clay functioned here as a water-impermeable layer, which caused the surface to become saturated with water from precipitation. Datings for these extensions of bog are at the end of the Subboreal and in the Subatlanticum.

Tertiary clay

The Haaksbergerveen and the Korenburgerveen are situated in gullies of tertiary clay. The earliest deposits are usually fen peat; the ombrotrophic peat, which was formed after this, can spread over the flanks of these depressions and contains a relatively large amount of Eriophorum vaginatum. This development took place from the second half of the Subboreal period.

Fissures and impermeable layers

As a result of tectonic forces water impermeable layers can come into existence at the present surface above fissures in the subsoil, which together with certain barriers, give rise to water-saturated conditions, in which ombrotrophic peat formation can begin to dominate. Examples of peat formation between fissures in the subsoil are the following: Deurnse Peel, Mariapeel, Breukberg and bogs along the Roode Beek.

Hard pan

The washing out of humic material into the subsoil of former peat areas can develop into a layer, which is very impermeable to water. Encroaching bog can profit from the water-saturated conditions in the sand above the hard pan. This phenomenum is present for example on the slope of several sand hills in the Southerly part of the Bourtangerveen. The invasion of the peat can be dated at the end of the Subboreal or later.

Iron pan

Well developed iron pans (e.g. from a heathland podsol and a peaty podsol), which form the base of apparent water tables, can become overgrown with bog vegetation, which transgresses from the fens developed in the water perched over these hard pans and which grows over the slopes of the bowl-shaped iron pan. Under such conditions the store of water, mainly supplied by direct precipitation, is usually so limited, that influences from outside the system hinder the progress of the ombrotrophic peat formation repeatedly. This type of peat production took place at the earliest in the beginning of the Sub-atlantic period.

2.3.2. Peat producing substrates, originated in the past, in which increasing oligotrophic conditions played a role at the start of raised bog development

Fen peat

The botanical composition and degree of humification of the peat can be various; Phragmites peat, sedge peat, alder or birch peat, from hardly to very highly humified, sometimes with remains of Menyanthes trifoliata. We are usually dealing with mesotrophic vegetations, in which ombrotrophy takes over, as can be deduced from the fact that vegetations with Sphagnum take over gradually. Sometimes a sudden transition to ombrotrophic peat takes place, which means that the (slight) rising of the groundwater ended suddenly or that a lowering occurred. In such a situation pools can remain in the lower parts of the fen surface, in which the transition to ombrotrophic peat can occur, for example via Sphagnum cuspidatum and Scheuchzeria palustris vegetations.

Seepage peat

In many cases this is Hypnaceae peat, which distinguishes itself from Braunmoostorf by a different ionic composition of the water (bicarbonate, phosphate, iron).
Almost always it can be shown that the following occurs: a lessening of the intensity of seepage, and thus an increase of the influence of direct precipitation on the environment, in which the peat is produced. Sometimes seepage stops suddenly, followed by drying out, after which the substrate has become suitable for ombrotrophic vegetations in a very short time.

Pinus wood peat

Pinus could establish itself at various times on fen peat. Sometimes the Pinus forests remained present for a few centuries. Although in a number of cases the establishment took place after drying out of the fen peat, a moist substrate is always present, in which organic material accumulates (primarily bark, needles). Gradually on this forest soil Sphagnum rubellum and S. cuspidatum, as well as various Ericaceae and Polytrichum strictum, could establish, and with this ombrotrophic conditions took over. Repeated drying out of the peat results again in the expansion of Pinus, but finally bog is formed. In Southeast Drenthe such a development took place between 4,500 and 4,000 B.C., and here Pinus expanded 3 or 4 times. This peat-bog forest extended for a few square kilometers. The Pinus stumps were overgrown by ombrotrophic peat.

In the same area of the bog a parallel development took place between 5,300 and 4,900 B.C., however the vegetation which superceeded the Pinus forest formed alder fen-wood peat. The cause of this was an increase in the level of the groundwater table.

Lagg zone

Here direct precipitation has a large influence on the peat forming environment and this creates conditions close to those for ombrotrophic peat production. An increase in the importance of precipitation or in the share of the surplus of water from nearby bog complexes can swing the balance in the direction of true ombrotrophic bog formation, which is pushed back repeatedly by decreases in the water table.

Peat mud

In wet depressions peat mud can collect, which results in a strongly acid environment and which causes also a stagnating of the water discharge. These conditions occur on (eroding) somewhat damaged bog surfaces in e.g. deep holes, in gullies and near fen peat formations. A thick peat mud deposit can also be layed down outside the actual bog, on which Sphagnum vegetations can start to grow.

2.3.3. Strongly changed hydrological conditions caused by recent or subrecent human influences

Floating cut-away peat blocks

As a result of recent hydrological management for nature conservation considerable increases in water-table are realised. In areas were this took place in (partly) dug-away terrain, pieces of cut-away peat started to float sometimes. The upper side of these blocks of peat appears to be an excellent substratum for ombrotrophic plant species, including Sphagnum magellanicum. The influence of direct precipitation on the immediate environment is apparently great.
In the water extensive Sphagnum vegetations can develop, mostly floating mats of S. cuspidatum and S. recurvum.
If the water is quite acid and poor in nutrients ombrotrophic vegetations can establish on these mats.

Floating peat mats

As a result of many cultural-technical interventions hydrological condititons came into existence, which do not naturally occur in these parts, but which can apparently lead to peat formation all the same. Fairly deep water is involved, in which rooting aquatic plants can not thrive and in which the water surface facilitates the expansion of floating peat vegetations (e.g. Phragmites peat); parallels with the natural formation of a mat of floating vegetation exist.
As on naturally occuring floating mats Sphagnum vegetations can develop on this type of floating vegetation, but because of the more nutrient rich status of this situation the establishment of ombrotrophic bog is much slower.

Flooded peat surfaces, which were dried-out previously

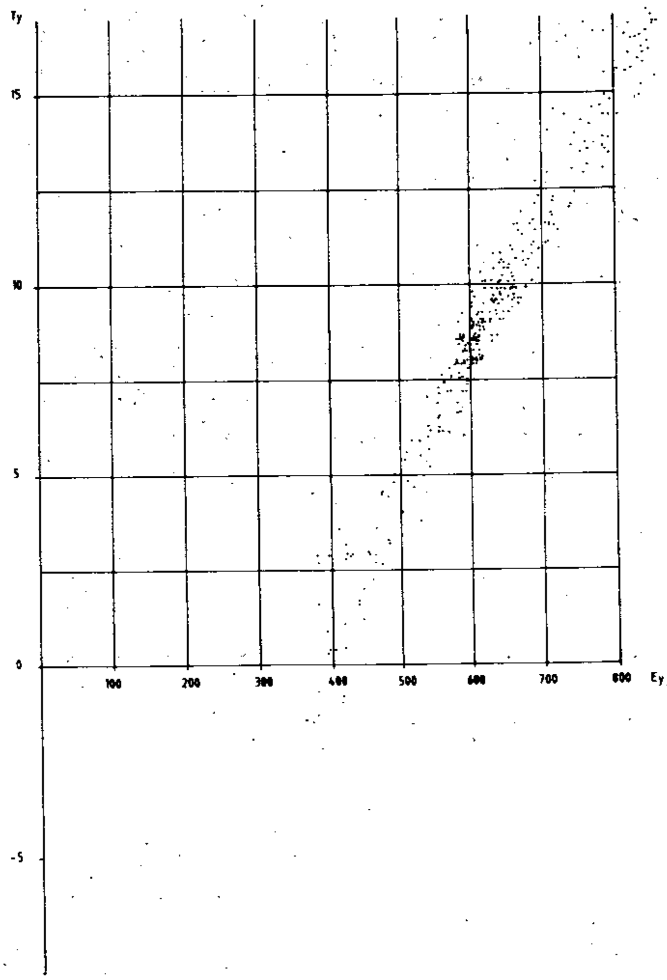
With nature management, which is orientated towards the containment of as much precipitation as possible on the surface of little damaged or resting bogs (drained or partly dug away), a sufficiently moist substratum developes in a relatively short time, on which e.g. Sphagnum magillanicum can establish and presumably also survive for a longer time. Inundated peat surfaces offer living space for S. recurvum and S. cuspidatum. Although these are anthropogenic interventions, it seems that in the past similar situations occurred naturally, e.g. after erosion on a large scale (bog bursts) or as a result of frequent erosion of a smaller extent.
The start of ombrotrophic peat growth is not determined in the first place by the substratum, but by changes in the quality of the water, which feeds the peat-producing environment. This change in water quality involves a considerable enlargment of the role which precipitation plays, which ensures that the environment becomes more acid and more oligotrophic.
Dependent on the local circumstances large differences in timing, duration, peat accumulation and composition of the peat producing vegetations develop, as described by peat stratigraphical research. These differences can occur within one particular bog.

3. CLIMATE - DUTCH BOGS IN AN EUROPEAN CONTEXT

3.1. GENERAL

Raised bogs can only exist if sufficient soil moisture is present for the Sphagna during the entire year. Bogs are exclusively fed by precipitation, which means that precipitation must be available for a certain period of the year or even for the whole year, in order to prevent drying out of the peat or at least to limit this to short periods. Evaporation plays an important role in the loss of moisture of bogs. In general moisture shortages occur more easily in warmer regions. Precipitation in these regions needs to be higher in order to guarantee sufficiently moist conditions for bog growth. The change in temperature is an important factor in relation to the intensity of evaporation, as is shown in figure 3, data are from meteorological stations in Europe (Müller, 1980).

Figure 3 Relation between average yearly temperature (T_y) and potential evaporation (Ep_y) in Europe (not including Russia)



Legend:

T_y = average yearly temperature;

Ep_y = potential evaporation

According to the figure the potential evaporation (Ep_y) increases with increasing average yearly temperature (T_y)

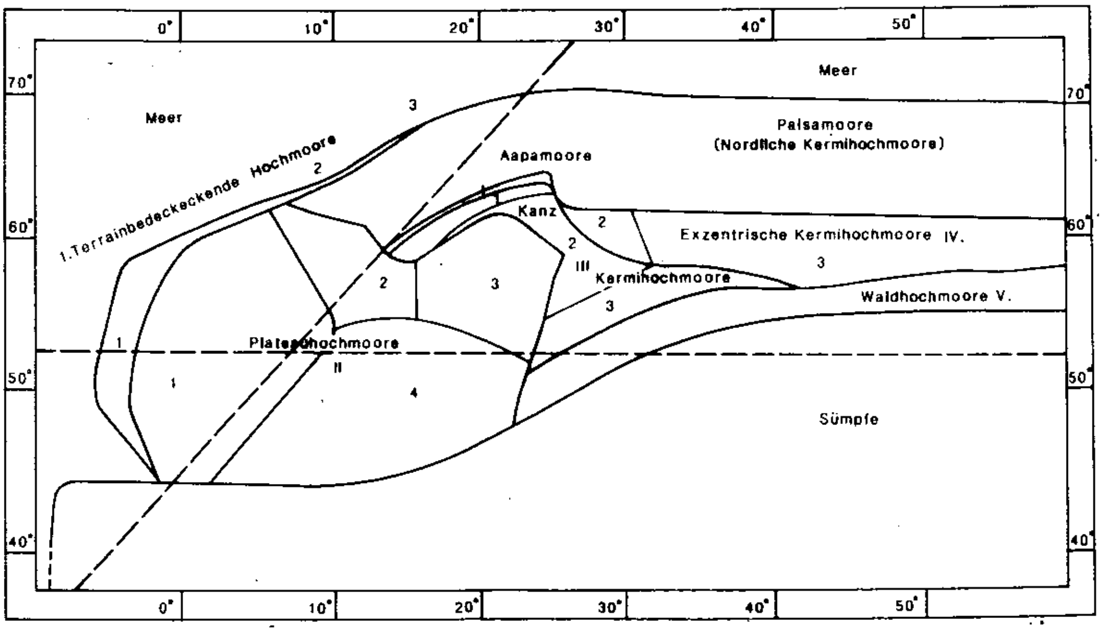
High temperatures go hand in hand with high intensities of evaporation and peat-growth will not be possible because of a lack of moisture, unless precipitation increases proportionally, as happens for example in Southeast Asia.
Climatological conditions therefore determine bog formation. Below the spatial and temporal expansion of bogs is discussed in relation to the climate, the Dutch situation is given special emphasis.

3.2. CLIMATE AND BOG IN EUROPE; SPATIAL ASPECTS

3.2.1. <u>Distribution and typification of ombrotrophic peatlands in Europe</u>

Eurola describes a classification of the distribution and typification of ombrotrophic peatlands in Europe. The ombrotrophic peatlands are classified according to the morphology of the bog-surface. Figure 4 below indicates this division.

Figure 4 Distribution map showing the types of ombrotrophic bog in Europe, following Eurola, 1962.



The ombrotrophic bog types are described along the two dashed lines, as given in fig. 4. For a characterization of the climate the <u>Handbuch ausgewählter Klimatstationen der Erde</u>, by Müller, 1980 was used.

Figure 5 and 6 picture the situation in Europe from north to south an from west to east.

Figure 5 Transect through Europe from north to south, along which climate and ombrotrophic peat types are described.

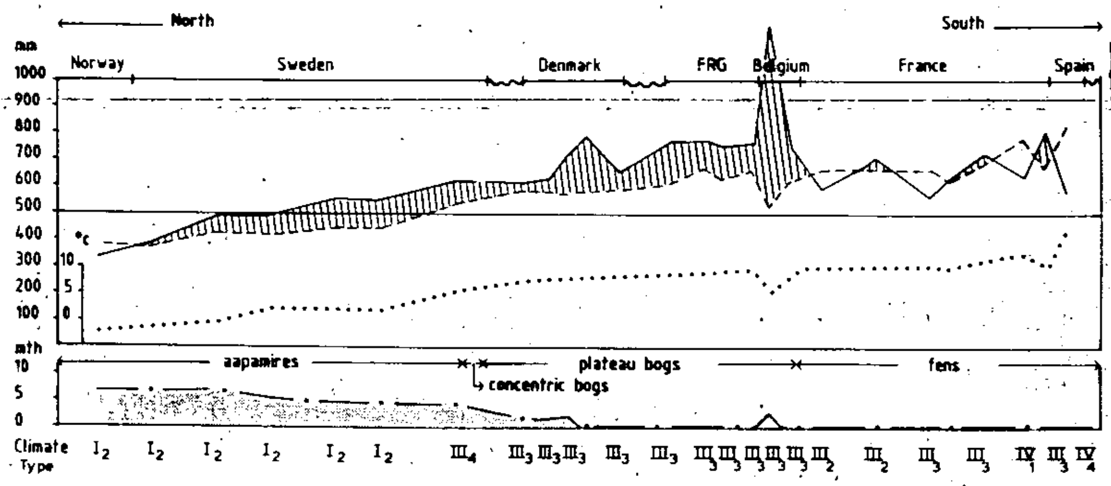
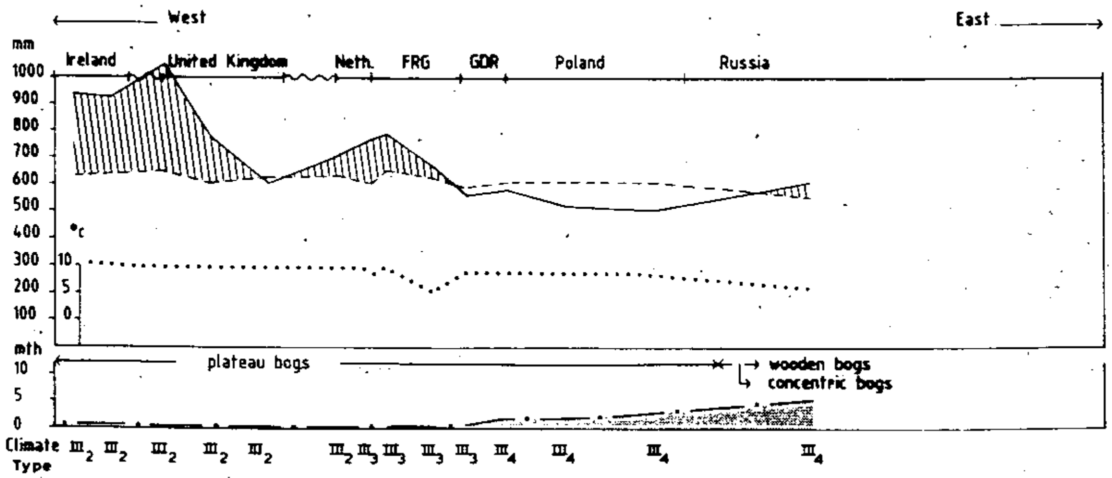


Figure 6 Transect through Europe from west to east, along which climate and ombrotrophic peat types are described.



Legend for figures 5 and 6:

Metereological data (according to Müller)

P average precipitation mm/yr
E average evaporation mm/yr
T average yearly temperature °C
V number of months in the year with frost

Symbols related to climate indicate the following:

Climate type (according to Müller)

I_2 Continental Boreal
III_2 Oceanic
III_3 Suboceanic
IV_1 Mediterranean
IV_4 Subtropical

Figures 5 and 6 indicate that a correlation exists between the occurrence of a certain type of ombrotrophic bog and the climatic conditions in Europe. The types of climate, in which the different bog types occur, are discussed in more detail, followed by a discussion of the distribution and characterisation of ombrotrophic bogs in Europe. Some characteristics of climate types, in which different bog types occur, are pictured in table 3.

Table 3. Some characteristics of climate types, after Müller (1980).

climate type	annual fluctuation in air temperature	mean temperature coldest month (°C)	warmest month (°C)	no. of months of frost	period with maximum intensity of precipitation
Oceanic	<16	>2	<20	0	autumn/winter
Suboceanic	16 to 25	2 to - 3	>16	0	autumn/winter
Subcontinental	20 to 30	- 3 to -13	>20	4	summer/autumn
Continental	30 to 40	-10 to -20	15 to 20	4 to 5	spring
Continental Boreal	20 to 40	-15 to -20	10 to 20	5 to 7	winter

Oceanic type

Typical of the oceanic climate is that temperature fluctuations over the year span less than 16°C. Furthermore, this type of climate is characterised by mild winters, in which the average temperature of the coldest month is higher than 2°C. In summer the temperature of the warmest summer month does not reach more than 20°C. In the autumn and winter months the precipitation intensity is the greatest.

Suboceanic type

This type of climate is characterised by temperature fluctuations over the year of 16 to 25°C. The winters are mild to moderately cold; the temperature in the coldest month can drop to 2 to -3°C. In the warmest month the temperature reaches on an average more than 16°C. Precipitation falls mainly in summer and autumn.

Subcontinental type

The sub-continental climate is characterised by cold winters (average temperature of the coldest month -3 to -13°C) and moderately warm summers (average temperature of warmest month less than 20°C). The period of frost in winter lasts approximately four months, and therefore the soil is frozen and covered in snow for extended periods.

Continental type

The continental climate is characterised by very cold winters (average temperature of the coldest month -10 to -20°C) and moderately warm and moderately moist summers (average temperature of warmest month 15 to 20°C). The frost period in winter lasts generally four to five months, and therefore the soil remains frozen for extended periods. The intensity of precipitation is usually high in spring.

Continental Boreal type

This climate is characterized by large fluctuations in temperature during the year, which are easily larger than 20°C. The winters are generally very cold and rich in snow. The period of frost lasts usually five to seven months. Summers are generally short, and the average temperature of the warmest month reaches from 10 to 20°C.

The division of these types of climate is not absolute. The distribution and typification of the European ombrotrophic bogs in relation to climate can now be described as follows below.
We restrict ourselves to the lowland bogs (below about 200 m in altitude); the climatological conditions for ombrotrophic peat growth in mountain-bogs are very different.

Plateau-bogs or raised bogs (Atlantic raised bogs)

These bogs reach their optimum development in central Ireland, the United Kingdom and in Norway, the Netherlands and West Germany. In Poland, Denmark, the south and the southeast of Sweden and in the southwest of Finland one finds gradual transitions to concentric bog. Transition to blanket bog occurs in Ireland and Scotland.
The plateau-bogs are marked by a somewhat domed relief (lens shaped). The centre of the dome approaches a flat surface. The names of plateau-, lens- or domed bog are derived from this feature. In the existing Dutch literature they are also called 'flat bogs'. The plateau-bogs occur in oceanic, sub-oceanic and sub-continental climates. These climates belong to the temperate and cool climatic zone of the world. The Netherlands are situated on the transition of oceanic to sub-oceanic climate. Well developed plateau-bogs occur in areas with a high effective humidity and with a relatively high intensity of precipitation in particular, to a measure of 700 to 1,150 mm per year (Schouten,1984; Overbeck and Happach,1956).

This is the case in Ireland, the United Kingdom, western Norway, the Netherlands and northwest Germany. Bogs in these countries have a tendency to extend beyond the depressions in which they originally developed. This can lead to fusing of bogs over relatively low ridges, which functioned previously as watersheds between these bogs. Less well-developed plateau-bogs are found in Poland, Denmark, south and southeastern Sweden and in southwest Finland. These countries have generally a precipitation of less than 700 mm/year (Von Post and Granlund, 1926). The effective humidity (precipitation minus evaporation) in these regions is just sufficient to maintain bog growth, as a result of the occurrence of the frost period of one to three months in winter.

Blanket-bogs

This type of bog occurs in Ireland and Scotland. Blanket-bogs characteristically spread out over the landscape like a blanket; the occurrence of blanket-bogs is therefore not dependent on depressions in the landscape; slopes up to 25^{o} can be covered (Schouten,1984). Blanket-bogs occur only in an oceanic climate. This type of bog occurs when the yearly intensity of precipation is 1,150 to 2,000 mm/year (Schouten,1984).

Aapa mires

These mires occur in central Norway and Sweden, central Finland and the northern European part of Russia. An aapa mire shares some of its features with fens. Ombrogenous bog development occurs only on a small scale in places with hydrolologically suitable conditions, where the excess of precipitation can drain away only slowly. Aapa mires occur in the continental-boreal climate. Precipitation intensity is below 550 mm/year, a large proportion becomes available in spring as melt water of snow and ice.

Palsa mires (Arctic bogs)

Ombrotrophic bogs on permafrost, usually with a frozen centre. They reach a height of on average over a meter: the diameter is usually several tens of meters. The tundra soil, which surrounds a palsa mire, is usually saturated with water in the period of vegetation growth. These mires occur above the Polar circle in Norway, Sweden, Finland and Russia.

Concentric bogs (Baltic raised-bogs)

Concentric bogs occur in northern Poland, the Baltic States of Russia, southern Finland, and eastern Sweden. When the effective humidity is sufficiently large and a favourable growing season is present, the bog centre can grow upwards and thus forms a convex profile. In Finland this is called a 'kermi-' or hummock-bog. Kermi-bogs are characterised by hummocks and hollows, which are located concentically around the highest central point of the bog. Concentric bogs occur in areas with a sub-continental climate.

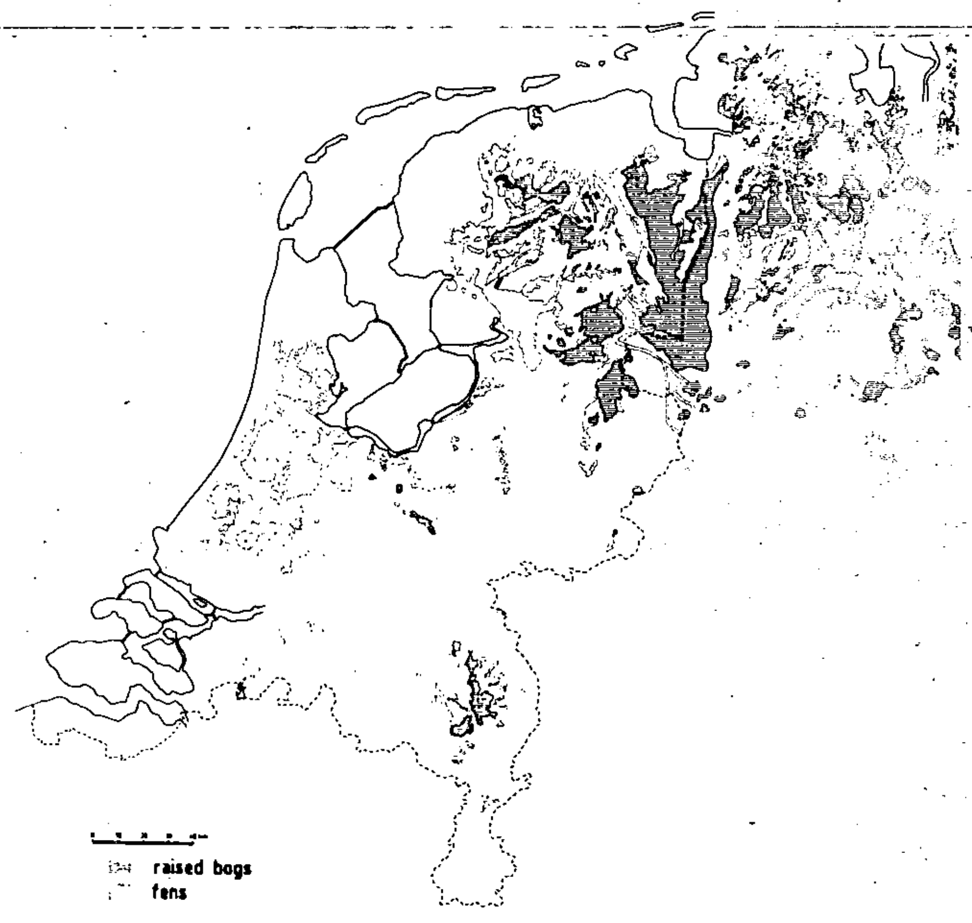
Wooded bog (continental raised-bog)

This kind of bog occurs in northeast Poland, and in European and central Russia. They are plateau-bogs or concentric bogs which are mostly wooded or sometimes covered with groups of trees. They occur in areas with a sub-continental or continental climate.

3.2.2. DISTRIBUTION OF BOGS IN THE NETHERLANDS IN RELATION TO THE CLIMATE

Figure 11 indicates the distribution of bogs and fens in the Netherlands (Casparie, 1986).

Figure 11 Distribution of peatland in the Netherlands: explanation in text



This map does not show all bogs and fens in a consistent way, but is intended to indicate the extent and occurrence of the main raised bog areas. The optimum extent of approximately 1,500 A.D. is portrayed.
The extent of the fens relates to the situation in the 19th and 20th centuries. As a result of this starting-point the eroded raised bogs in the western part of the Netherlands, which were flooded in later times, are indicated as fens. Bogs of the 'IJsselmeer' area and of the province of Zeeland are not indicated. The peatlands that once occurred outside the present coastline (the former "coastal barriers") have also been excluded.

Table 4 lists the average precipitation and average temperature for the former bog areas (or cut-away relicts of the same areas) over the period 1951-1980, as indicated on the distribution map.

Table 4 Average precipitation and average temperature for former bog areas or its relicts in the Netherlands.

bogs	average precipitation mm/yr	average temperature °C
Bourtangerveen *	730 à 770	8.6
Smildervenen	835 à 840	8.7
Friezenveen	805 à 820	8.8
Drents-Overijsselse border venen	765 à 810	8.9
Engbertsdijksvenen	765	8.9
Haakbergerveen	763	8.9
Bogs in de Gelderse Vallei	770	9.1
De Peel	700 à 725	9.4

* veen = bog
venen = bogs

It can be deduced, from the knowledge of section 3.1. and 3.2.1. and the information on the distribution of bogs, that the following conditions are of great importance for the formation of bogs: a precipitation of approximately 700 mm per year or more and an average temperature in July of at most 16-17 ^{o}C (average yearly temperature of approximately 9 ^{o}C).
The following remarks can be made in relation to the bog areas 'De Peel' and parts of the 'Bourtangerveen'. These areas are situated respectively either wholly or partly outside the above limits of climatic conditions, for shorter or longer periods, according to an interpretation with the aid of the table of Lamb (section 3.2.1.). It follows that conditions promoting ombrogenous peat formation were not or hardly present in these areas for shorter or longer periods. This could be the result of too little precipitation or too high an average temperature. In the 'Bourtangerveen' this is partly supported by paleobotanical research, see section 3.3.
The average yearly precipitation in the 'Peel' is presently 700 to 730 mm. According to Lamb's table (Table 5) this would indicate a precipitation of 645 to 840 mm per year, over longer periods; partly lower than the 700 mm/yr deduced above to be necessary for bog growth. The average summer temperature in the area of the 'Deurnse Peel' is at present approximately 17 ^{o}C; about 1 ^{o}C higher than in the north-east of the Netherlands, where very extensive bogs occurred. It is not unthinkable that summer temperatures were too high for bog formation in the south of the Netherlands for shorter or longer periods.
It is not known if the marginal location of the 'Peel' is expressed by the type of peat that grew there; e.g. by the occurrence of large layers indicating drier conditions or by a lack of deposits indicating vegetation typical of hollows and an extensive occurrence of hummock vegetations or a greater capacity for the retention of water in the hollows. The local micro-climate and topography were apparently sufficiently favourable for the development of bog.

3.3. CLIMATE AND BOG: TEMPORAL ASPECTS

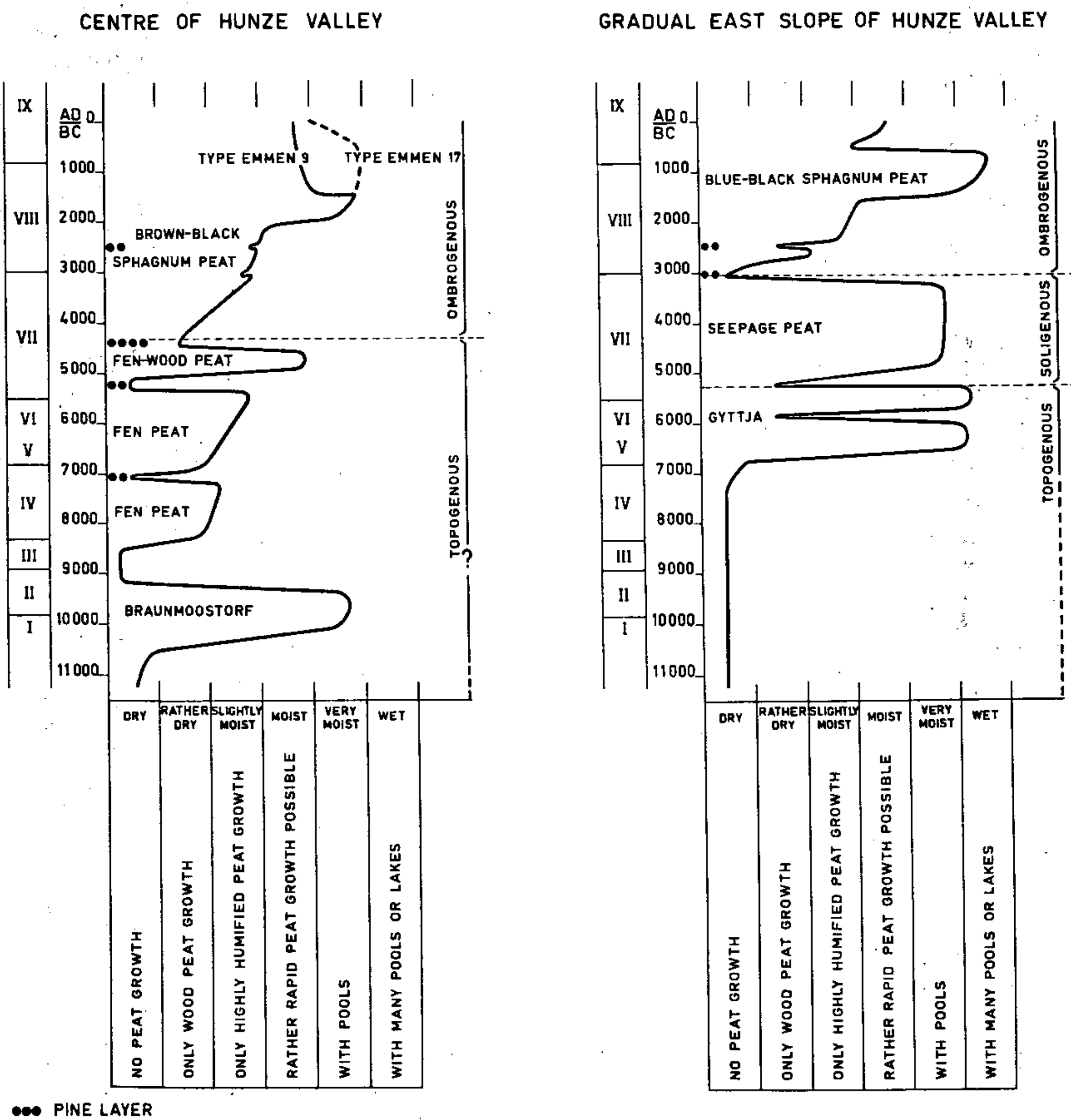
From about 5,000 B.C. or possibly somewhat earlier up to the present the climate of northwest Europe was suitable for ombrogenous peat growth. Highly humified moss-peat was already produced before 4,500 B.C. in the southern part of the 'Bourtangerveen' (Casparie,1972; Dupont,1985); the starting-point for this, e.g. in the form of the production of Scheuzeria peat, can be dated at approximately 5,000 B.C. Overbeck (1975) also supplies some examples, which can be dated in the early part of the Atlantic period.

The data on the distribution of the start of the ombrogenous bog growth do not give a clear picture of possible zonation or of spatial development. This may be partly due to difficulties with the establishment of exact dates for the start of raised bog growth and naturally with the exact definition of the concept bog. More important, this is due to the fact that the initial conditions for ombrogenous bog formation are rather complex. Precipitation and humidity of the air do not necessarily have to be the only limiting factors. It is just as thinkable that the correct substrates are lacking or that the rare condition of a water-saturated subsoil is not fulfilled or that the subsoil is too rich in nutrients, which prevents the ombrotrophic environment from developing. It is certain that leached water-saturated sandy subsoils, on which raised bog developed, came into existence much later, generally after 2,000 B.C. The next section (3.3.1.) discusses the relationship between climatic trends and bog development.

3.3.1. <u>Peat growth and climatic trends</u>

Paleobotanical and peatstratigraphycal research does not provide direct information on climate and climatic changes. It does not supply data concerning the moisture status of the peat-producing environment and its changes. Climatological causes for at least part of these changes seem a reasonable suggestion, but rules of general application cannot be given. Figure 7 indicates the trends of the moisture contents of the peat producing environment in terms of the type of peat produced, at two sites in the 'Bourtangerveen' east of the city of Emmen.
These sites are at a distance of approximately 2 km from each other. The differences between the two graphs of fig. 7 are so large that a direct climatic influence on the peat produced, also where ombrotrophic peat is concerned, seems unlikely initially. Many kinds of local conditions determine the processes of peat formation; a closer analysis of the phenomena is necessary in order to be able to state what (direct) influence the climate may have had.

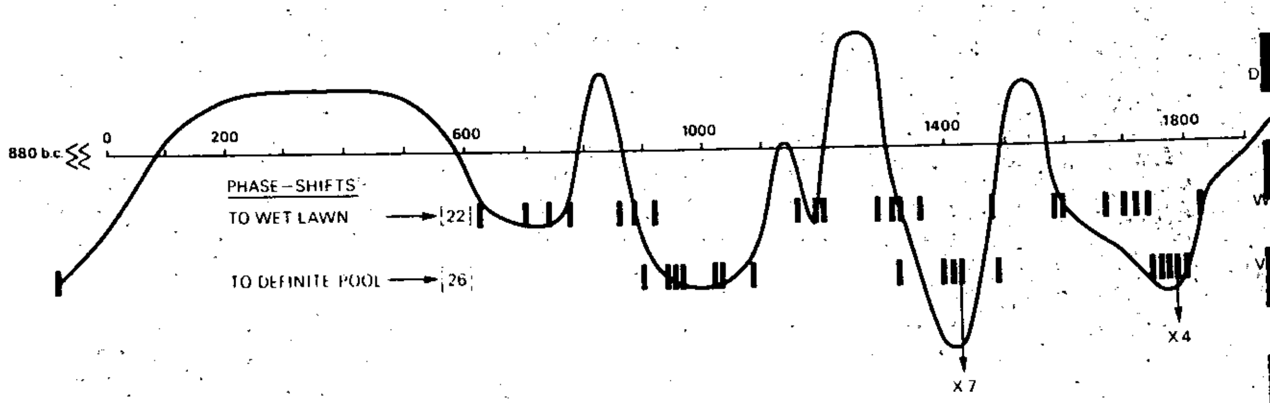
Figure 7. The 'Bourtangerveen' east of the city of Emmen; trends of the moisture contents in peat producing processes, graphed against time.
Curve on the left: central part of the valley of the river Hunze; on the right: the gradual east slope of the valley of the Hunze. The peat stratigraphy, from which this information is derived, is given in appendix 1. (After Casparie, 1972).



Dating the start of as many ombrotrophic peat formations as possible can be a way to acquire insight into the question as to what extent the different periods of the Holocene were more or less suitable for ombrotrophic peat growth. The method has its limitations, as already remarked at the start of section 3.3., because far more factors apart from those related to climate play a part. Examples of this are e.g. progression of the peat production, condition of landscape (suitable soils etc.) and the extent of the bog formation. As the peat growth extends itself over the landscape the possibilities for the beginning of new bog become naturally smaller. It is almost certain that the assumption that e.g. in the Subboreal the circumstances for new bog formation were somewhat less favourable because the number of new Subboreal peatlands is small, does not take into account that in the Atlantic the best localities were already occupied by bog.

In the West-English bog Bolton Fell Moss the trends of the moisture contents of the bog-surface with time are registered in great detail (Barber,1981). A large proportion of these wet-dry trends (see figure 8) could be correlated satisfactorily with changes in climate known from other sources over the last 2,000 years. The bog vegetation seems to react rather fast to changes in temperature and precipitation.

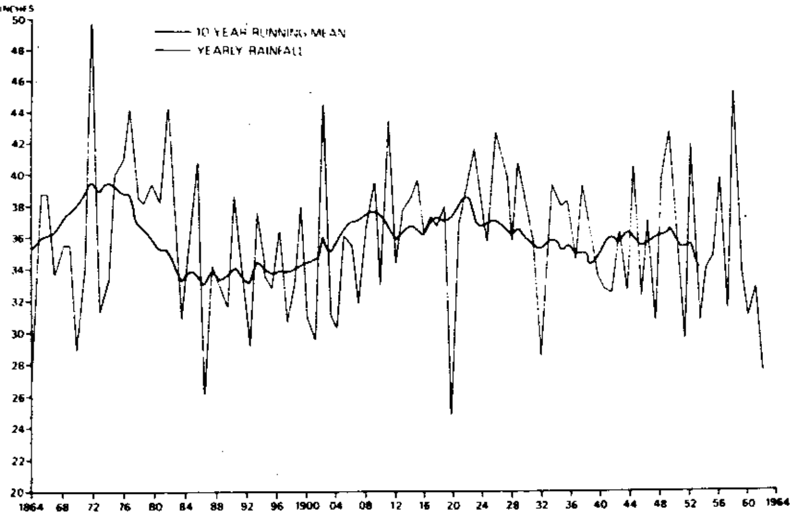
Figure 8 Bolton Fell Moss, England



The graph from Bolton Fell Moss portrays the trends of the moisture contents of the peat producing surfaces since 90 A.D. (Barber,1981), which is based on various paleobotanical information. The height of the 'dry' peaks of the graph is an indication of the extent, the vegetation and the state of erosion of the hummocks.

Detailed stratigraphical research of bogs in the Netherlands indicates that the formation of ombrotrophic bog could generally take place since 4,000 to 3,000 B.C. up to the Middle Ages, at least in the northern part of the Netherlands. Clear fluctuations can be demonstrated in the degree of moisture of the peat producing environment. Erosion of the peat surface through drying out and oxidation, caused by changes in climate, do not really occur. In that respect the results of the Dutch research agree well with those of Bolton Fell Moss, although the precipitation at Bolton Fell is on an average 920 mm, measured in periods of ten years; this is 135 mm more than the present average precipitattion in the Netherlands.

Figure 9. Precipitation in England and Wales, in the years 1864 to 1984, expressed in inches. Thin line: yearly precipitation; fat line: the 10-yearly average (After Barber, 1981).



There are no indications that peat production at Bolton Fell Moss developed differently in the 2,000 years (figure 8) previous to the registration of meteorological data (figure 9); in other words conditions for peat production at this site remain still suitable today. It is also certain that optimum conditions for peat formation existed in the Netherlands since approximately 800 B.C. till far into the Middle Ages. There is no reason to assume that in the Netherlands in particular a change in climate occurred since then, which would lead to the end of bog production, which would not also be registered in the English peat formation records.
For this reason we assume that in the Netherlands too the climatic conditions are still suitable for the growth of ombrotrophic peat today. In section 3.3.2. this will be discussed in greater detail.

Extensive drying out is known for some Dutch bogs in the period before 2,000 B.C., in which it can be shown that this is not the result of a drought caused by changes in climate in the form of very little precipitation and/or high temperatures. For example part of the 'Bourtangerveen' east of the city of Emmen dries out around 2,500 B.C. as a result of a strong withdrawal of water (Casparie, 1972). In the 'Engbertsdijksveen' a considerable area of bog was burnt around 2,100 B.C., as a result of deep drainage into the sandy subsoil (Van Geel & Dallmeijer, 1986).
After 2,000 B.C. drying out of bog-surfaces also took place, which was partly of a shorter duration or more superficial, and in which the climatological compoment can be recognized. Between about 1,200 to 700 B.C. somewhat larger fluctuations in precipitation and temperature took place. Around 850 B.C. the average temperature went down by perhaps $1^{o}C$. Very detailed peat

stratigraphical research from the 'Bargerveen' (Dupont, 1985) describes a succession of somewhat wetter, sometimes very wet and somewhat dryer phases, which results in totality in a greater humidity. This is in agreement with this type of research in other places. (Casparie, 1972, van Geel, 1978). Around 1.200 B.C. e.g. a few hectares of the surface of the southern part of the 'Bourtangerveen' dried out, while the contact areas remained wet; this was caused by decreased precipitation. After less than a century the bog-surface has become considerably wetter, followed by an apparently less wet period also indicated by the expansion of the growth of the large-leaved Sphagnum imbricatum and S. papillosum. Around 800 B.C. the bog becomes more moist again; the store of water at the bog-surface increases, also as a result of a decrease in temperature. Around 500 B.C. extensive erosion takes place as a result of a bogburst in the southern part of the 'Bourtangerveen'; the resulting increase in discharge of water does not lead to drying out at greater depths in the peat.
The remarkable peat-stratigraphical phenomena which took place between 1,200 and 700 B.C. indicate that the ombrotrophic peat growth reached an new hydrological equilibrium at a somewhat lower temperature and a little more precipitation.
Between 1,300 and 1,400 A.D. Sphagnum magellanicum takes over from S. imbricatum at the bog-surface of Bolton Fell Moss (Barber, 1981). This phenomenon has been recorded for many bogs and is thought to be due to a very wet period (fig. 10) that occurred after the small climate optimum (table 5). There are no data available to explain the influence of this increase in precipitation on the Dutch bogs. It is however known that during the 'small optimum' in many parts of the Netherlands fen deposits in particular become more accessible to man and could be reclaimed and that at least locally this peat became again much wetter after around 1,300 A.D.

3.3.2. Meteorological research into the trends of climate

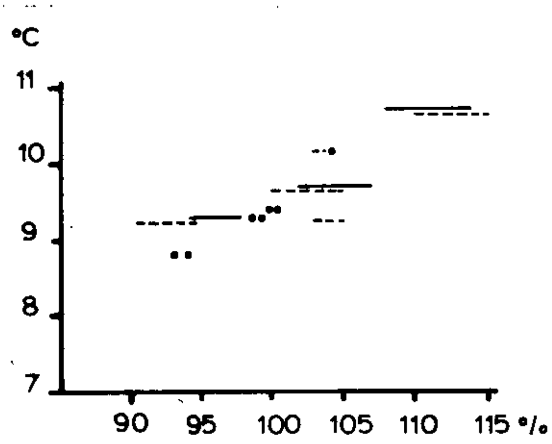
The evolvement of the climate since the Late-Glacial shows clear fluctuations in precipitation, temperature and therefore also in the humidity of the air, as is indicated for Wales e.g. in table 5, after Lamb, 1977.

Table 5 Temperature (T) and humidity (P=precipitation; E=evaporation) during the Holocene in England and Wales, after Lamb, 1977. Temperature in ^{o}C, humidity in % of the average for the period of 1900-1950

Date	Period	Temperature			Humidity	
		T_{ja}	T_{djf}	T_{jaar}	P	E
± 7000 v Chr.	Preboreal	16,3	3,2	9,3	92-95	94-98
± 6500 v Chr.	Boreal					
± 4500 v Chr.	Atlantic	17,8	5,2	10,7	110-115	108-114
± 2500 v Chr.	Subboreal	16,8	3,7	9,7	100-105	102-104
900-450 v Chr.	Subatlantic	15,1	4,7	9,3	103-105	97
1150-1300	Small climate optimum	16,3	4,2	10,2	103-104	104
1550-1700	Little Ice Age	15,3	3,2	8,8	93	94
1900-1950	England Wales	15,8	4,2	9,4	100	100
maximum difference		2,7	2,0	1,9		

The interpretation of this table gives the following results. In general the surplus of precipitation changes but little over a period of 9,000 years, because the quantity of precipitation and evaporation increases and decreases more or less evenly as the temperature rises or falls (see figure 10).

Figure 10 Change in temperature in relation to the change in precipitation and evaporation in % (the position of 1900-1950 is equal to 100%).



Legend
------ percentage evaporation (estimated)
o percentage evaporation (more accurate)
______ percentage precipitation (estimated)
. percentage precipitation (more accurate)

The position at the end of the Subboreal and in particular towards the start of the Subatlantic is clearly an exception to this. During these periods the quantity of precipitation seems to be relatively higher than can be expected from the fluctuation of temperature in the same period. As a result this period is relatively wetter than other periods. The data of paleobotanial peat-bog research by Casparie (1972) and by Dupont (1985) in Southeast Drenthe shows this development towards greater wetness. This was discussed earlier in section 3.3.1..
The absolute humidity, in the form of precipitation and evaporation, changes moderately with time relative to the period 1900-1950. It decreases by a maximum of 8%, and increases by a maximum of 14% and 15%. Very great changes in the moisture balance did not take place, but the climate during the Holocene was not constant in relative terms. A number of periods primarily determined by climatic changes can be distinguished after the end of the last Ice Age although these changes are generally characterized by only small fluctuations in temperature. Below these periods are described concisely; see also figure 7 and table 1.

Preboreal (8,300-6,800 B.C.)

A period of increasing temperatures, with summers which were just as warm, or even warmer than those of the period 1900-1950 A.D..

Boreal (6,800-5,500 B.C.)

A period with continuing increase in temperatures. The winters were less cold and possibly somewhat dryer than those of today. The summers were warmer and somewhat dryer than at present.

Atlantic (5,500-3,000 B.C.)

The warmest period of the Holocene; more damp than the previous periods. Also a wet period with winds from a predominantly westerly direction. Maximum humidity occurred between 4,000 and 3,000 B.C.

Subboreal (3,000-800 B.C.)

A cooling took place. The climate was characterised by somewhat larger fluctuations, and up to 2,000 B.C. conditions were a little dryer. Around 1200 B.C. it was very dry in Northern Europe, after which rather large fluctuations in precipitation and temperature occurred, which resulted in lower temperatures (1°C or perhaps a little more) and more precipitation around 800 B.C..

Subatlantic (800 B.C.-present)

A further cooling of the climate; the average temperature was 2°C lower in 700 to 500 B.C. than 500 years previous.
Between 500 B.C. and 500 A.D. it was considerably wetter here, while the period after that was dryer up to about 1,000 A.D.. From around 1,500 A.D. a wetter and cooler time was experienced, until after about 1,700 A.D.. After that the temperature increased a little, but it remained damp, which is continuing till

the present day. Overall it seems reasonable to assume that the Atlantic and the start of the Subatlantic were periods which were very suitable for the development of bogs. The first half of the Atlantic, the Subboreal and also the later part of the Subatlantic can be considered as moderately favourable for the start of bogs.

From a peat-stratigraphical research point of view above train of thought appears to be in need of some adjustments. For example the southern part of the 'Bourtangerveen' enjoyed ombrotrophic peat formation during the first half of the Subboreal; the 'Smildevenen' grow considerably in extent because of ombrotrophic peat accumulation and in the valley of the 'Drentse A' a nucleus of ombrotrophic peat formation has started. In many remains of pingo's a considerable deposit of more or less ombrotrophic peat was, or is still, present which is of Subboreal age.
The yearly temperature fluctuations in the Netherlands are of the same order of magnitude as those in Wales i.e. between 9 and 11^{o}C (Dupont, 1985).
The average intensity of evaporation through time will therefore have been quite similar to that in Wales. The same goes for the course of precipitation with time goes the same, but average precipitation in the Netherlands will have been much lower than in Wales, as was already mentioned in section 3.3.1.. The surplus of precipitation with time was therefore also much lower in the Netherlands than in Wales.

The fluctuations in temperature given by Lamb correspond with a shift of the isotherms over a distance of 200 to 500 km. This means that part of the Netherlands was outside the area suitable for ombrotrophic bog formation for a longer or a shorter period, if we assume a distance between the July-isotherms of about 150 km per degree. This is especially so for the peatland area in the province of Noord-Brabant called de 'Peel', which has a present-day precipitation intensity of about 730 mm/year. Barkman (1959) who did research into epiphytes, reaches similar conclusions (see figures on his p.277).

3.4. CONCLUSION

- The Dutch ombrogenic bogs and their remains can be classified as Atlantic raised bogs (plateau-bogs or lens-shaped bogs). A plateau-bog is characterised by a slightly domed relief. The centre of the bog-surface approaches a flat plain. Overall it resembles a weakly convex lens. Plateau-bogs can be found in the Oceanic, Sub-Oceanic and Sub-Continental climate zones. The Netherlands is situated on the transition between the Oceanic and the Sub-Oceanic climate zones;
- Peat-stratigraphical research indicates that in general ombrotrophic peat could well be formed, at least in the northern part of the Netherlands from 4,000 to 3,000 years B.C. up to the Middle Ages. During this period fluctuations in humidity of the peat producing environment are clearly indicated. Erosion of the peat through oxidation and drying out, caused by climatological developments, does not really take place.
- The arrest of ombrogenic bog formation in the Netherlands was not caused by a change in climate. This is certain from peat-stratigraphical records from the surrounding countries (England and North-West Germany). Raised bog can still grow today, at least in principle;
- Based on the climatological analysis of Lamb it seems likely that the second half of the Atlantic and the start of the Subatlantic were periods, which were very favourable for the start of ombrogenic peat growth, because

optimum conditions as far as moisture is concerned existed; i.e. a relatively high intensity of precipitation and relatively low temperatures.
The first half of the Atlantic, the Subboreal and the later part of the Subatlantic can be considered as moderately favourable to favourable for the start and growth of bogs (less moist);

- On the basis of the knowledge of the distribution and classification of ombrotrophic bogs in Europe in relation to climate, the climatological developments in relation to peat growth, and the existing distribution of raised bogs in the Netherlands, it can be assumed that for ombrogenic bog formation a precipitation of about 700 mm/year or more and an average July temperature of about 16-17 ^{o}C or less (average temperature of about 9 ^{o}C) are important prerequisites.

4. ECOLOGICAL ASPECTS OF BOGS

4.1. GENERAL

Generally the assumption exists that a raised bog is fed exclusively from atmospheric sources. This is correct, although it is incorrect to assume that the yearly input of minerals alone determines the growth of the bog. To a certain extent the mineral input of previous years does also play a role. The peat below the peat-forming surface and the living bog-vegetation itself maintain a relationship of nutrition, which partly occurs through the communal medium of water, and which partly takes place through the roots of the vascular plants of that vegetation.
Within a bog complex a certain division of nutrients also takes place. Hummocks discharge to hollows, hollows can expand into small or larger bog pools, and these can function in turn as the start of flushes. The vegetation of these different elements contains, apart from species they have in common, also a number of differential species. The connecting element is flow of water, and with the increase of flow, the supply of nutrients increases, per unit of time.

Various peat-mosses (Sphagna) are well suited to the wet, nutrient-poor and acid environmental conditions. Peat-moss is the most characteristic plant of bogs. These relatively small mosses in particular cause the formation of a bog, by means of their specific anatomy, mode of growth and ecological qualities.

However, vascular plants are not uncommon either, and these species in particular can grow, at least in part rather far below the level of the groundwater. Many of these species contain mycorhiza. Because they have e.g. hollow rhizomes, they can create locally an environment rich in oxygen and mobilize the nutrients which have been locked up in the dead substrate, and so the oxidation of the peat is promoted. All kinds of micro-organism contribute also to the breakdown of the wet, fresh peat, a process which is often described as humification.

It is a characteristic of bogs that mechanisms exist which contribute to the fact that as many nutrients as possible are available to the living vegetation: an exchange takes place between "living" and "dead" peat, in which much is concentrated in the top layer. Peat-mosses are able to redistribute a considerable amount of nutrients in favour of living parts. The presence of water around the plant is a primary condition - peat-mosses have no roots, vascular bundles and such like.
The more remarkable properties of peat-mosses will be further discussed in section 4.2. and 4.3..

4.2. MOISTURE AND NUTRIENT BALANCE OF SPHAGNA

4.2.1. Internal and external moisture balance

Paul (in Beijerinck, 1934) notes that Sphagna (peat-mosses) are essentially waterplants, which have become partly adapted to the environment - rich in oxygen - above the water-level of the bog. Peat-mosses occur just below or just above the water-table. Furthermore Beijerinck (1934) notes that peat-mosses, which occur generally above the water-table, can adapt to an existence under water for the greater part of their life-span and change into the so-called 'water forms', while the typically aquatic species of peat-moss have much more difficulty in adapting to a life above the water-table. Presumably this is related to differences in structure between the different peat-moss species and the related differences in internal and external water-balance (Rijdin, 1985). It is however clear that the occurrence of all peat-mosses is tied to very wet conditions. The question of how the moisture balance of these plants operates will be discussed now.

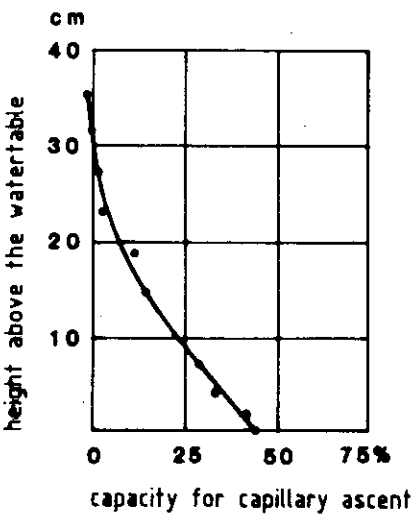
Internal moisture balance

As is the case in all mosses, Sphagna are plants without roots. The tip of the stem continues to grow, while the lower parts die off (0.10 to 0.30 m below the growing point), and therefore the lower parts do not have any function for the water support to the tip of the plant. The water uptake of the plant takes place via certain cells, which are present in particular in the leaves of peat-moss. Two types of cells occur in the leaves, i.e. cells containing chlorophyl, which take care of photosynthesis, and the so-called hyaline cells. The latter have reinforced walls containing pores, through which water can pass in and out. Romanov (1968) calls these cellular spaces the internal porosity of the peat-mosses. These spaces can contain large amounts of water. Beijerinck (1934) and Romanov (1968) estimate that peat-mosses can take in up to 40 times their own dry-weight in water. According to Willems (1974) this is a quantity which is three to four times greater than in the case of other bog plants (e.g. Eriophorum vaginatum). The walls of the living cells are (semi-)permeable; this is also the case with the walls between hyaline cells and living cells. Peat-mosses can take up water and its dissolved nutrients from the hyaline cells via the process of osmosis. The hyaline cells therefore perform the function of roots in relation to nutrition, in a sense. Because the hyaline cells are in direct contact with the atmosphere a lot of water can evaporate directly from them at higher temperatures, especially in summer. Peat-mosses do not have stomata, which regulate evaporation in other plants, and which can curb the evaporation of the plant at higher temperatures. Evaporation of peat mosses is somewhat curbed by the white discolouration which appears when the peat-mosses dry out strongly, and which indicates that the water in the hyaline cells is being replaced by air. After all the white colouration reflects heat radiation a little. Schouwenaars (1989) show experimentally the reduction of evapotranspiration in a living Sphagnum papillosum layer as a consequence of only a limited lowering of the water table during a dry period. They also show that reduced evapotransporation is caused by the "mulch"-effect of the upper top layer of a Sphagnum cover, which dries out and becomes white soon after the water-table drops below c. 10 cm of the surface.
A second factor is also of importance in relation to the water supply of pea-mosses: the external moisture balance.

External moisture balance

Apart from the internal porosity Romanov (1968) also distinguishes an external porosity. This is the porosity between both stems, branches and leaves of the peat-moss plant and between different peat-moss plants. In these spaces water from the bog can be transported to the hyaline cells via capillary action. The source of water can be intercepted rain-water or water from below drawn up by capillary action. Evaporation is also clearly dependent on capillary transport. Schouwenaars and Vink (1989) investigated under laboratory conditions that after 60 mm extraction of water from less humified peat soil (without a Sphagnum cover with rootzone) capillary fluxes of 2 mm/day can still be measured with a water-table 40 cm below surface. However Romanov (1968) measured that the percentage of water held in a capillary bond in the peat profile in the acrotelm in relation to the total water contents of peat in the acrotelm (about 97%) decreases strongly when a small drop in water-table of the bog occurs. Figure 12 illustrates this.

Figure 12 Distribution of capillary water above the water-table of the bog.



It was established that a drop in water-table of a bog of more than 0.20 m below the surface results in a percentage of water in capillary bond of less than 5% of the total water contents of the bog. A logical explanation for less capillary rise in the acrotelm in dryer periods is the reduction of the evapotransporation caused by the "mulch"-effect of the upper top layer of the Sphagna cover. In combination with the usuallly unimpeded evaporation of peat-mosses the figure above indicates clearly that the water-table of a bog should not drop too far below the surface of the bog, during dry periods of the year, at least if the bog should not dry out and peat-mosses die off as a result. Growth of peat-moss can hardly take place in the dryer summer months. At the end of the summer the temperature decreases slowly and in conjunction the intensity of evaporation of the peat-mosses also decreases. A sufficient supply of precipitation results quickly in a surplus of precipitation and this results in a rise in the water-table of the bog, which makes for optimal moisture conditions for peat-mosses. Therefore in spring, and to a lesser extent in autumn, optimum Sphagnum growth takes place, because moisture shortages do not occur during these periods and cappilary rise is sufficient.

4.2.2. Nutrient balance

Ombrotrophic bogs are exclusively fed by rain. In this way the major part of the nutrients for the growth of peat-mosses is supplied. Rain-water is naturally low in nutrients and has a low ionic loading. Apart from the low ionic loading, rain-water is also rather acid. The characteristics of bog-water, from which peat-mosses derive their nutrients, are very similar to

those of rain-water. The specific properties of either are discussed further in section 4.3..
Apart from the supply of nutrients by precipitation, nutrients are also supplied from dead peat material at somewhat greater depth in the peat profile. These nutrients are released by means of mineralisation of dead plant material. The supply mechanism is described by Baaijens (1982) as the thermic pump of the bog. Essentially this pump works as follows. At night the bog-surface cools down. The temperature of the water at the surface lowers and reaches a temperature lower than that of the water at somewhat greater depth. Warm water is lighter in weight than colder water. An upward flow results, by means of which nutrients can be transported from these depths to the surface. As a result in the course of the night the water at the surface becomes richer in nutrients and less acid, because the peat-mosses do not take up nutrients since they do not assimilate at night. During the day the nutrients are taken up by the peatmosses from the upper layer of water, as soon as assimilation starts. The surrounding bog water becomes therefore more acid during the day. The creation of a more acid environment is a property typical of peat-moss.
Peat-mosses are able to exchange hydrogen ions (H^+-ions) for other cations (e.g. Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+), the latter are present in bog-water in low concentrations, as described by Beijerinck (1934), Baaijens (1982), and Boelter and Verry (1977). This results in a higher concentration of H^+-ions in the water and thus a lower pH. The result is a more acid environment.
According to Casparie (1984) and Boelter and Verry (1977) the optimum pH value lies around 4 or somewhat lower, for typical peat-forming peat-mosses. Baaijens concludes that under normal circumstances the pH does not continue to decrease and therefore an even poorer environment will not be formed, because during the period of growth the cell walls of the peat-moss age which causes a decrease in the capacity to exchange ions through the membrane of the hyaline cells. During this process less nutrients are absorbed and less H^+-ions excreted into the bog-water. At a pH of about 4 an equilibrium for the capacity to exchange ions is reached, by which the pH does not decrease further and remains relatively stable. A lower pH value of about 3.2 to 3.4 is toxic to the bog environment.

4.3. SPECIFIC ABIOTIC CHARACTERISTICS OF BOGS

After having paid attention to some specific physiological characteristics of peat-forming Sphagna, focus will now be on the specific abiotic characteristics of bogs, in which Sphagna play an important role. The morphology of the bog-surface, the hydrological characteristics of the acrotelm and the catotelm and the ombrotrophic conditions of bogs will be discussed in particular.

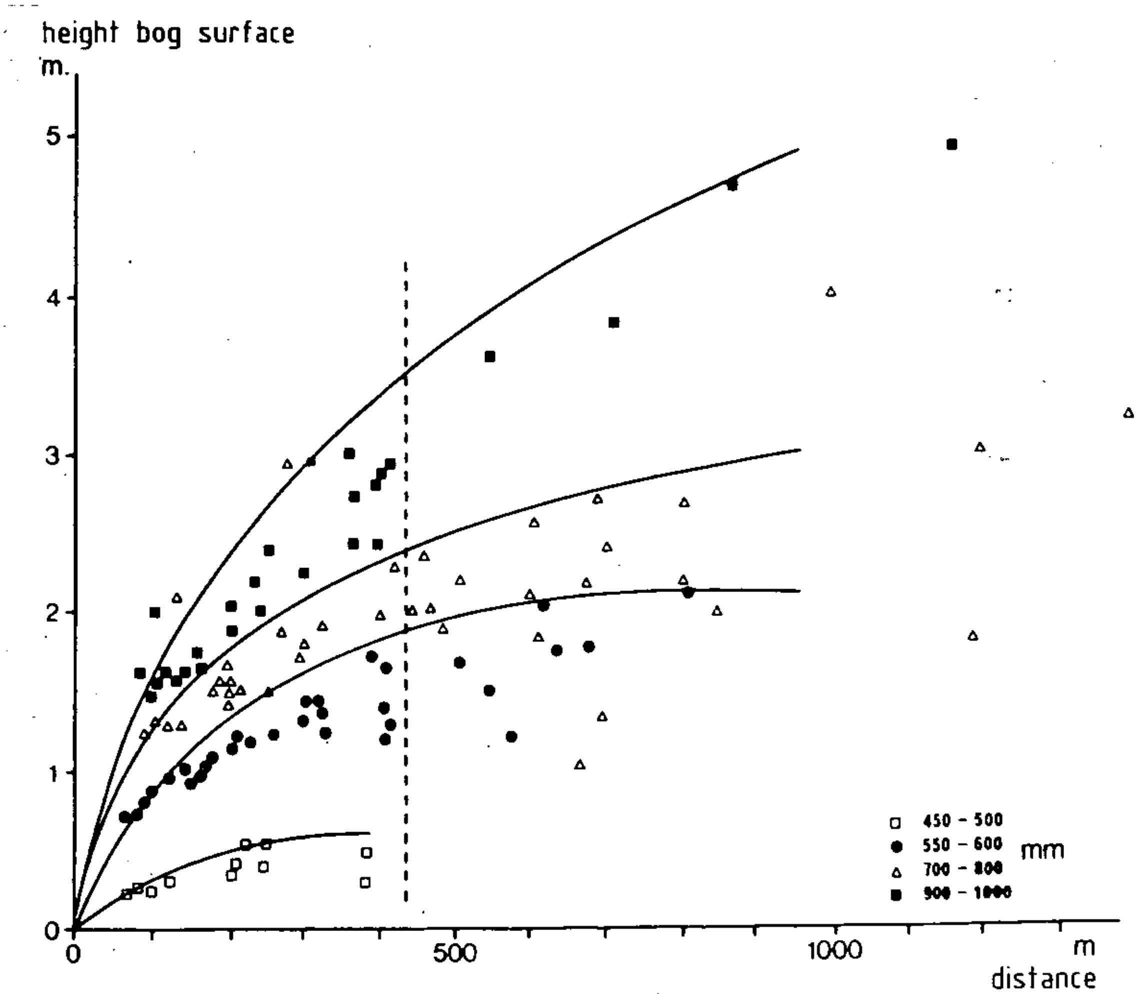
4.3.1. Morphology of the bog-surface in relation to the water-balance

The morphology of a peatland surface is mainly determined by the hydrological conditions of the peat complex. In general, according to Ivanov (1981), two main types of peat relief can be distinguished during peat formation processes. He determines that at the start of peat formation the relief is concave, while in later stages the relief is convex or domed. These types of relief can also be described in hydrological terms. Peat lands with a concave relief are supplied with water derived from their surroundings as well as from precipitation. A flow of ground- and surface-water rich in nutrients takes place.
Two initial conditions can be distinguished: the formation of fen and the formation of seepage peat. The latter can locally show a domed surface; in

relation to the water-table of the area of infiltration it is situated lower. When with further peat formation the peat-bog grows above the surroundings a somewhat domed relief appears. The surplus water flows from then on from the bog surface to the surroundings. This discharge water is poor in nutrients, as nutrition is now solely by precipitation. The extent of dome formation is explained by various theories.

According to Granlund (1932) the diameter and height of the bog complex are strongly dependent on the yearly amount of precipitation, which falls in a certain region. This can be seen in figure 13 below, which represents different precipitation rates from different bogs in Sweden.

Figur 13 The relation between the extent of swelling of the dome of raised bogs in the south of Sweden and the average precipitation, following Granlund (1932).



However, Clymo (1984) indicates that the height of a bog is the result of growth and decomposition and that this reaches a limit. Large bogs usually consist of a number of domed complexes, for example this is the case with the 'Bourtangerveen' in the northern part of the Netherlands, see figure 1. In the centre of the domed complex the relief approaches a practically flat plane. In this centre area in particular the bog pools can be found (Casparie, 1984). These are lakelets, which come into existence on this relatively flat part of the bog complex because water discharge proceeds very slowly as a result of the small difference in fall of the water-table. Because of this water can remain for longer periods in the lower parts of the bog-surface and so the bog pools can come into existence. The bog-pools function as areas of water supply, which maintain the periferal discharge via the hollows of the bog complex, and this functions also when precipitation has been absent for longer periods. The hollows form a net-shaped discharge system to the margins of the bog complex (contact zone). The micro relief of bogs is characterised by hummocks, in addition to the hollows. The hummocks rise only about 0.10 to 0.30 m above the level of the hollows. These usually round to oval spots of somewhat drier peat formation are commonly 0.5 to 6 m in diameter. The hummock-hollow pattern is well-known in the Netherlands from below prehistorie bog trackways. The bog-surface shows in fact a dry-wet pattern. A characteristic hummock-hollow pattern of a raised bog is shown in figure 14. A central part of Carbury Bog (Ireland) is portrayed here (Schouten, 1984).

Figure 14. Vegetation pattern of the cental part of Carbury Bog, Ireland. White areas portray hummocks; black areas represent for the most hollows and also some areas of open water.

Fewer peat-mosses occur on top of the hummock of a raised bog than lower down in the hollows. The following species are more abundant on the hummocks: Eriophorum vaginatum, Erica tetralix, Calluna vulgaris, and other vascular plants. On the flanks of the hummocks in particular Sphagnum grows often luxuriously. The peat-mosses which are best adapted to the hummock exist under the most acid conditions within the raised bog. Here the pH reaches values of about 3 to 4. In general this is also the most nutrient poor environment of the bog, as the hummocks are exclusively fed by precipitation and they are not influenced by the somewhat richer discharge water of the hollows.
In the hollows the vegetation retards the discharge of water; showers of rain flow off slowly which makes for the availability of water for peat-moss growth at almost all times. As was pointed out in paragraph 4.2., each Sphagnum species needs specific environmental conditions in order to grow. This relates in particular to the water-level in relation to the surface of the bog. Table 6 lists the different Sphagna and their requirements.

Table 6 Preference of Sphagna for range of pH and the bog water-level.

Sphagnum species	Growing spot	Depth of average water-table below the bog surface in m.	range of pH
S. fuscum	adapted to hummocks	0,25 à 0,37	3 - 4
S. magellanicum	hummocks/adapted to hollows	0,05 à 0,25	3 - 6
S. acutifolium	adapted to hollows	0,03 à 0,05	3 - 6,5
S. cuspidatum	adapted to hollows	0,00 à 0,01	3 - 6

The pH values have been added to the table to indicate that the conditions of the site where the different species grow, differ greatly, even at very short distances i.e. between hummocks and hollows. It can be concluded from these data that the dryer conditions of the hummocks coincide with a more acid environment, while in the wetter hollows conditions are less acid (data concerning pH have been taken from the research of Beijerinck, 1934).

A general remark remains to be made. The natural water supply to the surface of a raised bog is in fact a combination of the direct input of precipitation as well as of the very slow discharge of surplus surface-water from the highest part of the bog to the edge. This is called the system-linked or system-required discharge, see paragraph 4.3.3. The slight degree of relief of the raised bog plays an important role with regard to this factor.

Apart from the relief of the bog the acrotelm and catotelm also perform an important function for the proper development of a bog system. This will now be discussed further.

4.3.2. Characterisation of acrotelm and catotelm

According to Ingram (1983), raised bogs show two functionally different zones from a hydrological point of view, i.e. the acrotelm and the catotelm. This division differs basically from all other well known divisions, which are mainly based on the colour of the dried peat, the degree of decomposition, the botanical composition, the assumed genesis of the peat deposit or on combinaiions of these factors. For example the terms white peat, young moss peat and poorly humified peat have as their opposites black peat, old moss peat and humified peat. In this report the terms poorly humified, moderately humfied and highly humified moss peat are used regularly, see for instance table 13 on page 67.

As a preview to the description of acrotelm and catotelm below, it can be stated that in a living raised bog the upper part of the peat deposit can generally be considered as a component of the acrotelm. In a raised bog of this kind this will usually consist of fresh to poorly humified peat for the greater part, but this is not necessarily so. The highly humified peat and parts of the poorly humified and moderately humified peat belong generally to the catotelm, althoug the poorly humified moss peat in particular has several properties of the acrotelm. This concerns in particular the capacity for shrinkage and swelling.

Acrotelm

The acrotelm can be described as the system of living Sphagna, including its water supply. This is in practice the top layer of the living raised bog with a thickness of 0.10 to 0.30 m. The hydrological characteristics of this layer are its relatively good permeability ($K>1$ m/d) and its periodically fluctuating water-balance of the substratum, which is mainly regulated by the amount of precipitation and evaporation. Furthermore a change in height of the bog-surface occurs during the year, caused by the capacity of the substratum to swell and shrink, depending on the weather conditions. In Germany this is called 'Mooratmung'. And finally the evaporation of the Sphagna results in a decrease of the moisture content of the top layer and a decrease of the water-table in this layer, which facilitates the access of oxygen to the substratum which results in a relatively fast humification process under aerobic conditions.

Catotelm

The catotelm is defined as the hydrological system between the acrotelm and the mineral subsoil. The organic material in this system is usually more humified or at least it reacts as if this was the case. Because oxygen is lacking (O_2) the peaty material is broken down only very slowly. Because of the considerable change in the nature of the plant material the volume and hence the permeability is slight ($10^{-3} > K > 10^{-6}$ m/d). The substratum does not show changes of moisture content, so that the capacity to hold a certain amount of water is fairly constant. The capacity for shrinkage or swelling is smaller.

In table 7 the differences between acrotelm and catotelm are listed in summary.

Table 7 Characteristic differences between the properties of acrotelm and catotelm.

properties	characteristic differences acrotelm	catotelm
- degree of humification	zero/low	high
- permeability of the peat	large/variable	very small
- capacity to store water	large	small
- capacity to swell and shrink	large	small
- process of decomposition	relatively aerobic	relatively anecrobic
- peat-forming capacity	present	absent

Some specific properties of the acrotelm and the catotelm will now be discussed in greater detail.

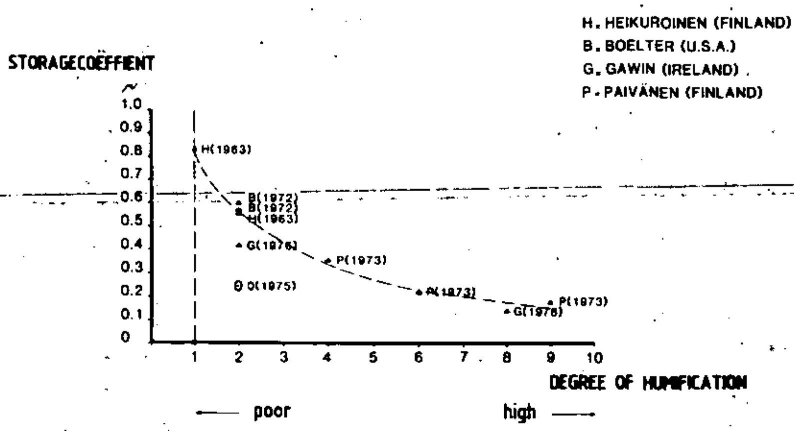
Storage coëfficient

The storage coefficient can be defined as the quotient of change in specific water storage or moisture contents of the substrata and the change in height of rise, in this case of the water-table in the peat. The storage coefficient can be expressed in a formula as follows:

$\mu = \frac{\Delta S}{\Delta G}$ μ = storage coefficient
ΔS = change in specific storage
ΔG = change in the height of the water-table

(Specific storage is defined as the storage above a particular level of reference per unit of horizontal surface)
The storage coefficient depends on the porosity of the medium; in this case Sphagnum peat. The porosity of a peat profile decreases with depth (Boelter and Verry, 1977). This decrease in porosity is caused on the one hand by the pressure of the peat deposit which lies above, and which is saturated with water, and is caused on the other hand by a further humification of the organic material.
The degree of humification of the peat is derived from the peat producing environment, and is not directly dependent on the peat stratigraphy. The humification of the organic material is a process in which plant remains are converted to humus. During this process an important change in structure of the organic material takes place. The degree to which the organic material is humified can be expressed in the form of different classes. Von Post and Granlund (1926) have set up a scale of humification of 1 to 10, in which the measure or degree of humification of the organic material is reflected. This scale of humification has been added to this report as appendix no. 3. Many researchers (e.g. Boelter and Verry, 1977; Heikurainen et al., 1964; Schouwenaars, 1978) worked on the relationship between the storage coefficient and the degree of humification of Sphagnum peat. If one graphs the data from the different research projects in one figure (figure 15) a clear correlation appears to exist between the coefficient of water storage and the degree of humification.

Figure 15 Correlation between coefficient of water storage and degree of humification



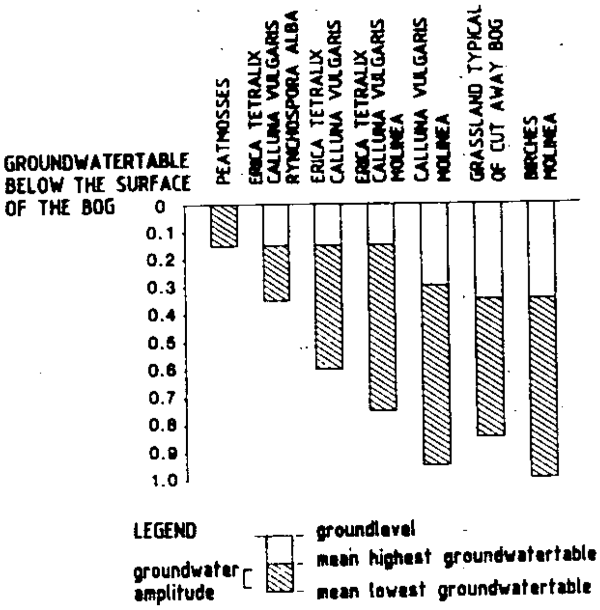
According to the graph the plant remains that have not been humified (which occur just under the surface of the bog) have a storage coefficient of 0.85. When the peat is highly humified the storage coefficient can decrease to a value below 0.1. In the former case the percentage volume of "free" water in the Sphagnum vegetation layer is 85%, while in the latter case it is only 8%. The differences in water storage coefficients in relation to the degree of humification, immediately explain why renewed peat growth on "black peat" (highly humified Sphagnum peat), exposed through peat digging cannot start spontaneously, while in an undisturbed acrotelm possibilities for growth are present in abundance. From a simple calculated example this can be made clear further.

Assume a loss of moisture or a water storage change of 70 mm. In that case the water-table in a fresh to poorly humified peat layer with a storage coefficient of 0.8 would drop by 87.5 mm or nearly 0.09 m. However in a highly humified substratum with a water storage coefficient of e.g. 0.2 the watertable in the peat would drop by 0.35 m. In the first example, as was described in paragraph 4.2.1., sufficient capillary action remains, to supply the Sphagnum vegetation in the second example this is not possible and the greater amplitude in ground water-table will lead to a vegetation type which is typical of a dried-out raised bog environment. This will happen even although the capillary action of humified peat is larger than that of unhumified peat.

Drying out of the raised bog environment can however also arise because of an increase in drainage to the subsoil, or as a result of an increase in surface discharge. In chapter 5 and 8 this will be discussed further. The result of these hydrological changes will be that the quantity of stored water (ΔS) in a raised bog is decreased, which will result in a decrease in water-table in the bog in the dry summer period.

Figure 16 clarifies the fact that a greater amplitude in the bog water-table results in a vegetation which favours drier habitats.

Figure 16. Average highest and lowest water-table below the bog-surface for different plant species.

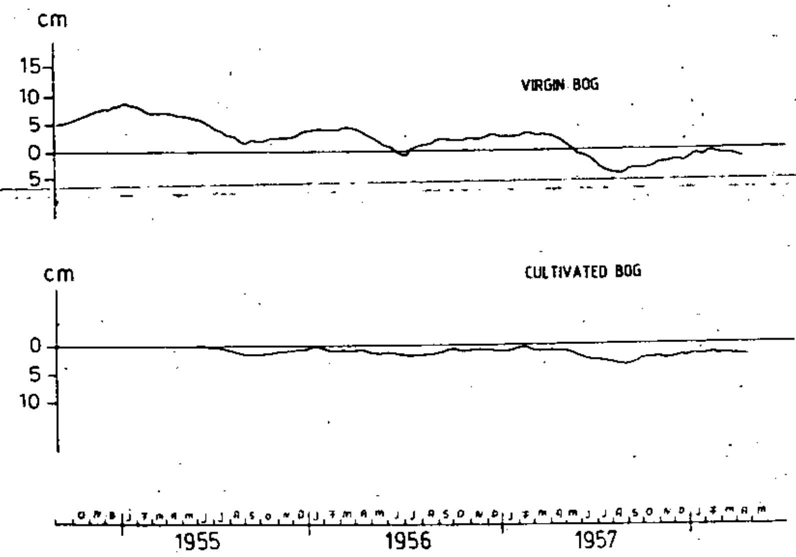


These data originate from the research of Willems (1974), which was carried out in the 'Bargerveen'.

Processes of swelling and shrinkage of the acrotelm

As already described a natural process of swelling or shrinkage of the bog-surface takes place in the acrotelm, when the water-table rises or drops as a result of precipitation or evaporation respectively.
Uhden (1967) and Ivanov (1981) recorded that the average yearly amplitude of the swelling and shrinkage of the bog-surface can be about 0.10 to 0.15 m. In figure 17 below two examples are given of swelling and shrinking of the bog-surface.

Figure 17 Swelling and shrinkage of the bog-surface of a nearly intact raised bog, and a bog which has been cultivated.



The data were taken from research by Uhden (1967) in the Esterweger Dose. The differences of swelling and shrinkage of the bog-surface can be explained from the change in porosity and the distribution of pore sizes near the surface, which have appeared because of drainage. Drained bog is more dense and has a higher mass. This results in a decrease in the capacity for swelling and shrinkage.
The process of swelling and shrinking of raised bogs in relation to the physical properties of Sphagna can be described as follows. In living bog the magnitude of the storage coefficient close to the bog-surface is somewhat variable, as a result of the capacity for swelling and shrinkage of the active peat-forming layer. In the winter months, when precipitation is abundant, the Sphagna can take up a lot of water in the hyaline cells and the pores between plants are almost totally saturated with water. The bog-surface expands primarily because of the filling up of the hyaline cells. The storage coefficient can increase to 0.95 in that case. In summer, when evaporation surplus exists, the water-table drops and the "Sphagnum sponge" dries out superficially and therefore the bog-surface goes down. The storage coefficient at the end of the summer can drop to a value of 0.8 to 0.75.

The relatively large storage coefficient in the acrotelm as well as the swelling and shrinkage capacity of this layer, are important hydrological properties of a living raised bog and therefore these properties indicate an essential condition for the existence and maintenance of this environment. Both properties assure that the water-table in the acrotelm of the bog does not drop more than about 0.10 to 0.20 m during the year. This can be illustrated by an example. A peat deposit of 0.25 m in thickness consists of living Sphagna and non-humified Sphagnum-peat. At the end of a dry summer this deposit contracts

to 40% of its original thickness, i.e. 0.10 m. The bog surface is lowered by 0.15 m. At the beginning of the period of evaporation surplus 0.25 m of peat is present, which consists of 5% (= 0.0125 m) organic material and 95% or 0.2375 m of water.
At the end of the summer season 0.10 m of peat is present consisting of 0.0125 m, or 12.5% organic material and 0.0857 m or 87% water. Or in other words the peat-surface has dropped by 0.15 m. The living Sphagna and the non- humified Sphagnum peat deposit contain, despite the serious evaporation, still a lot of water, i.e. 87% in this example.
A relatively small loss of moisture goes hand in hand with a very large vertical movement of the bog surface and in addition 150 mm of water is available for evaporation and discharge.

4.3.3. System-linked discharge

In this paragraph the supply of water to purely ombrotrophic, peat producing vegetations in hummock-hollow systems will be discussed. The system-linked or system-required discharge of hummock-hollow systems in particular will be given attention. The system-linked discharge can be defined as the flow of water, which is necessary in order to fullfill the following three functions: to maintain the high water-table of the bog, to expel the surplus of nutrients and to maintain the level of acidity.

System-linked discharge

The assumption of the existence of a system-linked discharge or a discharge required for the system rises from the following starting-points and observations.

- Water-balance
In its most simple form this can be defined from a discharge point of view, as follows. Given a maximum evaporation of Sphagnum plants, which are growing well, of 550 mm/year (Table 10) and an infiltration into the subsoil beneath living raised bog systems of 25 to 40 mm/year (Table 14), it should be possible for raised bogs to develop in areas with a precipitation of 590 mm or more per year, at a certain average yearly temperature.

- Distribution
In the lowlands of Western Germany and the Netherlands raised bogs occur or have only occurred in areas with an average precipitation of about 700 mm per year or more (3.3.3.) and an average yearly temperature of 9.5°C. Above 11°C raised bogs do not occur.

It seems that in the above lowland areas the precipitation has to be at least 110 mm/year more than the evaporation and infiltration together, which disappear from the raised bog system. This additional water loss consists exclusively of surface discharge. It is postulated that this discharge is necessary, as "feeding" for the growth of Sphagnum and for the maintenance of the oliogotrophic, ombrotrophic system.
Below information about system-linked discharge of different origins is brought together. The assumption is that peat producing Sphagnum vegetations, which grow well, are an indication of good ombrotrophic feeding of living raised bog. The information relates to the following:

- Observations from recent raised bog vegetations (by both authors) in bogs

which were not always virgin, but which were at least partly actively growing, carried out since the early sixties up to the present. These bogs were located in the lowlands of Ireland, Scotland, the Netherlands, West Germany, Poland and Finland;
- Peat-stratigraphical research, especially on hummock-hollow systems;
- Archeological research of the peat, especially research into prehistoric bog trackways with special reference to the manner in which the wooden trackway-surface has become overgrown;
- Data on water quality, in which the input and output balance has been considered.

Recent situations

Sphagnum cushions which are growing well, e.g. cushions of S. magellanicum and S. papillosum, are mainly found close to small superficial water flows and sometimes near small pools at the bog surface. Such cushions of peat-moss also occur between vegetations of Molinia or Erica on very wet raised bog surfaces, on which open water is often present. Cushions of peat-moss which are growing well can often develop on floating mats of poorly humified Sphagnum-peat ("bonkveen"-dug-off peat-blocks) in inundated pits left after peat digging. Further more S. cuspidatum and S. recurvum can be present also. On surfaces of poorly to moderately humified peat bare of vegetation (for example after removal of the vegetated top layer), Sphagnum can develop near flowing water, and the bare surface can be recolonised. In that case it always concerns peat-surfaces, which are moist to very moist during the greater part of the year.
As soon as flowing water is absent, Sphagnum vegetations do not appear in general.

Peat-stratigraphical research

Hummocks of highly to moderately humified Sphagnum-peat, which existed between about 2,000 and 200 B.C., often show extensive formation of cushions of Sphagnum, S. imbricatum on the flanks and somewhat lower down S. papillosum. The peat which is produced is usually little humified. On the highly humified bottom of hollows a poorly humified peat layer of S. papillosum and S. cuspidatum usually develops. Analysis of rhizopoda indicates that this concerns peat formation under moist to very moist conditions, respectively very moist to wet conditions, or open water. Where the hummock vegetation invades over the edges of hollows in many places poorly humified peat cushions of S.imbricatum develop; analysis of rhizopoda indicates that this happens when the wetness of the peat increases strongly locally. In many cases this will even lead to reoccurrence of open water in hollows.

Bog-archeological research

The wooden surface of bog trackways (toghers) is always overgrown with Sphagnum peat, which is less humified than the peat below the trackway. At many sites the structure of the plants is still so well defined that the overgrowing peat can be considered as unhumified (fresh peat). It is usually S. imbricatum or S. papillosum. The wood used for the trackways often shows perfectly preseved wood working marks (axe-marks). Such tracks were rather quickly overgrown by peat. This may only have taken as little as 10 years.
Because of the weight of the wood of the substrucure and the road surface

itself the peat deposit under the track is somewhat compressed. This is accompanied by a flow of water to the site from its surroundings. On the planks and between the beams of the road the conditions for the growth of poorly humified Sphagnum-peat became optimal, consisting of S. imbricatum, S. papillosum and sometimes also of S. cuspidatum. Analysis of rhizopoda indicates that the water-level, the level of the road-surface and the bog-surface were at approximately the same height.

System-linked discharge of hummock-hollow systems

The information above can be used to describe the discharge typical of the hummock-hollow systems of a raised bog.

Figure 18. Cross section through a hummock-hollow system, 500 to 200 B.C. – discharge through the hummock.

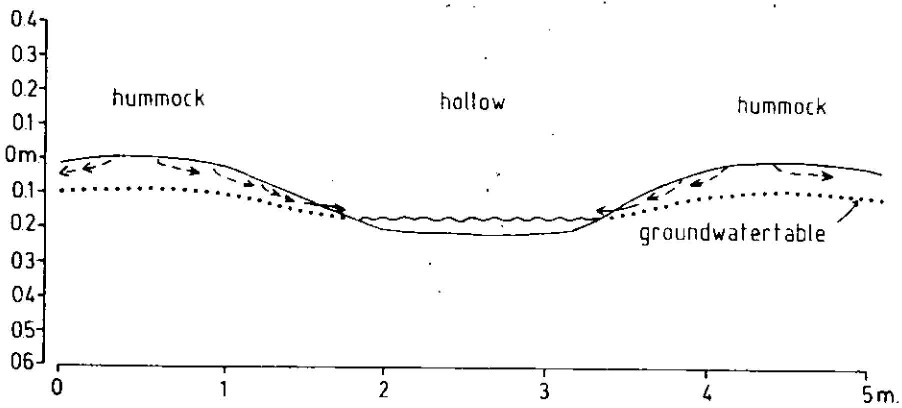
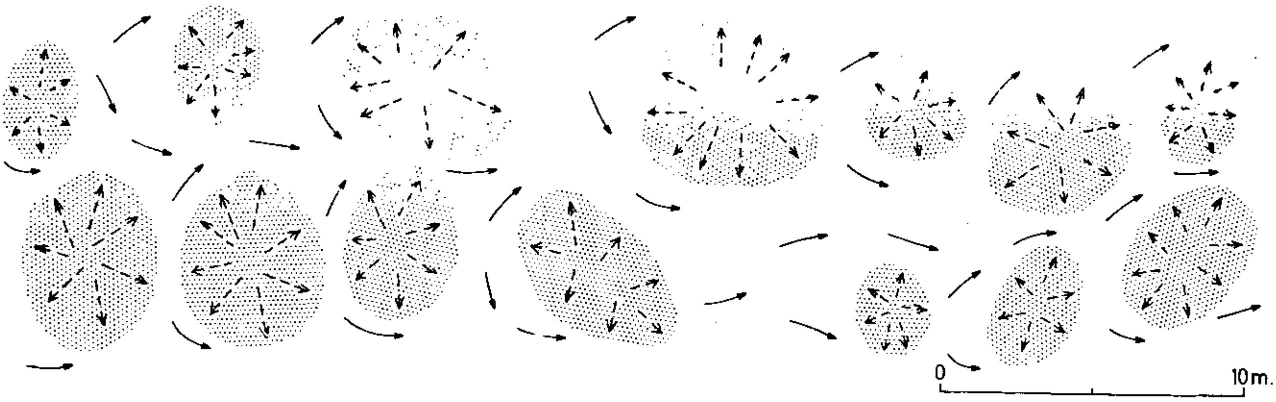


Figure 19. Water discharge in hummocks and via hollows of a raised bog



Figures 18 and 19 represent the hummock hollow pattern of that part of the 'Bourtangerveen' which is situated in southeast Drenthe, and which was present between 2,000 and 200 B.C.. In this system the sizes of the hummocks vary mostly between 3.8 and 5.2 m; this is especially so for the period of 500 to 200 B.C.. The distance between the centre of the hummocks varied from 5 to 8 m; considerable deviations from the above mentioned sizes are present, but are not considered here. In this period the differences in height between hummocks and hollows was 0.1 to 0.2 m. In the hollows and on the flanks of the hummocks poorly humified peat was formed predominantly at that time. In figure 19 it is assumed that the main direction of discharge in the net-shaped hollow pattern is to the right, towards the contact zone. In the winter period many hollows will have retained open water, the largest proportion of discharge took place along the surface, because the unsaturated permeabilitiy (on the surface) is much greater than the saturated permeability (in the peat). In the summer months, when open water has disappeared for the greater part, discharge takes place mainly in between the loose vegetation of the hollows. As the flow of water decreases this vegetation becomes more compact and thus the flow is more strongly retarded; this is a typical property of the acrotelm. This goes hand in hand with some shrinkage of the upper peat (Mooratmung). The discharge of rain falling on the hummocks follows a path through the peat of the hummocks, to the hollows, as represented in figure 18 (cross section). The peat deposit itself is saturated with water, however in dry symmers the drying out can penetrate somewhat deeper, so that the level of discharge drops below the bottom of the hollow. The growth of Sphagnum peat may stop in that case.
As was remarked in paragraph 4.3.1. the pH, at which the peat-mosses of hummocks or hollows grow, varies strongly. The more acid environment of the hummocks is indicative of the strong oligotrophic conditions, which can exist because of the discharge of nutrients to the hollows. The system of hollows is therefore less acid and a little less oligotrophic. Because of a continuous discharge via the system of hollows, a surplus of nutrients is discharged and the pH is maintained at a relatively acid level; in this way raised bogs are characterised by a discharge which is linked to the system.

Water quality data

Because of superficial discharge, via the hollows of the bog-surface, many of the dissolved substances presumably disappear from the raised bog system. Malmer (1975) measured for example in the south of Sweden that because of discharge at least 90% of potassium-, sodium- and chloride-ions and 70% of magnesium-, calcium- and sulphur-ions disappear from raised bogs. Because of this discharge the oligotropic status of the raised bog system is promoted. Moreover, Damman (1986) concludes that the lateral transport of water from the dome to the margin through the acrotelm is a very important process because this is the only effective way of removing nutrients from the bog, which can also enrich the lower marginal near of the bog. He explains that the occurrence of species with higher nutrient demands in watertracks and near the periphery of the plateau of bogs presents some indication that this process causes spatial differences in nutrient supply within an ombrotrophic bog. The quantity of the elements accumulated in the ombrotrophic peat on the central bog plain when compared with input data shows that elements have been retained in the order Mg>N>>Ca<K>Mn>Na (Damman, 1978). This suggest the lateral relocation or removal occurs in the reverse order.

The following can now be noted in relation to the oligotrophy of a raised bog.

4.3.4. Ombrotrophy as a characteristic of raised bogs

The position in the landscape of ombrotrophic bogs can, in an ecological sense, best be described from the cycling of water, which in turn can be described as follows. Sea-water which evaporates, condenses in colder layers of air above the surface of the earth and in this way clouds are formed. When sea-water evaporates its mineral constituents remain almost totally in the sea, which results finally in high concentrations of salts in the sea. The wind transports clouds to the continents. Depending e.g. on temperature and humidity of the air and relief of the surface of the earth this can result in precipitation, which falls on the surface of the earth for example in the form of rain. This precipitation is poor in nutrients; Rain-water then flows via the surface of the earth, or via ground-water, to streams and rivers and finally ends up in the sea once more, which closes the cycling of water. The longer the way is which the water takes, the longer it is in contact with the bottom substrata; the water becomes richer in nutrients because minerals from these substrata are dissolved and transported with the water.
Ombrotrophic bogs are solely fed by rain. Because of this they are characterised by low quantities of nutrients. An ombrotrophic bog is a bog poor in nutrients. This will now be discussed further.

A. The capacity for electrical conductivity (Cond.) of ombrotrophic water

Rain-water is naturally poor in nutrients and of low ionic content. The low ionic concentration can be expressed by the electrical conductivity (Cond.). (The conductivity is a measure for the quantity of dissolved ions in water). In table 8 the conductivity of rain-water is compared to that of other major types of water, which occur naturally (Van Wirdum, 1980).

Table 8 Conductivity of major water types occurring naturally.

Type of water	Electric conductivity in m Sm^{-1}
rain water	5 to 6
river water	50
sea water	5000

It is clear from this table that the conductivity of river water and of sea water is respectively 10 and 1,000 times as high as that of rain water. Willems (1974) states that low conductivity is one of the main characteristics of ombrotrophic bog water. According to his data the conductivity value of this type of water lies below 15 m Sm^{-1}. Boelter and Verry (1977) measured a conductivity value as low as 8 m Sm^{-1} in ombrotrophic bogs in the United States. The conductivity of water from raised bogs is only slightly higher than that of rain water, and is therefore of the same type.

B. The chemical composition and characterisation of water from ombrotrophic bog

As was already stated rain-water and water from ombrotrophic bogs both have low conductivity values. The chemical composition of the above water types is closely related to the hydrological cycle and the interrelated process of respectively uptake and accumulation of ions. Table 9 below illustrates this clearly.

Table 9 The chemical composition of ombrotrophic water in relation to the main types of water in the natural environment.

	sea water	river water	rain water*	ombrotrohophic bog water** Boelter	Sjörs
macro-anions	mg/l	mg/l	mg/l	mg/l	mg/l
chloride	19.000	12	4	0,7	1,4
sulphate	2.700	35	4,6	4,6	12,5
bicarbonate	142	160	2,6	-	0
nitrate	0	1,5	1	0,2	-
macro-cations					
sodium	10.500	5	2	0,6	2,0
potassium	380	5	-	1,3	0,39
calcium	400	50	1,7	2,4	1,6
magnesium	1.350	10	1,0	0,97	1,22
ammonia	0	0	0,5	0,45	-

* above the ocean
* above a continent

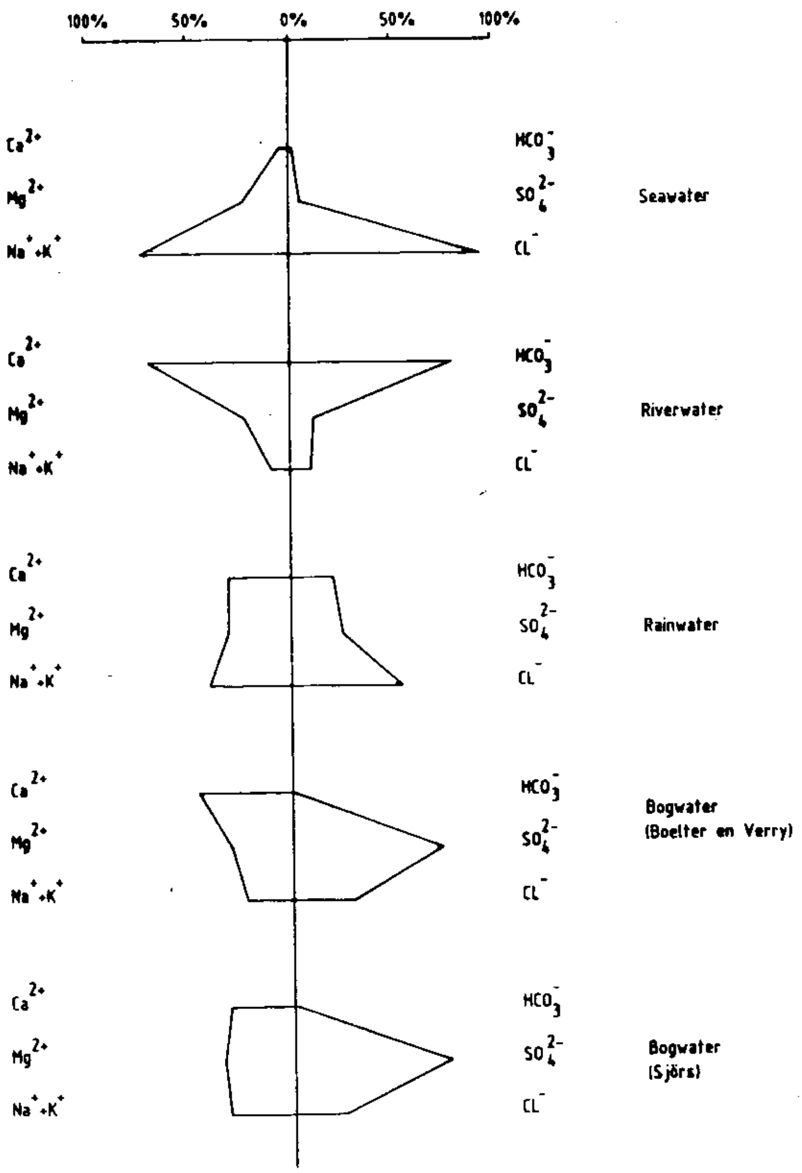
These data are taken from research by Van Meinardi (1976), Leeflang (1938), Boulter and Verry (1977) and Sjörs (in: Moore and Bellamy, 1973).

Sea-water, river-water and rain-water all have their own characteristic composition. Sea-water is the end point of the perpetual cycle: accumulation of compounds takes place to a much higher degree than the accumulation as a result of one cycle only. It therefore contains high quantities of salts, with high concentrations of chloride, sulphate, sodium and magnesium ions.
River-water takes up an intermediate position between the three water types under discussion. Rivers discharge a mixture of rain-water and ground-water. The quality of river-water is therefore closer related to rain-water than to sea-water. The concentrations of chloride, sulphate, sodium and magnesium ions are only a few percentages of those in sea-water or even less than that. In the case of bicarbonate- and calcium-ions this is different; the concentrations are either the same or 1/10 lower than those of sea-water. This can be explained by the fact that for long periods the water was in contact with bottom-substrata rich in calcium. In addition calcium carbonate is sedimented in the sea in the

Rain-water is, as was already clear from its low conductivity, very low in ionic contents. The concentrations of nitrate, sodium, chloride and sulphate ions are respectively 33%, 60%, 67% and 87% lower than the concentrations of these ions in river-water. The concentrations of the remaining compounds are only a few percentages of the concentrations present in river-water.

In relation to the three water types under discussion the chemical composition of ombrotrophic bog water comes closest to that of rain-water. However, there are striking differences between the chemical composition of rain-water and ombrotrophic bog-water. The differences in quality are expressed clearly in ionic diagrams, so called Stiff-diagramms (figure 20).
* remark:
In a Stiff-diagram the proportion of the different cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (HCO_3^-, Cl^-, SO_4^{2-}) can be shown clearly. The concentration of the different cations and anions is expressed in milli-equivalents per litre. The valences per litre are expressed as percentages of respectively the sum of cations and the sum of anions. The relative quantities of cations are expressed left of the vertical axis (fig. 20) and on the right hand side the quantities of anions are expressed.

Figure 20. Stiff diagrams for sea-water, river-water, rain-water and bog-water.



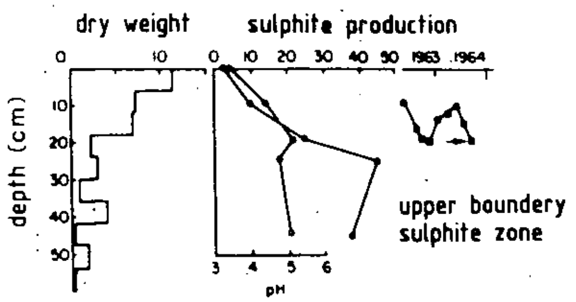
These diagrams represent, apart from the quality of bog-water, the characteristic quality of sea-water, river-water and rain-water as well. The description of the water quality, aided by the ionic diagrams, clearly shows that the bog-water is characterized by a relatively higher proportion of sulphate, than that found in rain-water. The following can be remarked about the presence of this higher concentration.

Sulphate is converted in bogs with a high water-table mostly by bacteria under anaerobic conditions via a biochemical process.
The sulphate reduction is as follows:

$$2\ CH_2O + 2H^+ + SO_4^{2-} \dashrightarrow 2\ CO_2 + H_2S + 2\ H_2O$$

In the process of reduction of sulphate to sulphide organic material, is decomposed. Sulphate is used instead of oxygen as electron acceptor.
Clymo (in Moore and Bellamy,1973) determines that the H_2S production increases with depth (figure 21).

Figure 21 Depth in Thursley bog related to the percentage of dry matter of Sphagnum papillosum (left). The right part of the graph describes the sulphide contents at different times of the year, the pH on the 31st of August and the H_2S production at arbitrary depths. The arrow indicates the highest level of sulphide contents, at the times of measurement of the pH and bacterial activity.



The figure conveys the following information. The percentage loss of dry matter (of S. papillosum) decreases strongly up to a depth of about 0.20 m below the bog surface from about 10% to 2.5%. Below this level the percentage of dry matter decreases only slightly. This indicates that the breakdown of organic matter takes place predominantly above the level of 0.20 m.
The sulphide production however increases to a level of about 0.25 m below the bog surface. At this level a maximal H_2S production is reached. Above this level the H_2S production fluctuates, which is related to e.g. the fluctuations of the water table of the bog, however the level of optimum H_2S production is not effected by this (at about 0.25 m), according to the experiment of Clymo. The reduction process of sulphate under optimum conditions takes place just below the level of the bog water table, after all anaerobic conditions prevail here.

An important conclusion which Clymo reaches is the following:
The general measure for accumulation of peat depends on the instant at which the organic material, produced in the top layer, reaches the sulphide layer, where the conversion takes place considerably slower as a result of the slow anearobic decomposition processes. This process is dependent on two factors, i.e. the extent of primary production at the bog surface and the height of the water table in the bog; in other words the distance between the point of production and the sulphide zone, and perhaps also the discharge of the decomposable material, which is used in the reduction process of H_2S.

The slow decomposition processes of sulphate under anearobic conditions and the relatively small availability of fresh material in that layer, are thus presumably the cause of accumulation of sulphate in that layer, and of the high concentration of sulphate-ions in bog water. Furthermore, part of the sulphate is returned to the system (Gorham, Bayley and Schindler, 1984), because sulphide is oxydized and changed into sulphate, as is expressed in the following chemical reaction:

$$H_2S + 2\ O_2 \text{ ---> } SO_4^{2-} + 2\ H^+$$

Finally the following remark remains to be made in relation to the management of drained and partly dug-away peat deposits. When peat surfaces are rewetted, much higher concentrations of sulphate-ions may be present in the bog water. than under natural conditions. This can be explained as follows. When bog is drained the sulphate is not reduced under anearobic conditions, which causes sulphate to accumulate in the peat profile above the level of the water table in the bog, or in other words, the input of sulphate-ions is larger than its discharge. Because the water table is raised, sulphate is released in large quantities and can escape slowly as H_2S gas under anearobic conditions, when the peat material is humified.

4.4. CONCLUSION

- Supply of moisture and nutrients to the Sphagna takes place solely by water from precipitation and can take place through interception of rainwater or through capillary action of water rising from the bog. The capillary rising of the water to the hyaline cells takes place via the pores, which are found between the parts of the peat moss plants and between the plants themselves;
- A raised bog is characterised morphologically by a domed relief. Raised bogs are therefore solely fed by precipitation, and surplus rain water flows off to the surroundings (periferal discharge);
- The natural water balance of a raised bog is characterised by a combination of direct supply from precipitation and a superficial discharge of the water surplus;
- Living raised bogs are therefore characterised by a superficial discharge which is system-linked. Under Dutch conditions, given a minimal quantity of precipitation of 700 mm per year, which is necessary to maintain a raised bog, the system-linked discharge is at least about 110 mm;
- The characteristic properties of the acrotelm are the most important conditions for the creation or maintenance of a living raised bog. With a given set of variables a high capacity for water storage is a necessity, in or near the bog surface, or it should be possible to create this (more than about 80% of the space on the bog surface needs to be occupied by water);

- Raised bogs are characterised by ombrotrophic water. This type of water is nutrient poor, and has a low ionic loading (conductivity less than 15 m Sm^{-1}). The chemical composition of bog water is to a great extent similar to that of rain water. However, the bicarbonate content is lower and the sulphate content is higher than that of rain water.

5. SOME IMPORTANT HYDROLOGICAL CHARACTERISTICS FROM STUDIES OF WATER BALANCE IN RAISED BOGS, IN PARTICULAR FOR THE DUTCH SITUATION

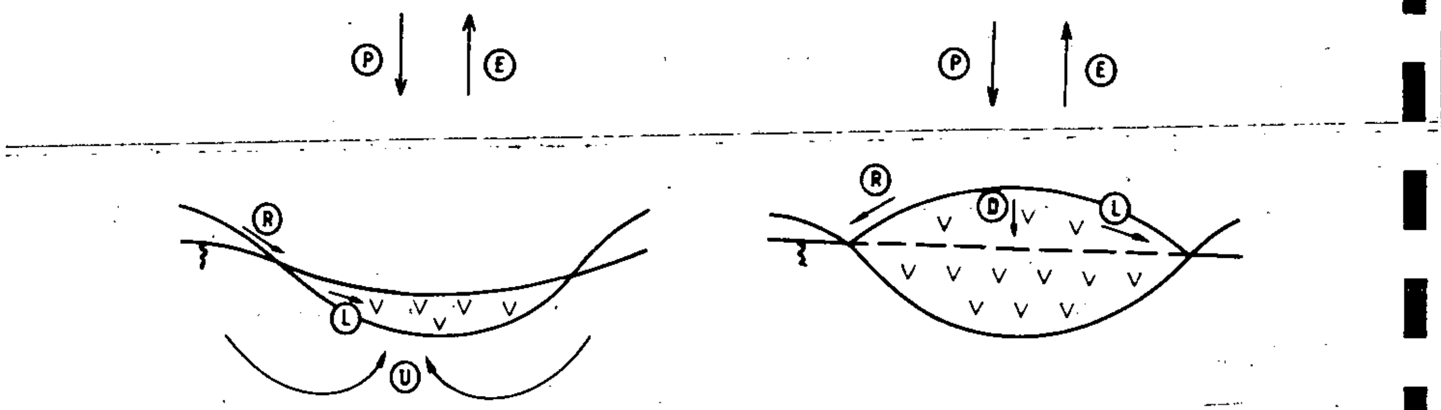
5.1. GENERAL

In general water balance studies of an area take prime place in hydrological observation, as these give good insight into the quantitative relationship between for example precipitation, evaporation, discharge and storage. In this way knowledge is gathered about the pedological or hydrological characteristics of an area, which is of importance to managers of peat reserves. This is the reason why the water balance of raised bogs is discussed further in this chapter. For the Dutch situation water balance studies of living raised bogs are not available and for the management of damaged areas the knowledge of characteristic soil and area properties of living raised bogs should be taken into account. It is useful to analyse further the hydrological conditions of specific Dutch raised bogs, because the climatic conditions for the formation of raised bog are not the same everywhere (see section 3.2.). The study of water balance is excellently suited to this purpose also. The equation for raised bog is discussed in section 5.2.. Section 5.3. pays attention to the conclusions of studies of water balance over several years. Emphasized is especially the occurrence of differences in yearly intensities of precipitation, evaporation and discharge under different climatological conditions. Section 5.4. to 5.7. discusses in particular the evaporation, surface runoff and the downwards seepage into the subsoil of raised bog areas. Finally section 5.8. contains an analysis of the water balance of living peat moss in a raised bog complex, as it could exist under Dutch conditions.

5.2. THE EQUATION OF WATER BALANCE OF RAISED BOGS

In section 4.3.1. were discussed the upwards seepage peats and fen peats of the Netherlands as starting phases of ombrotrophic bog formation. These fens are characterized by their hollow-round relief. Raised bogs are typically domed. In general the water balance of peatlands with a concave or a domed relief is different. This will be clarified in figure 21 and its water balance.

Figure 21. Diagrammatic representation of the supply and discharge of water in peatlands with concave and with domed relief.



Fen with concave relief

raised bog with domed relief

water-balance:

$P - E + R + L + U \text{ or } -D = \Delta S$

water-balance:

$P - E - R - L - D = \Delta S$

(P = precipitation, E = evaporation, R = surface runoff or supply, L = lateral seepage, D = downwards vertical seepage, U = upwards vertical seepage, ΔS = change in storage capacity).

Peatlands with a concave relief are fed by water from precipitation as well as by water from the surroundings. Raised bogs with a domed relief however are solely supplied by water from precipitation, because they lie higher than the surrounding lands (section 4.3.1.).

The relationship between the supply and discharge of water within the raised bog system is described by the water balance. The simplest form of a water balance for a raised bog is described by figure 21. It is clear from water balance studies of these bogs done over several years, that the average change in storage-capacity (ΔS) in a hydrological year is equal to zero. The water balance for an average year can be written as:

$P - E - R - L - D = 0$

In which $P - E = P_y$ and P_y is the surplus in precipitation, which is discharged in an average year. Thus applies: $R + L + D = D_y$.

5.3. CONCLUSIONS FROM WATER BALANCE STUDIES OF LIVING RAISED BOGS FROM SOME COUNTRIES IN EUROPE CARRIED OUT OVER MORE THAN ONE YEAR

One of the most important factors of water balance is discussed first: precipitation.

5.3.1. Precipitation

From the definition of a raised bog it is clear that precipitation is the only source of nutrients for such bogs. The importance of this factor for the water management of a bog is evident. According to Granlund (section 4.3.1.) the size of a bog is partly determined by the amount of precipitation, which falls in an area per year. The findings of Granlund do not directly apply to the Dutch situation. It has already been stated in chapter 2 and section 3.2. that the distribution of bogs depends on more than one variable. The level of temperature for example directly determines the intensity of evaporation. Finally the size of the surplus of precipitation (P - E) determines to a great extent how much water is available for growth of the bog. A picture of areas of different intensities of precipitation and evaporation is created with the aid of water balances of bogs in western, central and eastern Europe.

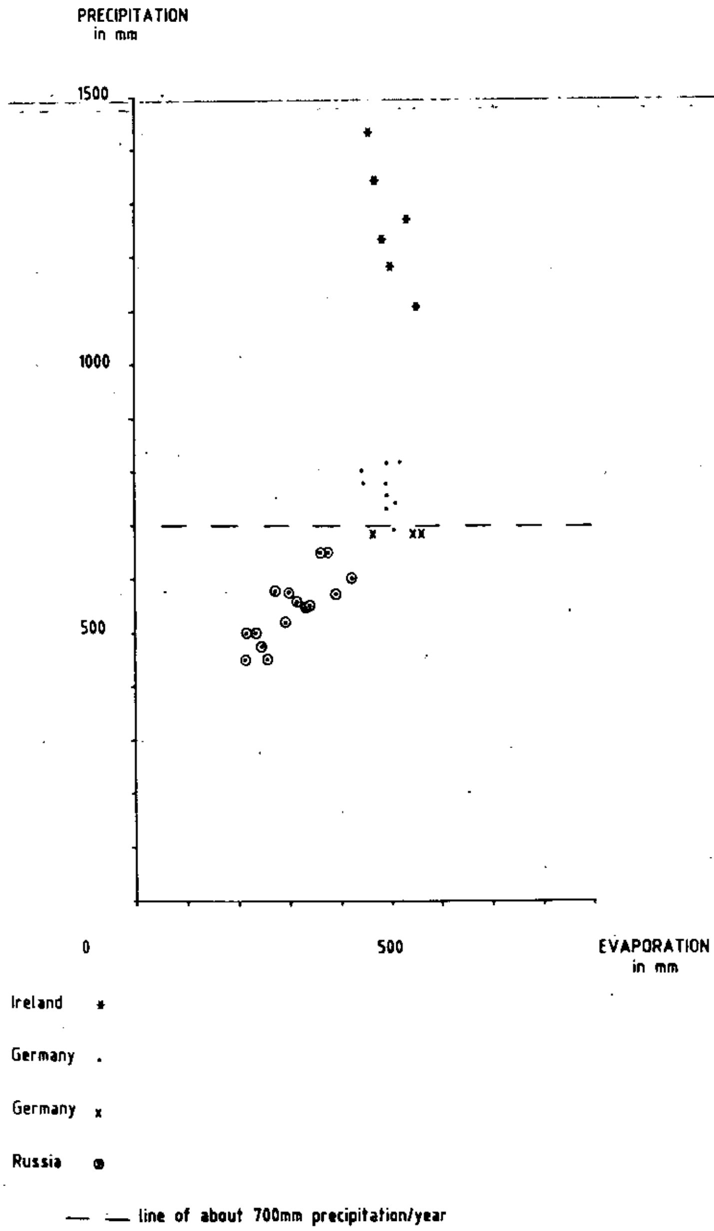
5.3.2. Precipitation and evaporation of bogs, going from western to eastern Europe and for the Dutch situation in particular

Water balance studies are available from Ireland (Burke, 1975), northwest Germany (Eggelsmann, 1981) and European Russia (Romanov, 1968). The raised bogs of Ireland and northwestern Germany and of the countries in between are situated in areas of comparable climatic type, i.e. a strongly to moderately oceanic climate. One of the characteristics of this climate is that the average monthly temperature is always above 0^{o}C, which means that the surplus of precipitation can be discharged during the whole year. The yearly quantities of precipitation and evaporation are graphed in figure 22.

From this graph it is clear that the two areas in Ireland and in northwestern Germany have an evaporation of the same order of magnitude and this is 450 to 550 mm per year. This observation agrees well with the climatological considerations concerning the transect from western to eastern Europe in section 3.2. (figure 5). It has been stated there that the mean intensity of evaporation over the section Ireland to northwest Germany remains fairly constant.
This also implies that the intensity of evaporation for bogs in the Netherlands must be of the same order of magnitude as that in the investigated areas in Ireland and northwest Germany. From an estimation of water balance for De Groote Peel in the Netherlands (Joosten and Bakker, 1988) it appears that the order of magnitude (evaporation 483 mm in 1985/1986) is in agreement with the above-mentioned data. According to the graph the yearly precipitation in both areas shows a great discrepancy. In Ireland the intensity of precipitation is 1100 to 1450 mm per year. In northwest Germany, however, the intensity of precipitation is much lower and amounts to 690 to 825 mm per year. In Germany the water balance closes with a negative figure for several years (P - E < 0). In the years of a negative water balance a permanent water shortage exists, which can only be reversed in years with relatively large precipitation and/or little evaporation. With a shortage of moisture peat growth is retarded, or can

even cease. The limit, at which moisture shortages become irreversible, lies somewhat below a value of about 700 mm per year.

Figure 22 Relationship between precipitation and evaporation



In the Netherlands climatolgical conditions exist which are comparable to those of northwest Germany and hence.
Bog formation can take place at sites at which the average intensity of precipitation is not less than about 700 mm per year.

Finally the graph indicates that in European Russia the intensity of precipitation can be less than 700 mm per year. This is closely related to the different climatological conditions in that country, as is also clear from figure 5 of section 3.2. The raised bogs of European Russia are situated in a continental climate, which is e.g. characterised by cold winters, as the temperature falls below freezing for several months year.
Discharge only occurs in the months of May to September, in the areas under investigation the evaporation of these bogs depends more on the late period in the year at which ice and snow starts melting. High quantities of evaporation as in western Europe, are therefore seldom reached here. The distribution of (lens) raised bogs in the oceanic climate of western Europe is bound not only by a lower limit, but probably also restricted by an upper limit. For the raised bogs of Ireland this upper limit lies at about 1150 mm per year. (Schouten, 1984). Above this level the lenses become obscured and transitions to true blanket-bog occur.

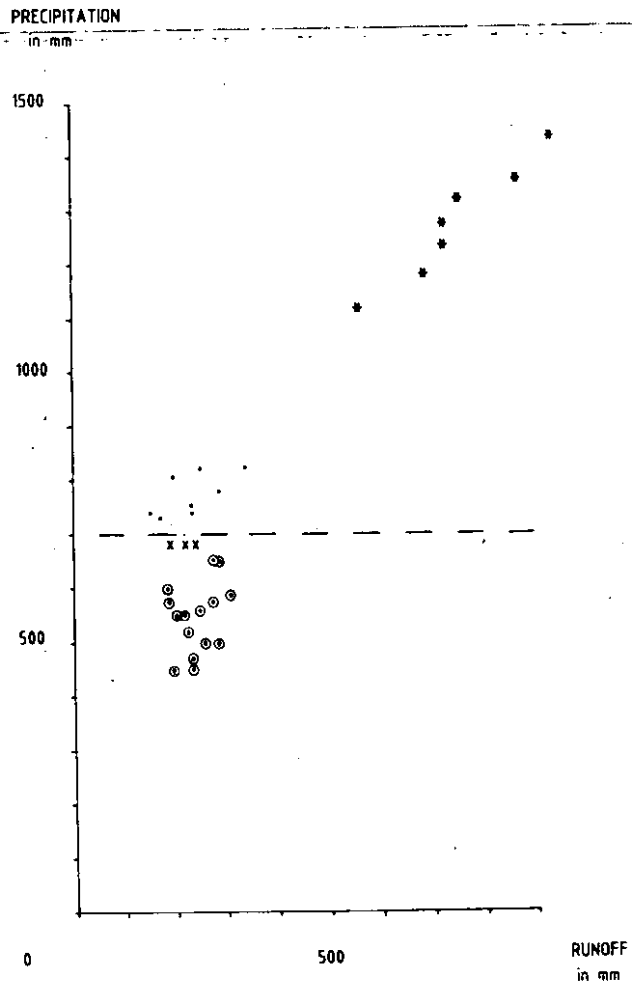
Surplus of precipitation

It is clear that the surplus of precipitation of the bogs of Ireland is much larger than that of northwest Germany. According to figure 22 the surplus of precipitation in Ireland is about 350 to 700 mm per year, while in northwest Germany values of 150 to 275 mm per year are reached.
In the raised bog area of European Russia the surplus of precipitation reaches 200 to 250 mm per year. This is of a comparable order of magnitude as that in the Netherlands and in northwest Germany.

5.3.3. The relationship between precipitation and discharge from bogs, going from west to east, and in particular under Dutch conditions

Finally the relationship between precipitation and discharge is described in short, from data of studies of water balance from the countries mentioned previously. According to figure 23 the intensity of the discharge decreases practically linearly with a decreasing intensity of precipitation, at least when the section Ireland to northwest Germany is under consideration. This is also expected; evaporation over this section remains after all at a relatively constant level (section 5.3.2.). At a mean intensity of precipitation for the Netherlands of 775 mm per year the intensity of discharge could reach a level of 200 to 275 mm per year.

Figure 23 Relationship between precipitation and discharge.



Ireland * positive waterbalance (P-E - discharge > 0)

Germany . positive waterbalance (P-E - discharge > 0)

Germany x negative waterbalance (P-E - discharge < 0)

Russia ⊙ positive waterbalance (P-E - discharge > 0)

— — line of about 700mm precipitation/year

5.4. FURTHER CONSIDERATIONS OF EVAPORATION

5.4.1. Mean yearly evaporation of raised bogs with different vegetation cover

Apart from precipitation, evaporation is an important factor of the water-balance equation. Especially in Germany a lot of research is done on evaporation of raised bogs which are not influenced by man, which are slightly drained and which are cultivated. Eggelsmann (1981) compiled a table of evaporation of raised bog complexes from his own data, as well as from the literature, see table 10 below. This table also lists the open water evaporation, as it is for example for peatland areas in the province of Drenthe. These latter data are taken from reports of the meteorological station KNMI at Dedemsvaart. The level of evaporation of open water is lower here than at other stations in the Netherlands.

Table 10. Mean evaporation of vegetated raised bogs in winter, in summer (over 6 months) and over the whole year

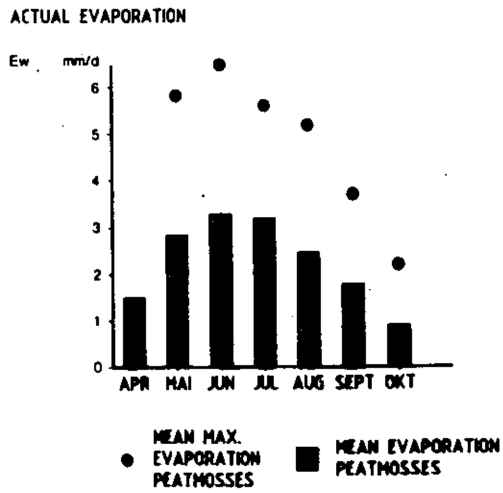
predominant vegetation cover	cultived status	evaporation (E_a)		
		winter	summer	year
peat moss/heather	unaffected	140	410	550
heather	slightly drained (small drains)	125	395	520
meadow and pasture	drained (large drains)	90	410	500
arable land	drained (large drains)	75	395	470
woodland	drained (large drains)	125	465	590
open water	-	80	530	610

It is clear from these data that woodland on drained raised bog evaporates more than other vegetations. The yearly evaporation of woodland approaches that of open water. In the winter half of the year the evaporation of vegetated raised bog complexes is higher than that of open water. In winter the surface of raised bogs with a Sphagnum cover consist out of open water for a maximum of 20 to 25%. These percentages are derived from aereal photographs of Scandinavian and Irish raised bogs and from the research into prehistoric bog trackways in southeast Drenthe. As a result of the surplus of precipitation in the winter months a relatively high water table occurs on the bog and a lot of rain is stored in the hollows and pools of the raised bog complex. Because of the smaller intensity of evaporation of open water in the winter, the surplus in the hollows and pools increases relatively more than that in the rest of the bog. This larger store of water is necessary to continue to supply the hollow relatively wet in this period too. In the hydrological summer half of the year the Sphagnum vegetations of the raised bog complex show on average a smaller evaporation than open water does; bog pools can then -at the end of the summer- be considered as extra (atmospheric) points of water-discharge for their surroundings (Ivanov, 1981).

5.4.2. Evaporation of Sphagna

Peat mosses evaporate strongly during the period of growth in spring and at the start of summer. Data of peat-moss evaporation are taken from the research of Scheidl (1960), who has checked his data against those occasionally collected by other researchers (e.g. Leick, Normals, Tinbergen, Overbeck and Happach, Virta).
The open water evaporation for the summer half year is an average for the Netherlands and is obtained from the Dutch meteorological stations.

Figure 24 The mean maximum evaporation and the mean evaporation of peat mosses.



According to figure 24 the mean evaporation of peat mosses in the months of May, June and July amounts to about 3 mm/d. This does not exceed the evaporation of open water during the summer half year (
$E_o = 530 : 182 = 3.0$ mm/d) and this will be less than the evaporation of open water in the months of highest evaporation.
For example: The maximum evaporation during these months can be taken to be on average 5 to 6.5 mm/d, while the equivalent figure for open water can be on average about 10 mm/d. Figure 24 also reflects an increase, respectively a decrease, of the intensity of evaporation at the beginning and at the end of the summer half year. This is a result of respectively the increase and the decrease of the temperature during this period.
The table indicates that the evaporation of peat moss vegetation is higher than that of open water during the winter months. During the summer half year (and on the basis of the whole year) however, this evaporation is less than that of open water, because of a water-shortage in the growing points of the peat mosses (osmosis cannot work faster and the capillary action becomes smaller).

5.5. SURFACE RUNOFF FROM RAISED BOG AREAS

First of all it is necessary to define further the surface runoff from a raised bog. Surface runoff is the discharge which finally leaves the bog, via hollows and contact zones and raised bog flushes. Two functions can be distinguished. The first function concerns the flow of water, which is necessary to maintain the high water-level of the bog, to discharge the surplus of nutrients and to maintain the degree of acidity.
This part of discharge can be described as necessary for the system, or in order words it is system-linked and it takes place for the greater part in the acrotelm. The minimum system-linked discharge for raised bog areas in the Netherlands amounts to about 110 mm/year (section 4.3.3.). That part of the discharge, which is not necessary to maintain the system, can be described as surplus water, which is discharged. When the surface runoff of undrained and of drained raised bogs in northwest Germany are compared (Engelsmann, 1981), it appears that the surface runoff over the winter period amounts to 71 to 75% of the total surface runoff over the whole year for both types according to table 11. Furthermore it is striking that the total yearly surface runoff of wooded raised bogs (drained) takes place wholly in the winter months.

Table 11 Characteristic surface runoff of raised bogs, which are undrained, drained or cultivated.

raised bog	yearly surface runoff (R_t) mm	winter surface runoff (R_w) mm	$\frac{Rw}{Rt}$ x 100%
- not drained (sphagna)	200	150	75
- slightly drained (Erica, Calluna)	230	168	73
- drained for meadow or pasture land	245	183	75
- drained for tillage	280	200	71
- drained for woodland	160	160	100

The surface runoff data above apply to a situation in which the mean precipitation is 750 mm.

If the total quantity of water to be discharged (R_x) is compared with the total yearly surface runoff (R_t) from October onwards at a certain instant, then it is shown that differences exist between undrained and drained raised bog complexes (Table 12). These data are taken from work by Eggelsmann (1964) and Uhden (1967).

Table 12 $\dfrac{\text{Total quantities of surface runoff } (R_x) \text{ of raised bogs at time x}}{\text{total surface runoff for the whole hydrological year}} \times 100\%$

	end of December	end of March	end of June	end of September
	%	%	%	%
- not drained	30	70	75	100
- slightly drained	30	80	90	100
- totally drained	30	80	95	100

From these data it can be deduced that by the end of June, in the case of an undrained raised bog, about 75% of the total yearly surface runoff has been discharged. In slightly or well drained raised bog complexes this quantity is at that time already 90 to 95% of the yearly surface runoff. It can also be seen from this table that for undrained raised bogs, about 25% of the yearly surface runoff is discharged during the months of July and September. These differences in percentages at the beginning and the end of the hydrological summer half year (from April to September) can be explained as follows.
Given a relatively equal distribution of precipitation intensity over the summer half year, a restricted surface runoff takes place from spring until summer while the intensity of evaporation rises quickly during that period, in undrained as well as in drained areas. This amounts to about 5 to 10% of the total yearly surface runoff.

The groundwater-table decreases further in spring as a result of drainage, which causes the capacity for storage in the substratum to increase more than in the case of undrained raised bogs, but also as a result of higher intensities of evaporation by crops (e.g. forestry). In undrained bogs only the surface dries out, which is closely related to the structure and composition of the acrotelm. This aspect is discussed in section 4.4. The intensity of surface runoff increases already from July to September, because of a forced decreased* intensity of evaporation of the peat mosses in that period (see figure 24).
This is different from the situation in drained raised bog complexes, in which the capacity of storage of the substratum must be filled up first, after which the surface runoff can start, which takes place at the end of September.
Based on these observations it is once more made clear, that especially at the start and at the end of the summer half year conditions of optimum moisture are present for moss growth in raised bog in the Netherlands and in northwest Germany.

* Remark: The decreased intensity of evaporation during the period July to September is on the one hand a result of the aging of the cell walls of the peat mosses; on the other hand it is a result of the white discoloration of the peat moss vegetations, which takes place with drying out (reflection of sunlight).

5.6. DISCHARGE VIA THE SUBSTRATUM; IN PARTICULAR DOWNWARD SEEPAGE

5.6.1. Horizontal and vertical permeability of the peat

In living raised bogs very large differences in permeability (k) occur in the acrotelm, both in horizontal (kh) and in vertical (kv) direction. In the catotelm the differences in horizontal and vertical permeability decrease rapidly. The peat moss material is humified to such an extent that the horizontal and vertical permeability reach a very low value and also differ from each other. At the transition of the peat to the mineral subsoil often a 'gliede' or sometimes a gyttja layer is present.
The gyttja layer is a lake deposit; it developed in inundated depressions and consists of lake sediments of mostly organic origin. The 'gliede' layer develops by washing in of diffuse humic material into the sandy subsoil. Both layers are characterized by a very low vertical permeability ($k = 9.10^{-5}$ m/d), so that even given a small thickness of this layer, for example d = 0.10 m, the hydrological resistance ($c = \frac{d}{k}$) can easily be a thousand days.

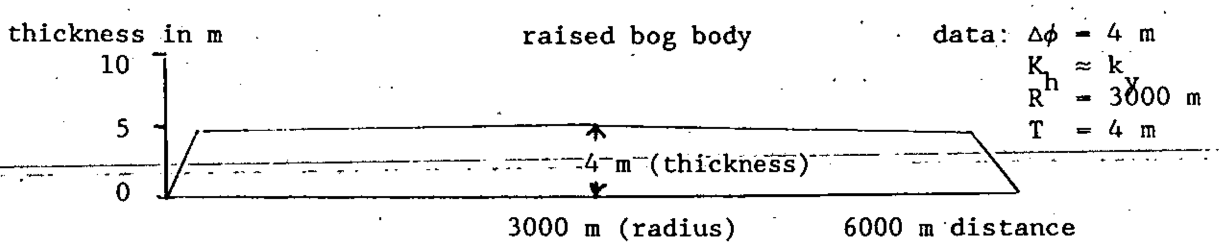
The following can be remarked about the proportion between the horizontal and vertical permeability of the peat deposit. Romanov (1968, for the acrotelm) and Boelter (1965, for the catotelm) investigated this. Their research resulted in the following data (see table 13).

Table 13 Proportion between horizontal and vertical permeability of the peat deposit.

humification	degree of humification	depth of sample below surface m	permeability horizontal m/d	vertical m/d
living peat moss.	(1)		109-10	< 10
not or poorly humified	(2-3)	0-0,10	3,3	5,4
moderately humified	(4-6)	0,35-0,45	$1,2\ 10^{-2}$	$4,4\ 10^{-2}$
highly humified	(7-10)	0,50-0,60	$9,6\ 10^{-4}$	$7,3\ 10^{-4}$

It is evident from this table that the horizontal and vertical permeability of Sphagnum peat decreases with an increasing degree of humification. With the exception of the acrotelm (living peat moss), large differences do not occur between the horizontal and vertical permeability, at comparable depths below the bog surface; the proportion of k_h to k_v is about 1.

Assuming that when the horizontal and vertical permeability are of the same order of magnitude, as is the case in the data above it follows that the vertical groundwater discharge in the catotelm of raised bog is much larger than the horizontal groundwater discharge. This is easily indicated in the example below.



The discharge below the bog surface in horizontal direction is:

$$q_h = 2\Pi \times KT \frac{\Delta\phi}{R} = 2\Pi \times 3000 \times 4 \times \frac{4}{3000} K = 10^2 K\ m^3/d$$

The downwards seepage:

$$q_v = \Pi R^2 \times K \frac{\Delta\phi}{\Delta T} = \Pi \times (3000)^2 \times \frac{4}{4} \times K = 2.8\ 10^7\ m^3/d$$

From this example it is clear, that the discharge via the substratum of a peat complex through the catotelm is greater in vertical direction than in horizontal direction. Therefore in any further considerations about groundwater discharge only the order of magnitude of the vertical discharge through the body of the peat is taken into account, this is called the downward seepage.

5.6.2. downward seepage

It is shown by studies of water balance, calculations of models and measurements of permeability that the downward discharge via the subsoil of raised bogs is small (Eggelsmann, 1960); Ivanov, 1981; Boelter, 1965; Bay, 1968; Streefkerk and Oosterlee, 1984). The results of research into the order of magnitude of the yearly downward seepage losses in undrained bogs is listed in table 14.

Table 14 Yearly quantities of downward seepage in mm and ditto as percentages in relation to yearly quantities of precipitation and discharge.

Reference	Yearly quantity of infiltration in mm	Percentage in relation to precipitation	Percentage in relation to discharge
Eggelsmann	36	5.5	
Ivanov	27	3.8	15
Streefkerk-Oosterlee	26	3.4	14

This relatively small downward seepage is explained from the fact that the resistance to vertical (and also to horizontal) water losses in the peat profile increases strongly as a result of humification of the organic matter and the pressure of the peat deposit which lies above, which leads to a decrease in the pore volume. In the unhumified top layer of the peat profile (about 0.10 to 0.15 m) the vertical permeability factor (k) is more than 1 metre per day (m/d), while above the base of the peat, in the strongly humified peat layers, this factor can decrease to values of less than 10^{-5} m/d (see also section 5.6.1.).
For the water balance of intact bog the downward seepage is therefore of little importance. The water balance of intact bogs is mainly characterised by a relatively large horizontal, surface runoff.

5.7. EXAMPLE OF THE WATER-BALANCE OF A LIVING RAISED BOG FOR THE DUTCH SITUATION

Eggelsmann (1981) formulated the following water balance for a year as well as for a winter and a summer half year of a living raised bog in northwest Germany (see table 15).

Table 15 Water balance of a raised bog with growing Sphagnum, for the northwest German situation.

	year	winter	summer
	mm	mm	mm
precipitation (P)	750	350	400
evaporation (E)	550	140	410
(P - E)	200	210	- 10
discharge (D_t)	200	150	50
change in storage (Δ St)	0	60	- 60

The order of magnitude of the different components of the water-balance will be much the same for Dutch circumstances as those found by Eggelsmann because comparable climatological conditions exist in the Netherlands. The data can therefore be considered as representative of a presumed Dutch condition.

Assume that a minimal system-linked discharge of about 110 mm per year is necessary (section 4.3.3.), this would mean that a maximum of 90 mm of water remains, which disappears from the bog as downward seepage or surplus water. Assuming a downward seepage percentage of about 4% of the yearly quantity of precipitation (section 5.6.2.) or about 30 mm a year, which would result in a discharge of only 60 mm surplus water. In practice it is not easy for a manager of a nature reserve to steer surface runoff out of a remnant of raised bog, because the surplus of precipitation can fluctuate considerably from year to year. Therefore it is important that in wet years water is retained in order to use it during dry periods. After all, living raised bogs have developed a natural mechanism to survive dry periods (Mooratmung).

Limiting conditions can be deduced for the minimal quantity of precipitation and the maximal tolerable downward seepage necessary to maintain or start the growth of a raised bog in the Netherlands, which are based on the factual data of previous chapters and sections. This means 700 mm precipitation for the Dutch situation and an downward seepage with a maximum value of 4% of the mean yearly precipitation. From the above a consideration of the measure of truth of these limiting conditions can be given.
First of all the minimal limit of 700 mm precipitation, which is necessary for ombrotrophic peat formation will be considered. The water balance of Eggelsmann would look like table 16, if the yearly quantity of precipitation is lowered to 700 mm.

Table 16 Example of the water balance of a raised bog with peat moss growth for the Dutch situation.

	year mm	winter mm	summer mm
precipitation (P)	700	343	357
evaporation (E)	550	140	410
(P - E)	150	203	- 53
discharge(D_t)	150	143	7
storage change (Δ St)	0	60	- 60

It can be established that in the summer half year only 7 mm is discharged, assuming a realistic value for evaporation, storage change and a proportional distribution of precipitation over the year. Based on this indicative calculation it becomes clear that the minimum limit of about 700 mm precipitation necessary for the formation of raised bog is a realistic limiting condition, because over the whole year a water-shortage does not occur.

With regard to order of magnitude of the downward seepage given in section 5.6.2. the following can be remarked with the aid of the calculated example. If for example one starts off from a position of about 4% of yearly precipitation which seeps away to the subsoil this could then be, according to the calculated example,

$\frac{4}{100}$ x 700 = 28 mm, or 14 mm in the summer half year.

Because of the order of magnitude of the discharge in the summer half year (only 7 mm), the size of the downward seepage has to be less, because otherwise drying out of the bog will take place.
For completeness sake it needs to be remarked, that at given higher intensities of precipitation the downward seepage can be larger, although because of the findings above and from factual field data from research the downward seepage must not be more than the difference between the mean yearly surplus of precipitation and the system-linked discharge of about 110 mm per year, which is considered necessary. After all the hydrological characteristics of a living raised bog show that the discharge from raised bog is mostly superficial for good reasons. Section 4.3.3. also supports such a situatation from an ecological point of view.

5.8. CONCLUSIONS

- Raised bogs have a domed relief and are therefore only fed by precipitation. This is also clear from the water-balance of raised bogs. This balance is characterized by only one source of supply, precipitation and for the rest the discharges are; evaporation, surface runoff and downward discharge into the subsoil;
- The formation of raised bog can develop in the Netherlands in those places where the intensity of precipitation is larger than about 700 mm per year. This however is not the only limiting factor for raised bog formation. The even distribution of precipitation over the year and the mean yearly temperature are important limiting conditions; this is in the Netherlands about $9^{o}C$;
- Evaporation of raised bog is primarily dependent on the occurrence of certain vegetation types. Peat moss vegetations evaporate more than heather vegetations or meadows. In the winter months, which are rich in precipitation, raised bogs can have up to 20 to 25% of open water at the surface. The yearly evaporation of peat moss covered raised bogs is for the Dutch and German situations about 550 mm. Evaporation of raised bogs covered with Sphagnum is higher than that of open water during the winter, but it is lower than that of open water during the summer half of the year;
- In drained bogs a strong decrease of the groundwater table occurs especially in spring, partly caused by the high rise in the intensity of evaporation of crops (e.g. forestry) on the drained bog.
  As a result the storage capacity of the subsoil increases strongly compared with that of undrained bogs. In intact bog only a slight superficial drying-out takes place, which is closely related to the structure and composition of the acrotelm. Because of forced decreased intensity of evaporation of the Sphagnum in the period from July to September the discharge increases already in this period. This is in contradiction to drained bogs in which the discharge only starts at the end of September.
- With the exception of the acrotelm great differences between the horizontal and vertical permeability at equal depths below the surface level do not occur in a living raised bog; the proportion between K_h and K_v is about 1;
- Discharge to the subsoil in undrained raised bogs, with a minimum quantity of precipitation of 700 mm per year, is only a few percentages of the yearly precipitation and it is about 10 to 15% of the total yearly discharge.

6. CULTURAL-HISTORICAL DEVELOPMENT; THE END OF RAISED BOG FORMATION ON A LARGE SCALE AND STARTING POINT OF THE PRESENT-DAY MANAGEMENT OF RAISED BOG

In section 1.1. it was remarked that of the original 1.000.000 ha of raised bog in the Netherlands only 8.000 ha remain, or less than 1%. Because of peat cutting on a large scale of the past few centuries all the large areas of raised bog have disappeared and in a spatial sense usually strongly cut-away remnants remained. In the following sections the discussion centres on the cultural-historical development and the effects of large-scale peat digging of the last few centuries, especially of the 19th and 20th centuries, which finally resulted in an almost complete halting of the raised bog formation in the Netherlands.

6.1. GENERAL

Prehistoric man exploited bogs for various purposes. He was confronted with the bog's richness in water, which affects both the passableness (2.1.) and the exploitation of the material. During exploitation attempts were undoubtedly made to keep the water literally out of the pits. There are no indications for hydrological interventions other than the digging of ditches along a few bog roads. Even before the Christian era the bogs in the west of the Netherlands were inhabited. This occupation was not preceeded by reclamation in the form of deep drainage, but the worst of the excess water was drained by surface ditches.
In the early Middle Ages peat was dug in several places, especially at the margins of bogs, which were somewhat drier. In general these were small works, and a methodical way to discharge the water did not exist. Presumably drainage was only carried out locally.
The winning of salt from peatlands which were formerly inundated by the sea ("selnering") was much more extensive and had a more far-reaching effect on the landscape. These works can be dated from the 8th to the 10th century. Very large peat surfaces, which were coverd by a thin layer of clay, were dug away for the winning of salt. There are no indications of methodical hydrological works accompanying these activities. It is assumed that with peat digging insight about the hydrology was gained, especially as these activities caused large areas of the landscape to disappear into the sea.
Into the 10th and the 11th centuries man was able to manipulate a stream in such a way as to push up the water, so that sufficent power was obtained in order to drive a water mill. The use of water mills was known to the Romans many centuries before.
From the 11th century onward large scale reclamation of the peatlands in the west of the Netherlands witness a considerable increase in hydrological knowledge, although the technical expertise to use this knowledge was often lacking. Possibly the hydrological insights on which these reclamations were based, were gained during the winning of salt.
The winning of turf at the edges of the peatlands in the 13th century and later took place on a relatively large scale. Probably the margins of the peatlands, which were sensitive to drying out, were drained somewhat during the small climate optimum (3.3.2.), which made them suitable for digging without the need for large-scale hydrological works.

6.2. RECLAMATION OF RAISED BOGS ON A LARGE SCALE

The very methodically designed, large scale reclamation of the large raised bogs, which finally resulted in the large scale landscapes of the "peat-colonies", are at first view based on a solid knowledge of the hydrology of raised bogs. On the one hand large masses of water had to be discharged without flooding the areas below-stream, and on the other hand an infra-structure of canals had to be developed in advance of the conversion of the peat into usuable fuel. The start of this process dates from the 16th century, the actualisation took place in the 17th century and lasted into the second half of the 20th century. For the construction of the hydraulic works a sufficiently large labour force was available, but the technical means were limited up to the second half of the 19th century. A well organized approach was necessary to master the water successfully.
Below follows a list of the measures, which resulted in drainage and digging away of peat; the organisational and historical aspects have not been considered:

1. In order to stop the growth of the ombrotrophic peat ditches were dug, which took care of superficial drainage. This caused the supply of precipitation to fall below the level necessary for the growth of Sphagna, which form peat. For this drainage to be effective the ditches had to be close together. Because of the drainage the top layer of the peat began to shrink, which reduced the efficiency of the system of ditches, this is further discussed in section 6.3. The water had to be transported by the ditches in a relatively short time; without discharge the ditches would fill up with water within a year under the prevailing climate, and the formation of raised bog would re-establish itself;

2. To aid the discharge of the water from the ditches a system of canals was dug, often into the sandy sub-soil. The side effect of this activity was, that the whole deposit of peat started to be drained. This resulted in a considerable shrinkage. This did not only result in the necessity of all kind of works to maintain the system of canals, but also resulted in a more dense peat, which made the digging of turf possible;

3. The opening-up of the bog areas by means of a system of canals for the purpose of exploitation demanded certain conditions of location and size. Shipping required a certain depth of canal. The drainage function prevailed because the peat deposits continued to leak some water. The capacity of drainage needed to be such that unacceptable drying out of surrounding areas was prevented, as well as the flooding of below stream lands, which might be inhabited;

4. The unhindered discharge of the water from the bog into the sea was limited by the pushing up of sea water near the points of discharge in the coastal area, especially in autumn and winter. The peak discharge from the bog areas which were drained, did not result in a surplus of water in these areas themselves. The construction of 'boezems', collection areas for this superfluous water, did not take place in the bog areas, but some way below-stream. As a result the drainage of the bog lands could continue at times of high precipitation and high water tables. The exploitation of fenland is completely different in this respect.

It is clear that with drainage the hydrological structure of the whole bog system was destroyed and that the structure of the peat deposits was also irreversibly altered, so that this material could be dug away. From a hydrological point of view the measures promoting exploitation aimed primarily at the destruction of the acrotelm. The catotelm was also broken down; a considerable proportion of the water present in the peat was replaced by air, which resulted in the disappearance of the following typical catotelm characteristic, i.e. the large vertical and horizontal resistance of the peat.

On the drying peat surfaces which were traversed by ditches Calluna vulgaris can expand enormously; these new heathlands were intensively grazed by sheep. These surfaces were rotivated and dried further for the cultivation of buckweed, for the purpose of which the dried material was burned off. On the ash-rich-top-layer buckweed could grow. This manner of agriculture gave rise to the loss of a thickness of 0.5 to 1 m of peat; which had been on average the result of 1,000 to 2,000 years of peat formation.
On the remnants of raised bog the growth of peat can not begin again. The water from precipitation sinks too deeply into the dry peat deposit, which results in the fact that only rooted plants can use this water. The period of time, in which the water is accessible for peat-forming Sphagna, is much too short.

6.3. THE EFFECT OF SHRINKAGE DUE TO DRAINAGE DITCHES IN LIVING RAISED BOG

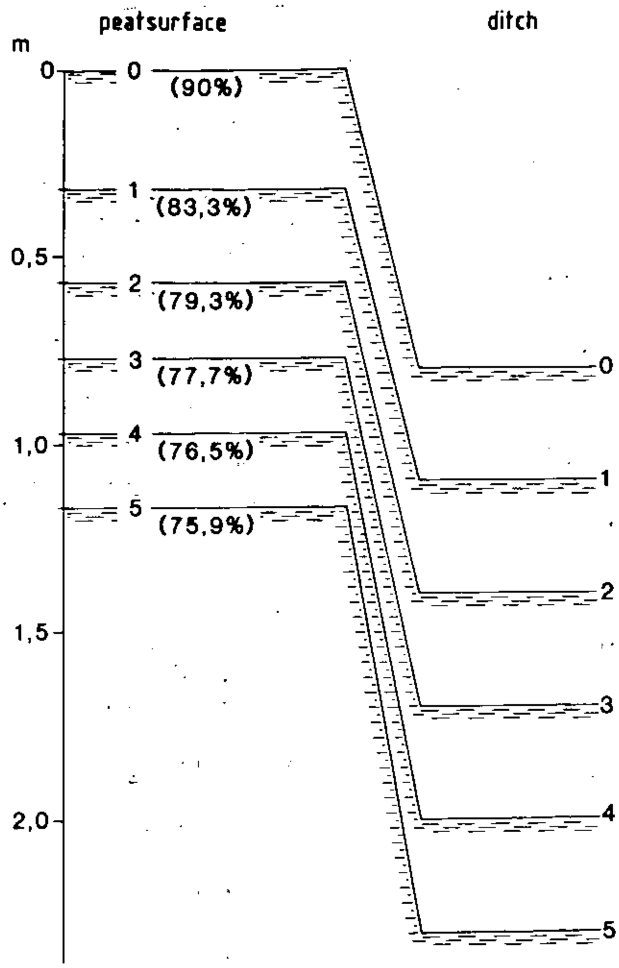
The digging of drainage ditches at short distances from each other on the surface destroys the acrotelm. In order to be able to dig away the peat for fuel it needs to be sufficiently dense. Both objectives were reached by surface drainage. The density was required to give the peat sods a regular shape and in order to provide access to the bog. Increasing density goes hand in hand with increasing carrying capacity of the bog surface.
Manuals of bog cutting from the first half of this century report on the usual measurements of the ditches, the distance they are situated from each other, the method of deepening of the ditches and the time it takes to prepare a living raised bog for cutting. The information relates mostly to the southern part of the 'Bourtangerveen' in the east of the province of Drenthe; the methodology used here was developed during the 19th century.

The ditches were dug at a distance of 10 m; sometimes a distance of 11 m was used. Width and depth of the ditches could vary from site to site. The size 0.93 x 0.77 m occurs, but also 0.80 x 0.80 m. The water from the ditches was transported to the central canals and border canals which were dug at 100 m distance from each other. The continuation of the works, e.g. the digging and deepening of the ditches and the expanding and widening and deepening of the larger canals always aimed at the discharge of water, until sufficient density of the peat was reached; the final water-content of the peat must be at most 75%.

To reach the necessary level of drainage the ditches were deepened by about 0.30 m each year. This process would take 2 to 10 years depending on the water-content of the peat. Based on these data, and with a few assumptions, we can sketch a picture of the process of shrinkage and of decreasing water-content (figures 25 and 26). Starting point is the fresh to poorly humified upper peat lager with a water-content of 90%; this is somewhat lower than that of living raised bog, but the digging of surface ditches always started after the bog had already been somewhat damaged by earlier drainage

below-stream for the sake of peat digging. The compaction was obtained by draining the upper 2 to 3 m of poorly humified peat and the highly humified peat lying under it; the deeper lying peat was not affected by this procedure, however, it dried somewhat, because of drainage via the large canals. The latter will not be considered here.
When we assume a distance between the ditches of 10 m, and a width and depth of 0.80 x 0.80 m, and a yearly deepening of the ditches of 0.30 m during 5 consecutive years, then the bog surface will subside, as is indicated in figure 25.

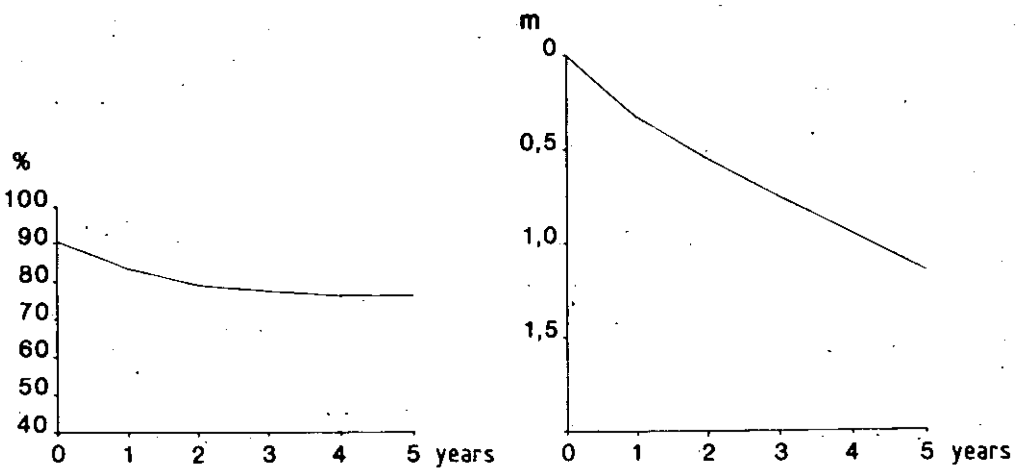
Figure 25 Model of shrinkage of the peat surface after ditches have been dug in a raised bog.



The above model shows the shrinkage of the peat surface after the digging of ditches, starting from a water content of the peat of 90% (starting-situation), with a depth of ditches of 0.80 m, which are deepened yearly by 0.30 m (indicated at bog surface and at the bottom of the ditch). The figures in brackets indicate the water content of the peat for each year. The slope of the sides of the ditch is fictional.

Ditches never reached a depth greater than 1 m; the shrinkage in the first year, which makes deepening by 0.30 m necessary in the second year, will undoubtedly be of the order of magnitude of 0.30 m or somewhat larger. In the following years the shrinkage becomes less. In figure 25 it was assumed that the peat surface subsided in the first years by 0.32 m; this is 40% of the depth of the ditches. We assume that the surface was lowered by an other 0.25 m in the second year and in the succeeding years by 0.20 m each year. After 5 years this results in a subsidence of 1.17 m; this value agrees with what took place in reality. The depths of the ditches are undoubtedly not exactly equal to what is pictured in the figure, the ditch bottom will be covered with peat sludge.

figure 26; The shrinkage (right) and the decrease in water-content (left) of peat are pictured, given a fall in water content from 90% to 70% after 5 years.



The figure on the right shows the subsidence of the surface of the raised bog, starting with a water content of the peat of 90%, with a depth of ditches of 0.80 m, and a yearly deepening of 0.30 m. Left: decrease in water content of the peat as a result of digging of ditches and a yearly deepening of the ditches by 0.30 m, as indicated by figure 25.

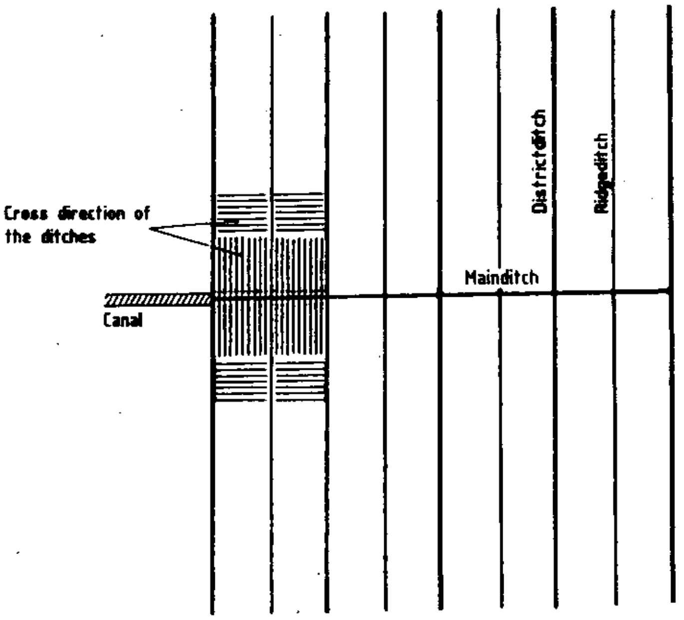
The digging of ditches on the surface of a raised bog resulted in a halting of the growth of the bog and the total destruction of the acrotelm. With the exploitation of the bogs the catotelm was also affected. The section below gives an impression of the manner of exploitation.

6.4. PEAT DIGGING; FROM RAISED BOG TO EXPLOITATION LANDSCAPE

The digging of peat sods for home use and for small scale trade took place from the time of the Middle Ages, when man was able to drain the bog locally. Peat digging on a very large scale took off only in the second half of the 19th century, when the possibilities of a better infra-structure (canals and roads) improved because of technical and economical developments and the advance of mechanisation. As an example of peat extraction on a large scale the diggings of southeast Drenthe will be discussed; these were described by F. Pelder in the beginning of the 20th century.

Before large scale peat extraction could start a plan was drawn up. Part of this plan was to measure the area to establish the thickness of the peat deposits, as well as the depth of the sandy subsoil. The former gives an estimate of the quantity of turf, which can be extracted, the latter was important for the siting and the required depth of the canals. The methodical peat digging started with the division of the peatland into a pattern of ditches. The main canal was elongated by digging a ditch, which connectd to the already existing canal (see figure 27).

Figure 27 The drainage pattern for the peat digging of raised bog in sout-east Drenthe.

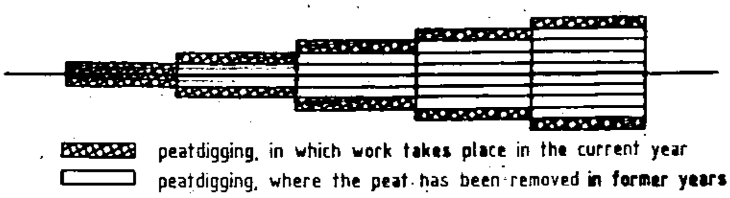


Al types of ditches which are dug in the raised bog at the start of exploitation. The main ditch is sited , extending an already existing canal

All types of ditches are dug into the raised bog at the start of exploitation. The main ditch is sited, extending an already existing canal.
"wijk" = draining canal in the centre of a parcel of peat
"rugge" = backditch = the border ditch between two properties of peat
Ditches were dug into the bog at right angles to this main canal on both sides at a distance of 180 to 200 m, these are the so-called central ditches. The 'back' ditches were dug parallel to and in between central ditches. The main ditch, the 'central' ditches and the 'back' ditches determined the plan of the future landscape, because at the sites of these ditches the present-day channel, the "central canals" and "back canals" are situated. To improve the drainage from the bog, ditches were dug into the bog starting from the main ditch and central ditches at 10 m intervals (section 6.3); these ditches were deepened each year by 0.30 m. This process was continued until the main dith was about 1.50 m in depth and the central ditches about 1 m. According to the speed at which the bog dried out, these works which were preliminary to the actual peat digging, took two or more years. The bog shrank strongly due to drainage, as was discussed in section 6.3. A layer of peat deposit of 5 m in thickness could end up as only 3.5 m. To start peat digging the upper, somewhat

reworked, peat layer was removed and spread out regularly over the bog surface on either side of the main ditch over a certain length and width. This layer is called the "bonk-aarde", a local name for the upper 1 m of peat, which after cutting is spread. This provided a level terrain, the so-called placing-field, on which the wet cut away peat-sods were laid out to dry at a later stage. During the peat cutting the poorly humified peat, the highly humified peat and the fen peat below the latter were dug away, preferably until the sandy sub-soil was reached. This created a pit on both sides of the main ditch. As a result of the new diggings this pit was widenend the following year, while in the length of the old pit a new pit or ditch was also dug (see fig. 28).

Figure 28 Peat digging patterns from raised bog in southeast Drenthe



The canal was dug at the site of the main ditch into the sandy subsoil, which had been uncovered. Via this canal the dried peat sods were transported outside the area. Initially the cost of exploitation was highest; when the cutting proceeded more into the bog the cost of transport went up because of the distance from the placing fields to the ships became larger. In order to keep these distances as small as possible the large canals were dug every 200 m. In this way the distance to the ship was at most 100 m.

Here ends this short exposé about the large scale peat diggings in southeast Drenthe. Although in the Netherlands peat exploitation was not carried out in the same fashion everywhere, the above gives an impression of how this was done. Most of the cut-aways were taken into use as agricultural land. At the start of the sixties, when nature conservation organisations started to manage raised bog, only remnants had remained. These remnants are now the nuclei for the formation of new raised bog. These starting points are further described in the sections below.

6.5. POINTS OF DEPARTURE FOR PRESENT DAY RAISED BOG MANAGEMENT

Depending on the measure of interference by man, as farmer or peat cutter, the following starting situations are present, after peat exploitation was finished.

6.5.1. <u>Lightly drained, uncut remnants of raised bog; (left after the cultivation of buckwheat which involved burning-off of the peat surface</u>.

These remnants of raised bog consist of an almost intact peat profile of several metres in thickness. These bogs were drained to a greater or lesser extent because of exploitation at the edges. Surface ditches were dug in the past to aid the buckwheat agriculture and this resulted in shrinkage of the peat. The surface was burnt to take care of fertilisation of the substratum and this resulted in the loss of part of the upper layer. The poorly humified moss peat is still partly present despite these cultural-technical measures of the past. The peat surface can still swell and shrink. In some of these areas the shrinkage process proceeds further than the swelling process, hence these areas are drying out slowly (Oldert, 1979). Examples of this type of peat remnant are parts of the 'Fochteloërveen', the 'Engbertsdijksvenen', the 'Witten' and the 'Meerstalblok' of the 'Bargerveen'. In the last mentioned site former bog pools are present. These are preserved as the living centres of raised bog formation in the area.

6.5.2. Moderately drained, uncut raised bog remnants; (left after agriculture on the bog surface)

This type of agriculture developed along the sandy ridges of the bogs. Farmers had established themselves here and their cattle grazed in the valleys of the streams. When the demand for meat and milk increased, the quantity of manure increased likewise and part of the bog behind the houses started to be used as agricultural land. The more the demand, the further these new fields went into the bog. In this way arable fields with a length of at least 2,000 m were developed. The width varied between 12 and 100 m. Because of fertilisation and drainage these lands can be compared to the 'es' (raised arable) elsewhere in the Netherlands. The 'Bargerveen' in southeast Drenthe still contains some of these agricultural lands.

6.5.3. Partly dug-away remnants of raised bog

This type of bog remnant is different from those above, in that the top layer of poorly humified peat has been removed, in preparation for cutting. This layer is called "bonk-aarde" (see p.154) and is used after cutting, by mixing it with the underlying sandy soil for agricultural purposes. In preparation of cutting ditches were dug first, which varied in depth from 0.50 m to 1 m; depending on the stage of exploitation. The poorly humified peat is generally dug away, which has led to a strong reduction in the capacity of shrinkage and swelling of the bog surface. The 'Bargerveen' and the 'Deurnse Peel' still contain sites of this type.

6.5.4. Peat remnants which are almost completely cut-away

The peat of these sites has been dug away almost completely; the remaining layer is never thicker than 0.50 m. In the 'Bargerveen', apart from this layer, a layer of "bonk-aarde" of about 0.50 m has also remained. In the 'Peel' this has gone. Cut-aways of this type usually have the impermeable 'gliede' layer broken only at the sites of canals and ditches. The remaining peat deposit is therefore still relatively resistant to vertical loss of water. However, the substratum is very sensitive to drought. Cracking occurs easily, which increases discharge to the subsoil considerably. This type of peat remnant is present in the 'Bargerveen', for instance the 'Amsterdamse Veld', a site of 800 ha.

6.5.5. Completely cut-away raised bog (no peat remaining)

The peat has been cut away down to the mineral soil. Only in depressions a small amount of peat may still be present, which could not be removed by the peat cutting machines. The impermeable 'gliede' layer is missing completely in some places. This situation is present in the 'Peel' area in many places.

6.5.6. Agricultural soils which remain after peat cutting

This is reclaimed peatland, which after the peat was removed, had been turned into agricultural land. In order to do so sand was mixed with the "bonkaarde" which was left for this purpose. These lands were also called "peat colony lands". The sand which was used, often came from the larger canals.

Remark

Before the peat-litter factories were established at the end of the last century, the "bonkaarde" was usually put back, after the peat was cut away, because this upper layer had no value as a fuel. After one had discovered that peat litter had agricultural value the "bonkaarde" was more and more often sold to peat litter factories. At the end of the last century regulations came into force, which prescribed that some of this "bonkaarde" must be put back in the cut-away pits. Because of a lack of enforcement this did not always take place, and now causes problems for management. This will be further discussed in chapter 8.

6.6. RAISED BOG MANAGEMENT STARTING FROM OTHER SITUATION

Apart from the large raised bogs with a surface area of many hundreds of hectares, smaller raised bogs exist in the landscape, mostly occupying small depressions. Ombrotrophic peat formation took place on a small scale: the surface area often occupied less than 1 ha. Obviously ombrotrophic vegetation types could remain here and accumulate peat, although the vegetation could also contain less ombrotrophic characteristics. It is clear that apart from sufficient moisture - usually a situation of water surplus - the following situation is present here: hydrological isolation from nutrient rich influences of the ground-water, the surface-water and the surrounding landscape. Many of these wet depressions have disappeared because of peat digging and reclamation. What is still present today, is badly affected by turf digging, drainage, eutrophication etc. In a few cases the potential for new ombrotrophic peat formation is still present. Because the influence from outside on the formation and accumulation of peat in the small depressions was much greater than in the case of the large bogs, it is of importance to know exactly how they were formed, so that adequate management measures can be taken. Especially the development of the hydrological isolation under natural undisturbed conditions and the present-day situation with regard to nutritional status will determine the nature of the management measures. The latter will be discussed in section 8.4.3. Below a description of small depressions follows, which are filled with peat, e.g. marshes, fens and small bogs which have formed ombrotrophic peat.

6.6.1. Pingo ruins

These depressions which are left behind after hills of ice melted date from the last cold phases of the last glacial period Oldest Dryas, Older Dryas and Late Dryas.

They developed in permanently frozen soil (permafrost). The first organic deposits are usually 'Braunmoostorf' and gyttja which were deposited in an oligotrophic environment. The hydrological isolation which was necessary for this development, was mainly due to the frozen substrata and to a lesser extent to the boulder clay on which pingos developed. The depressions had no means of discharge, so that they soon filled with water. From Preboreal times (table 1) fen peat was formed here, which gradually changed into mesotrophic peat and finally into oligotrophic peat, which proceeds to have strong ombrotrophic characteristics. The transition to ombrotrophic peat can take place from Atlantic times on. Some pingos which were situated in lower areas of the landscape remained under the influence of an increasing ground water table and remained eutrophic. The formation of fen peat preceeded here. Large pingos especially maintained open water of a fair depth for a very long time, which filled up in the long run. On the surface of some pingos, which were superficially drained, buckweed was farmed in the past. Peat was dug from many pingos. In the water-filled hollows that resulted, peat growth could start again, usually eutrophic at first, followed by growth of mesotrophic peat. The influence of precipitation on the peat growth increases gradually in these cases. The hydrological isolation of this environment is guaranteed, because the pingo is situated on substrata of boulder clay.

6.6.2. <u>Cut-off valleys of streams</u>

In some cases peat producing conditions originated because sand blew into the valleys of streams, stagnating discharge in that way. An important period in which sand was blown about took place almost at the end of the glacial period (formation of cover-sands). After the permafrost had finally disappeared, at the end of the last glacial period, sand could start shifting again as a result of a strong lowering of the ground water table. In the upper reaches of the streams the influence of precipitation in particular could cause the formation of ombrotrophic peat, although the formation of fen peat was more common. Drainage on a regional scale stopped the production of ombrotrophic peat. The peat has mostly completely disappeared (exploitation, fuel winning, filling with sand etc.), but the starting conditions i.e. the relief of the subsoil is mostly still present.

6.6.3. <u>Blown-out depressions, bowls</u>

These originated in general from over-usage of the land by agriculture in which the vegetation was so damaged that the barren soil began to blow away. This took place even in prehistoric times. The sand was often blown away until the groundwatertable was reached, and relatively deep depressions were formed. When the ground water rose in later times these depressions were inundated, which resulted in the formation of fen peat in an usually mesotrophic environment. Finally oligotrophic conditions developed, with an increasing influence of direct precipitation on the peat forming environment, which finally led to ombrotrophy. Such development started after about 2000 B.C. Many of such pea-lands are now damaged by drainage, peat digging, flooding with nutrient-rich water and by pollution. The reversal of these influences can gives rise to formation of new ombrotrophic peat.

6.6.4. Perched bogs

In the case of perched bogs an apparent water-table is maintained by an impermeable podzol, with an iron hardpan. Peat growth can take place, if this hard pan is shaped in the form of a saucer, almost always under meso- to oligotrophic conditions. Ombrotrophic peat formation can take place relatively quickly, because the peat is almost completely dependent on the rain for its nutrition. Such bogs originated only after 2,000 to 3,000 B.C. Lowering of the ground water table around these bogs, digging ditches, discharging of the perched water by digging an outlet, overflowing with nutrient-rich water etc. interfere with the impermeable layer, which finally results in the disappearance of these types of bogs.

6.6.5. Depressions of boulder clay

In this case saucer-shaped depressions are present in the undulating boulder-clay relief, which can contain so much water that peat formation can take place. The peat formation which may be initially eutrophic can slowly change into meso- and oligotrophic forms, when the supply of water solely takes place by means of precipitation, which finally leads to ombrotrophic peat formation. Drainage and supply of nutrient-rich water signal the end of this ombrotrophic environment.

6.6.6. Oxbows

In general these are nutrient-rich situations, in which a fen deposit rich in minerals is layed down, and the remnant of a channel is filled in completely. The filling in with eutrophic peat can go over into meso- and oligotrophic peat formation with ombrotrophic vegetation, when the supply of nutrient-rich river water or ground-water to the channel stops. The extent of such developments is usually limited. The ombrotrophic situation is very sensitive to changes in the hydrological regime of the river. In addition drainage, afforestation, extraction of clay etc. usually signal the end of the ombrotrophic peat growth.

6.6.7. Antropogenic situations

Ombrotrophic peat growth started also because of the influence of man, especially through peat cutting. We refer here to the filling in of the pools and lakes left after cutting, in which the formation of Sphagnum peat is the end stadium of the succession. This development can take place starting from either nutrient-rich or nutrient-poor conditions.

In the case of nutrient-rich conditons these situation developed mainly from the exploitation of fen peat (e.g. "petgaten" or "peat-holes"). The initially eutrophic filling in which originates after peat extraction, results finally in a hydrological isolation of the peat forming vegetation to just above the level of the ground-water of the peat cuttings, and the species typical of oligotrophic peat formation can take over. This leads to ombrotrophic peat formation (see also 2.3. and 2.4.). Conditional is that the ground water table does not rise further and that precipitation water can remain within the peat forming vegetation for a considerable time.

Nutrient-poor conditions mainly arose in the pits of raised bogs and after peat extraction from fens to far below the water-table in the peat, but without contacting the nutrient-rich ground-water. Vegetations of an oligotrophic nature with strongly ombrotrophic characteristics developed, after a period of mesotrophic peat formation. The level at which this peat forming environment exist, is almost always lower than that of the surrounding uncut bog. Sensitivity to a change in the hydrological conditions is rather large. Sections 9.4.2. and 9.4.3. discuss the management.

PART II - POINTS OF DEPARTURE FOR MANAGEMENT

7. INTRODUCTION

From the end of the 60's a start was made to re-wet drained and cut-away raised bog remnants in the Netherlands, in order to create conditions for regeneration of raised bog and finally to make possible new growth of raised bog. The first area which was re-wetted was the 'Bargerveen' in southeast Drenthe. The manager had to act in an empirical way and was partly helped by the knowledge of peat researchers, since no other experience was available concerning re-wetting and regeneration of raised bog. The first measures of management were carried out on an area of about 66 ha, the 'Meerstalblok', this is a raised bog remnant which was mostly uncut and which consist of a moderately dry bog pool and surrounding heathland. The heathland was drained by surface ditches and used in the past to grow buckwheat. In general trees and bushes were removed from the surface to decrease evaporation and in the next phase the ditches were blocked. These measures aimed at decreasing strong falls in water-level and at retardatien of surface discharge. At a later stage the pits which originated from peat cutting were also dammed, and dams were built with highly humified peat in places where the upper peat layer was dug away. Behind these dams water from precipitation was stored, which prevented deep drainage of the nucleus as much as possible. On a large scale similar measures were carried out by managers of nature reserves elewhere, based on these early experiences. In this way practical experience of the management of raised bog remnants increased over the years. Working with water plays an important role in the management of these areas. A special aspect of this work is the availability of sufficient water of good quality at the right place at the right time. For the raised bog areas in particular this meant a lot of water, which preferably has to be nutrient-poor. The aim of management is the creation of hydrological conditions which facilitate the optimum growth of raised bog. It is not immediately evident what is meant by <u>optimum</u> growth as the development of raised bog in the existing reserves can only be measured after a considerable time. This holds good in particular for the formation of raised bog. However, it has to be clear to the manager that his management at least guarantees the formation of peat, which in time can progress to the formation of raised bog. Chapter 8 discusses the aims of management, and the possibilities and limiting conditions for the formation of raised bog. The latter two subjects are discussed in short, as they were more extensively discussed in part I and as they are of great importance for the management and posssibilities for development of raised bog. Chapter 9 discusses the hydrological management of raised bogs in detail.

8. AIMS FOR MANAGEMENT, POSSIBILITIES AND LIMITING CONDITIONS FOR RAISED BOG FORMATION: IN PARTICULAR FOR THE DUTCH SITUATION

8.1. AIMS FOR MANAGEMENT

In the Netherlands large raised bogs are not present any more, as was already stated in part I and in chapter 6. These areas disappeared because of drainage and cutting and now only remnants of bogs remain. The nature conservation organisations attempt to promote the formation of new raised bog as much as possible. This means in many cases that one aims to reconstruct a raised bog landscape, and that one creates possibilities for the maintenance and development of raised bog vegetation. In reserves where the aim is the maintenance or development of vegetation which forms raised bog management is directed towards the following:

1. the development or maintenance of an open, nutrient poor, wet raised bog landscape;
2. the development or maintenance of ecosystems and biotopes of a wet raised bog landscape;
3. setting into motion of processes, which gradually will lead to new raised bog formation.

8.2. POSSIBILITIES FOR THE FORMATION OF RAISED BOG IN GENERAL

The fact that present-day living raised bog is extremely rare in the Netherlands does not mean that ombrogenic peat producing processes can only start under very restricted circumstances. The formation of raised bog is a process which takes place under a range of climatological (section 3.2.), historical (section 3.3.), spatial (section 3.2.) and pedological (section 2.2.6.) conditions.
Raised bogs have therefore a wide distribution in Europe, from Ireland to Russia and from Finland to the Netherlands and Germany (section 3.2). The following can be said in relation to the formation of raised bog in Europe.

8.2.1. Climatological possibilities

quantity of precipitation

Raised bogs occur at intensities of precipitation ranging from about 500 to 2,000 mm per year, depending on climatoligical conditions like the temperature range during the year.

temperature

Raised bog occur below a mean yearly temperature of about 11°C. The temperature can even be quite low, as raised bogs also occur within the polar circle on permafrost soils.

historical

Circumstances are suitable for the growth of raised bogs from 5,000 B.C. up to the present time; during this period there were no time spans which must be considered as unsuitable or impossible for the formation of raised bog in the Netherlands.

8.2.2. Pedological possibilities

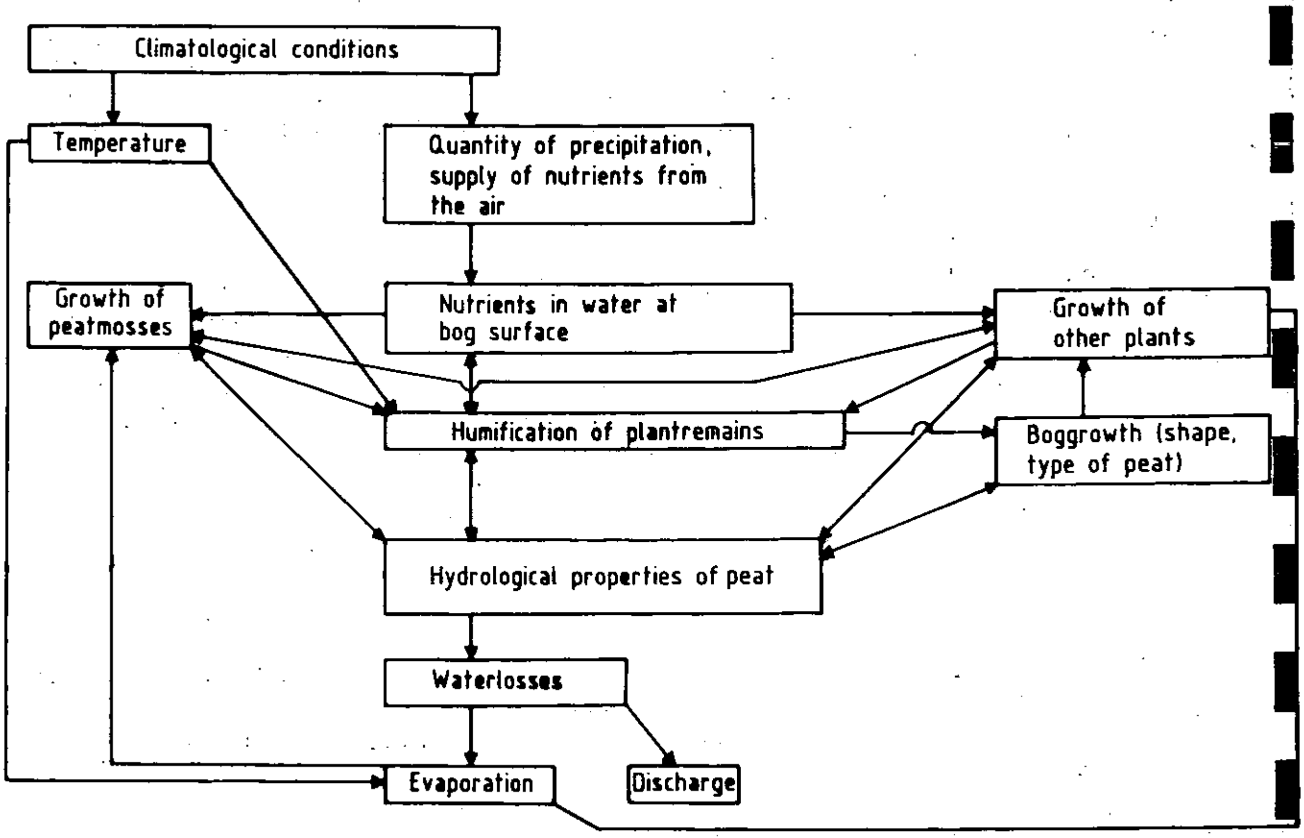
The formation of raised bog is not tied to a certain type of soil. Raised bogs occur on sand, clay, organic deposits, calcium rich soils, granite and other rock types, in open water, in forest on abandoned agricultural soils which may be podsolized or not.
The regeneration of raised bog, which has taken place over the last few decades, occurs on all sorts of substrata. This does not imply that, if potentially suitable substrata are present, raised bog formation will take place. Management of these substrata is necessary. To reach the aim of raised bog formation a number of limiting factors must be fulfilled. The next section discusses this in more detail.

8.3. LIMITING CONDITIONS FOR THE FORMATION OF RAISED BOG IN THE NETHERLANDS

8.3.1. Limiting conditions for the formation of raised bog, controllable and not-controllable.

As is already clear from previous chapters, the growth of raised bog is tied to certain hydrological conditions of the growing peat. The manner in which the peat forms and the type of peat that forms depends to a great extent on the climatological conditions and on the type of peat-forming vegetation. The most important controlling factors for peat growth are represented in figure 29.

Figure 29. Schematic representation of the most important controlling factors for the growth of raised bog.



The climatological conditions for the formation of raised bog can be considered as limiting conditions, which cannot be controlled.

In the Netherlands the present possibilities for the formation of raised bog, in particular the climatological limiting factors, are considered suitable to favourable for ombrotrophic peat formation assuming an intensity of precipitation, which is greater than 700 mm per year (chapter 3; section 5.3.2.; section 5.7.).

The mean yearly temperature is $9^{o}C$ (section 3.3.3.) and lies well below the limit, at which raised bog formation is still possible.

8.3.2. Controllable limiting conditions

The controllable factors, of which the hydrological conditions are important, cannot all be called favourable. Management has the task to direct the limiting conditions in such a way that the aim of the formation of raised bog can be realised. First of all it is necessary to gather a thorough knowledge of the hydrological possibilities of an area. The question is in which way can the available water be managed, so that useful measures of management and design can be developed.
The following means are available in order to reach the aims of management:

1. hydrological management;
   This means maintenance or creation of base-line conditions for (ombrotrophic) peat formation in the different reserves;
2. mechanical and biological management;
   Grazing, mowing, transport of the product of mowing and grubbing up can contribute to the realisation of the aims.

The second point will not be discussed further because this report only deals with the hydrological aspects of raised bog management. In the next section the hydrological limiting conditions for the formation of ombrogenic peat will be further discussed. This is best done from a description of the management for formation of raised bog.

8.3.3. Hydrological limiting conditions for the formation of raised bog

The creation of the base-line conditions for the growth of raised bog, in particular the creation of the right hydrological conditions, involves on the one hand the reversal of the present day processes of peat decomposition, e.g. drying out, mixing with soil, and on the other hand the development of a hydrological design, in which the peat forming Sphagna and other plants of the ombrotrophic bog can maintain themselves on the substrata they create. When this situation has been reached the destruction of that particular site has come to an end. The formation of raised bog can be defined as follows: the growth of peat forming Sphagna and accompanying plants in a situation of water-surplus (acrotelm conditions), which has properties of a system of infiltration, in which nutrient poor conditions are created as nutrition takes place solely by precipitation (ombrotrophic conditions). The situation of water-surplus takes place on substrata which are saturated with water (catotelm conditions), in which biological processes have come to a halt almost completely. The hydrological conditions for the formation of a raised bog will be discussed further.

Acrotelm conditions

The formation of raised bog takes place only in the vegetation cover; this fairly thin layer of living Sphagna is called acrotelm (see section 4.3.2.). The acrotelm is usually 0.10 to 0.30 m thick in a well growing raised bog. In the acrotelm horizontal flows of water of slow speed take place (system-linked discharge), which create the situation of water-surplus necessary for the growth of Sphagna, in other words necessary for the maintenance of evapotranspiration of the vegetation cover and the discharge of nutrients from the raised bog system. The situation of water-surplus of the acrotelm and the related horizontal flow of water is directly correlated with the presence of large stores of water at the surface of the bog, which are formed of surplus precipitation accumulated over a year. As already discussed is section 4.4., at a given starting-point, water-storage facilities need to be created in or near the surface of the bog, in which permanently about 80% of the storage capacity needs to be occupied by water. During the period of growth of the Sphagna the level of water decreases gradually in the acrotelm. The growth of Sphagna ceases if the level of the water in the bog falls more than 0.10 - 0.20 m below the vegetation cover. The coefficient of storage of the acrotelm is therefore at the end of the winter and at the end of the summer respectively 0.95 and 0.70. The situation is more stable when the stores of water at the surface are larger at the beginning of the period of growth. The situation is influenced primarily by the size of the yearly amounts of precipitation, which has to be at least about 700 mm in the Netherlands.

Ombrotrophic conditions

The water needs to be nutrient-poor (few cations and anions) as well as reasonably oxygen-rich (see section 4.3.4.); its position is at the beginning of the hydrological cycle. These conditions are created in an infiltration system, in which nutrition is solely by precipitation. In water that is stagnant the nutrient content increases because discharge does not take place and concentration by evaporation occurs. The water also becomes less acid. Flow of water is therefore essential for the discharge of nutrients from the raised bog system (system-linked discharge).

Catotelm conditions

The water saturated substrata, on which ombrotrophic peat formation takes place, consists of died off, and only partly decomposed peat vegetation (catotelm), mostly composed of the same species as the acrotelm.
In the catotelm horizontal and vertical water movement is very slight (section 5.6.1.), and approaching zero; this functions as a base for the situation of water-surplus in the acrotelm. In this water, which is practically void of oxygen, biological activity is lacking almost completely. If water disappears from the catotelm too quickly than it is replenished with water from the acrotelm; the drying out of the vegetation cover which can occur as a result can affect the vitality of the peat-producing Sphagna strongly. If the drying out takes a longer time the Sphagna will die. A stable water-saturated catotelm can be maintained in particular when discharge to the subsoil does not take place, or only takes place to a very minimal extent. According to section 5.8. the vertical discharge should not be greater than the difference between the mean yearly surplus of precipitation and the necessary system-linked discharge of about 110 mm per year. (A condition is that the

ground-water-table of the mineral subsoil must reach the base of the peat, so that mineralisation of the peat is prevented. Mineralisation of the base of the peat deposit causes humic particles to be discharged and this increases the pore volume, which increases the permeability and causes greater water-losses to occur.)

8.4. CONCLUSIONS

Controllable and uncontrollable limiting conditions are involved in the formulation of conditions for the formation of raised bog in the Netherlands. Climatological conditions are considered as uncontrollable limiting factors. The biological and hydrological conditions are controllable.
The following limiting conditions are of importance for the management of the raised bog reserves in the Netherlands and for the maintenance and development of raised bog:

- climatological conditions;

  A quantity of precipitation of about 700 mm per year or more and a mean yearly temperature of about 9 ^{o}C are important conditions for the formation of raised bog;

- degree of trophy;

  Raised bogs are characterised by an acid and nutrient poor environment. Therefore oligotrophic conditions prevail in a raised bog;

- hydrological conditions;

  The creation and maintenance of acrotelm and catotelm conditions is of the utmost importance for the formation of raised bog.

A well defined management is necessary to create and maintain certain limiting conditions for the formation of raised bog in the reserves. Management measures realise the management of the reserves. The hydrological management of raised bogs will be discussed in the last chapter. Up till now it has been assumed without saying that the quality of precipitation is such that the supply of nutrients and other compounds is not toxic for the peat producing environment or that it can influence the peat formation negatively in other ways. At the present time this can no longer be taken for granted, the quality of the water from precipitation has also become a limiting condition. In section 9.2. this will be further discussed.

9. HYDROLOGICAL MANAGEMENT OF RAISED BOG IN THE NETHERLANDS

9.1. GENERAL

Management of an intact raised bog and its inherent hydrological system seems a simple matter. When the climatological conditions (section 8.2.1.) are good the bog maintains itself. We can not know if this statement is correct. However, we suspect that e.g. the quality of the precipitation - discussed in short in section 9.2 - and possibly other external anthropogenic influences threaten the existence of raised bog in the present day.

As was stated in chapter 6, large areas of raised bog have disappeared from the Netherlands. What remains are areas of peat which are strongly cut-over and dryed out, with a totally different water balance. This will be further discussed in section 9.3. Hydrological and other external conditions are of such a nature that management, which is characterised by the prevention of further interference, in the absence of active management measures, does not automatically result in the formation of raised bog. In practise the discharge of water is usually much to high; an important role is played especially by surface discharge, downwards seepage and an intensity of evaporation, which are to high. In sections 9.3. and 9.4. this is further discussed.

An important question for the manager of a bog area is: can he manage discharge to such an extent, that a sufficient quantity of water becomes available to facilitate the growth of raised bog, and if this is the case does the growth of Spagnum actually start again? In that case one can talk about the possibility of recreating acrotelm and catotelm conditions. An other large problem in peat areas is the increased nutritional richness and the decreased acidity. In section 9.4. this is discussed further.
At first we shall concentrate on the increased air pollution and its influence on the vegetation, which forms raised bog.

9.2. AIR POLLUTION AND ITS POSSIBLE INFLUENCE ON RAISED BOG

Acid and nutrient poor conditions are maintained under normal conditions because raised bog is fed exclusively by precipitation. In the current century air pollution from industrial and urban development has increased strongly. Foreign compounds, or certain compounds, which occur in air normally are present now in higher concentrations than would have been the case previously. Little is known about the effects of air pollution on the vegetation of raised bog.

Preliminary investigations are primarily focussed on compounds such as nitrogen and sulphate (Gorham, Bayley and Schindler, 1984). The Catholic University of Nijmegen is currently involved in research into the effects of air pollution caused by the very intensive castle-farms ("bio-industry") on peat areas of the National Park "De Groote Peel". Definitive results of this research are not yet available. In general the following can be remarked in relation to pollution of nitrogen via the air. Nitrogen occurs in air under natural conditions in three forms, i.e. nitrate (NO_3^-), ammonia (NH_4^+) and gaseous nitrogen (N_2). Plants assimilate nitrogen in the form of nitrate, or as gaseous nitrogen in microbacterial processes. Ammonia can be converted to nitrate under oxygen-rich conditions, i.e. as occurs above the level of the water table of the bog.

This process takes place as follows:

$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H_2O + 2H^+$.

In this process of nitrification H^+ ions are released; this process makes the environment more acid. Only a limited amount of nitrogen is present in bog water, according to Gorham and others. The nitrate and ammonia content of bog water is only a few micro-equivalents per litre.

However, in nature the nitrogen supply from the air is higher; on average 10 times higher than the nitrogen content of bog water. It is likely that nitrogen is absorbed directly by plants, or is used for reduction by bacteria or for denitrification. This latter process is the conversion of nitrate into gaseous nitrogen. Chemically this procress can be described as follows:

$5CH_2O + 4NO_3^- + 4H^+ \rightarrow 5CO_2 + 2N_2 + 7H_2O$

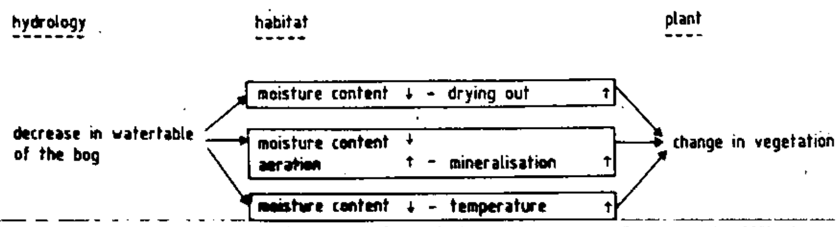
For the process of denitrification of nitrate fresh organic material is required and H^+ ions are taken up from the bog water. This process makes the environment more alkaline; conditions in peat producing vegetation are generally to acid for this process to take place. This process also slows down under anaerobic conditions.

A low supply of nitrogen occurs naturally and is amply sufficient to feed the plants and is also characteristic of the raised bog environment. The need for nitrogen of bog plants is low and therefore supply and demand are in equilibrium. In this way the nutrient poor nature of the bog remains preserved. This does however change, if air pollution of the bio-industries supplies large amounts of ammonia to the air. Ammonia (NH_4^+) results from the reaction with other gasses and water in the atmosphere. Ammonia is the only source of nitrogen for plants of an acid environment. An increase in the deposition of ammonia results in a shift of the position of competition of the plants in the raised bog in favour of the opportunists. True raised bog mosses also show to be very sensitive to pollution with sulphur containing ions (Gorham et al, 1984).
In the next section the hydrological effects of measures like drainage and cutting will be discussed. Drainage and peat cutting were discussed already in chapter 6.

9.3. THE EFFECTS OF DRAINAGE AND PEAT CUTTING ON RAISED BOG

Plants from raised bogs are characterised by certain habitat characteristics; the most important examples of those are the moisture content, the oxygen content and the temperature characteristics of the substrate. The water table in the bog can be considered as the regulator of physical and chemical conditions in the soil. The function of the water table as a regulator of the bog is shown in figure 30, in a schematic way.

Figure 30. Schematic representation of the effects of a decrease in water table at the site of a particular plant.



The regulating function of the water table of the bog will now be discussed in short.

Water table of the bog, physical conditions of the substrate and changes in vegetation

The water table in a living raised bog needs to be high because of the supply of moisture to the Sphagna, which have only a limited capacity for vertical capillary action (section 4.2.1.). Changes in water table level should be small and this is assured by the large capacity of storage (section 4.3.2.). The moisture content of the soil increases or decreases and the water table rises or falls as a result of precipitation and evaporation respectively. When the water table falls the capillary rising of water to the vegetation also decreases. In periods with a surplus of evaporation, deficits of moisture can develop, as the supply of cappillary water decreases.

Sphagna die off if longer periods of moisture shortage occur, caused by for example a continuing drought or through drainage, and the peat surface becomes dominated by plants which need less moisture, for example Eriophorum vaginatum, Erica and Calluna vulgaris, which are present in hummock forming vegetation. When the drying out proceeds further the following get established: Molinia caerulea, Juncus effusus, Betula and Pinus sylvestris. An other property of peat is its low capacity for the conduction of heat. For example when the sun shines the increasing warmth of the surface does not dissipate easily to the surrounding, if little moisture is present in the substrate. Table 17 represents these facts (Van Wijk and others, 1974).

Table 17. Relationship between soil moisture, capacity to conduct heat, heat capacities and depth of penetration of heat into the soil.

Percentage of moisture in the soil. %	capacity to conduct heat cal/9 x ^{o}C	heat capacity 10_{-3}cal/cm x sec x ^{o}C	depth of penetration cm
0	0,14	0,35	3,3
40	0,7	0,75	5,1
80	1,2	1,5	5,5

The larger the moisture content of the soil the larger the capacity to conduct heat. When the water table of the bog is high heat can easily be dissipated to the surroundings via the water, which causes a rise of temperature in the soil with depth, the increase is somewhat more than in a dryer situation and at the surface the rise in temperature is slowed down somewhat. Given a low water table in the bog the opposite happens; the temperature at the bog surface increases more, while the temperature with depth hardly changes.
Plants which can germinate at a higher temperature and thus at a lower water table are clearly at an advantage. Calluna vulgaris and Molinia caerulea are examples of such plants, especially because they germinate well in an oxygen rich environment.

Water table of the bog, chemical conditions in the soil and changes in vegetation

When the water table in the bog falls, the oxygen content in the soil increases. Greater aeration leads to faster mineralisation, which releases nutrients (for example phosphate and nitrogen). Concentration of these nutrients is caused by a decrease in volume of the upper peat layers, caused by compression which results in a concentration of nutrients well above the level which occurs under natural conditions. The pH falls because of oxydation of S^{2-} and $SO4^{2-}$. More nutrient rich conditions result in the establishment of plants of more nutrient rich habitats on the bog; the peat forming Sphagna disappear because of moisture shortage, very low pH, the high level of nutrients and the competition with other plants. (Ellenberg, 1978). As a result of the penetration of roots into the drained peat oxydation and mineralisation occur also at greater depth in the bog. Catotelm conditions are disturbed.

Drainage and cutting (sections 6.1.4.) result in the appearance of different substrates with a different water budget and nutrient content. In the following sections the hydrological effects of this interference are described from different starting situations.

9.3.1. Surface drainage of raised bogs

Physical changes in the substrate

Surface drainage lowers the water table to far below the bog's surface. This has consequences for the physical and chemical conditions in the peat. When the moisture content in the peat above the base of the drainage decreases, a greater capacity to store water will result temporarily, so that the aeration of the peat increases. The organic material mineralies relatively fast under the more oxygen rich conditions and as a result the organic particles become smaller. This results in a denser peat. The pore volume gets smaller; the coefficient of storage decreases and remains small. The decrease in porosity leads to shrinkage of the peat, which decreases the capacity for storage above the water table. The permeability of the peat decreases also, because of the decrease in pore volume. The physical changes in the soil mentioned above continue to happen when drainage proceeds (1 to 2 years). The acrotelm conditions of the remaining peat substrate are totally or almost totally destroyed in the long term.

Chemical changes in the substrate

Apart from changes in the physical conditions of the substrate the chemical conditions also change when the peat is drained. The mineralisation process of the organic material results in the release of minerals and the creation of a more nutrient rich environment: K^+, PO_4^- NO_3^- SO_4^{2-}, as well as water, CO_2 and methane are released. The enrichment with these macro-nutrients is very bad for certain species, which are sensitive to the release of potassium, phosphate, nitrogen and sulphate. This enrichment takes place in an environment which is typically nutrient poor. The oligotrophic conditions are damaged. The peat surface subsides with continuing oxydation and shrinkage of the drained peat. The water table in the peat is once more (6.1.1., 6.1.2.) approached after sometime, with drainage remaining equal. This slows down the process of chemical changes in the peat.

If precipitation is not drained away again quickly (as would happen if new drainage works were performed), a water saturated condition will build up slowly once more. If the nutrients, which were released with oxydation, are discharged with the surplus of precipitation, or are locked up in the peat, the environment becomes more oligotrophic once more; if ombrotrophy is sufficient the formation of raised bog can start again, if the hydrological characteristics of the substrate are still suitable. This sequence of events is known from the management of bog areas as well as from peat stratigraphical research (Van Geel & Dallmeijer, 1986). The time scale can vary widely, from a few decades to almost a thousand years. Surface drainage can result in drying out of the bog surface to such an extent that it burnes easily, as was intended to happen for the cultivation of buckwheat. It is unclear if the resulting charcoal in the peat surface has a benificial or damaging effect on the processes, which lead to regeneration of the raised bog.

Hydrological changes

An other important hydrological effect takes place as a result of the drainage of a raised bog: the water balance changes as the size of the surface runoff (D_h) increases in the winter half year and decreases in the summer half year (section 5.5.). The water storage (Δ St), or the water surplus situation, becomes smaller as a result of this increase of the winter discharge. Because of the smaller water surplus in the winter months larger moisture shortages occur in periods of a surplus of evaporation; the bog area dries out further.

After cultivation of the bog, or after peat cutting, was initiated, the drainage was improved, or the bog was cut away. The surface runoff increases even further in the winter months and the bog dries out even further in the summer because of this. The capacity of storage is even further reduced and the water table falls more. With a very low water table tree growth becomes possible. When trees start to grow evaporation increases (section 5.4.) and discharge hardly takes place in summer (section 5.5.). The water balance of raised bogs changes more dramatically when drainage of the bog increases and the pressure from anthropogenic influences becomes larger.

Apart from the effects mentioned above the effects of cutting are still more dramatic. This is discussed in the next section.

9.3.2. Cutting away of raised bog and drainage of the surrounding land.

Physical changes of the substrate

It is indicated in section 4.3.2. that the pore volume decreases with depth because of further humification of the peat. The coefficient of storage becomes smaller with decreasing pore volume. Eggelsmann (1981) gives the following values for the degree of humification for poorly humified peat, highly humified peat and fen peat after von Post, see table 18.

Table 18. Types of peat and degree of humification.

Type of peat	degree of humification following von Post
poorly humified Sphagnum peat	H 2 - 4
highly humified Sphagnum peat	H 5 - 7
fen peat	H 8 - 10

* Von Post developed the system of the degree of humification for raised bog peats; if the concept of humification is interpreted in a broad sense, this scale can also be used for fen peat.

From figure 15 (page 47) it is clear that the coefficient of storage decreases with an increasing degree of humification of the peat. When bog is dug away up to the highly humified peat or up to rest peat layer a substrate with a smaller coefficient of storage comes to the surface. Therefore the watertable sinks far below the peat surface in dry periods of the year. The supply of moisture for peat-moss growth is insufficient, which makes the substrate unsuitable for the growth of raised bog peat, at least in that condition.

Chemical changes of the substrate

Aeration occurs up to great depths below the peat surface because of the large amplitude in the level of the water table in the drained substrate. The process of mineralisation,takes place at great speed under aerobic conditions and this releases nutrients into the peat deposit, which leads to enrichment of the substrate. In contradiction to the development in the case of (once off) surface drainage the chemical processes do not cease, but expand to cover the whole peat deposit. The oxydation causes, apart from mineralisation, decomposition of the peat to the formation of amorphous humic material. This material has a very small capacity of water storage. It is akin to "gliede", which has a great resistance against downwards when it is present at the basis of the peat. In the peat deposit however, it does not have this property. The decomposition goes hand in hand with a reduction in volume, which results more and more in the access of air to the peat deposit. The recreation of strictly anaerobic conditions, in fact the recreation of water saturated acrotelm conditions, is the only possibility to stop these chemical changes in the substrate.

Hydrological changes

The resistance against vertical water loss is reduced when the peat deposit is dug away. The discussion below clarifies this and as is known, the resistance of the peat increases with the thickness of the peat layer; at least this is so when water saturated conditions exist.
According to the formula below the resistance of the peat layer is as follows.

$$c = \frac{t}{k} \text{ [d]}$$

c = resistance of the peat layer [days]
t = thickness of peat layer [metres]
k = vertical permeability factor [metres/day]

The resistance in the peat layer however does not increase linearily with the thickness. The vertical permeability becomes smaller with increasing depth, as was described in section 5.6.1.
In this way the total resistance of the peat deposit can be desbribed as a chain of resistances of boundaries of peat layers. The resistance is determined per thickness of peat layer (t_x) and its factor of permeability (k_x).
The above formula becomes as follows for the whole peat deposit.

$$C= \Sigma \frac{t}{k} = c_1 + c_2 + \ldots + c_x = \frac{t_1}{k_2^1} + \frac{t_2}{k_2^2} + \ldots + \frac{t_x}{k_x^x} \text{ [days]}$$

As is known one calculates the vertical water loss from the quotient between the difference in height of rise ($\Delta\phi$) over the (vertical) peat layer, which is resistant, and the resistance of the peat deposit. The formula can now be represented as follows:

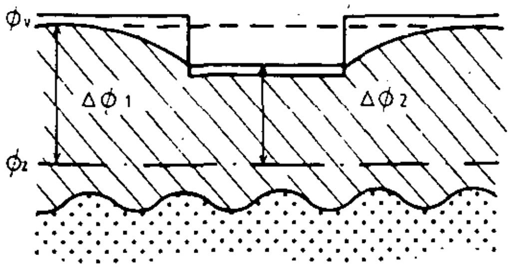
$$W= \frac{\Delta\phi}{c} = \Sigma \frac{k}{t} \cdot \Delta\phi \text{ [m/d]}$$

The effect of peat cutting, or drainage of the surroundings, on the vertical water loss from raised bogs and peat producing environments will now be discussed from a number of commonly occurring situations.

Digging of a pit

The surrounding of the raised bog is not drained in this case. A pit is dug in the raised bog surface, as is shown in figure 31.

Figure 31. Sketch of the hydrological results after digging of a pit in the peat.



ϕ_v = height or piezometric head of groundwater in peat

ϕ_z = height of piezometric head of groundwater in the mineral subsoil

ϕ_p = height of piezometric head of the water in pit

ϕ_1 = difference in height of piezometric heads (ϕ_v - ϕ_z)

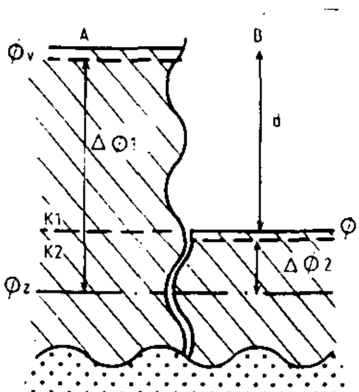
ϕ_2 = difference in height of piezometric heads (ϕ_p - ϕ_z)

After digging of the pit a lower water table (ϕ_p) is established in the pit than in the surrounding by. The pore volume consists in this case of water for the full 100% and the intensity of evaporation increases also because of the open water conditions (section 5.4.).
The resistance of the peat deposit becomes smaller, which causes the downwards seepage to the subsoil to increase initially, until a new equilibrium establishes itself at an even lower water level in the pit. Now the pit draines the surroundings, which causes the peat at the surface near the pit to mineralize somewhat. The nutrients which are released drain into the pit, which becomes more nutrient-rich and therefore less suitable for ombrotrophic peat growth. The surroundings of the pit dry out and part of the peat-moss vegetation dies off.
Remark: with a decrease in permeability with depth the water table in the pit will fall less, because the resistance in the peat deposit below the pit is still relatively large at that stage.

Digging away of the peat up to the highly humified peat layer

The hydrological situation of the subsoil remains the same, but the peat deposit is gradually dug away up to the higly humufied peat layer, as is indicated in figure 32. In other words ϕ_v changes and ϕ_z remains the same.

Figure 32. Sketch of the hydrological results of digging away the raised bog up to the humified peat.



ϕ_v = height of piezometric head of groundwater in peat

ϕ_z = height of piezometric head of groundwater in mineral subsoil

$\Delta\phi_1$ = difference in height of piezometric heads (ϕ_v - ϕ_z)

$\Delta\phi_2$ = difference in height og piezometric heads (ϕ_v - ϕ_z)

t = thickness of the removed peat layer

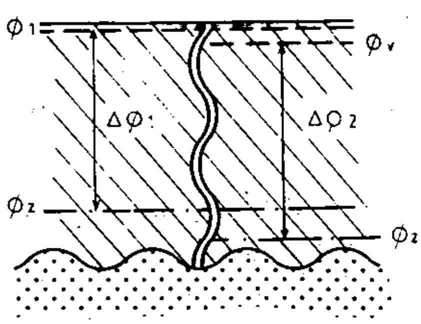
k_1 and k_2 = factors of permeability

According to the above situation the water level in the uncut peat (ϕ_v) falls about as much as in the part that is dug away (t), or $\Delta\phi_1 - t \approx \Delta\phi_2$.
The factor of permeability k_1 is larger than k_2. The vertical infiltration in the case of the cut away does not increase, in comparison with the raised bog that is intact. The water from precipitation which falls on the peat surface B, and which does not disappear via downwards seepage, is discharged from the system for the most part as surface runoff (R), because the capacity of storage is reduced in the case of ΔSt; therefore less water can be retained.
The growth of Sphagnum on the remaining peat layer is however not possible. The water table falls in periods of a surplus of evaporation to well below the peat surface, because of the small coefficient of storage of the highly humified peat substrate, and thus the top layer dries out. Certain measures can be taken to create conditions suitable for the development of acrotelm situations. This will be discussed further in section 9.4.

Lowering of the water table in the surroundings of the raised bog

The hydrological situation in the surroundings of the raised bog changes. The height of rise of the water table in the mineral subsoil falls, while the peat deposit does not change, as is shown in figure 33. In other words ϕ_v remains constant at first and ϕ_z becomes smaller.

Figure 33. Sketch of the hydrological results of lowering of the water level in the surroundings of a raised bog.



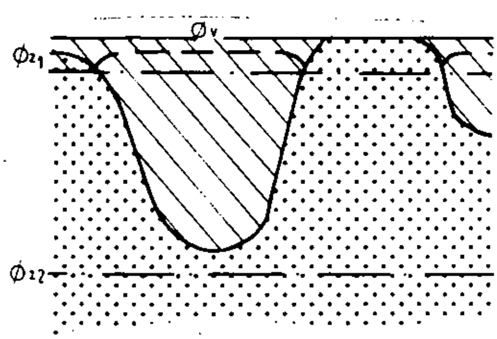
ϕv = height of piezometric head of groundwater in peat
ϕt = height of piezometric head of groundwater in the mineral subsoil
$\Delta\phi_1$ = difference in height of piezometric heads ($\phi_v - \phi_z$)
$\Delta\phi_2$ = difference in height of piezometric heads ($\phi_v - \phi_z$)

Because of the fall in piezometric head of groundwater table in the mineral subsoil (ϕ_z) the downwards seepage will increase initially. Because the water table of the bog near its surface is supplied only by water from precipitation, which is constant in its quantity, the water table in the peat will fall as a result of the increased discharge to the subsoil, until a new equilibrium is reached. Above measures will initially influence the operation of the thermic pump, which was discussed earlier (section 4.2.2.). Initially the upward flow of groundwater, as a result of differences in temperature of the substrate, will be inhibited because of an increase in downwards seepage. Nutrients are than transported to the surface to a lesser extent during the night and this results in the peat water becoming more acid and porer in nutrients. In the long run however, apart from the risk of drying out, the nutrient budget of the peat mosses will also be more disturbed. In the new conditions of equilibrium, with the lower water table of the peat, mineralization will take place, which will result in more nutrient rich conditions, which retard ombrotrophic peat growth.

Cutting away of the peat up to the mineral sub-soil

In this situation the ground water table in the mineral sub-soil (ϕ_z) varies and we assume that the peat has been dug away practically down to the mineral soil. Only in depressions in the relief of the mineral soil are remnants of peat left behind, because these could not be removed by the cutting machinery. Figure 34 shows an example of this situation.

Figure 34. Sketch of the hydrological results of cutting of peat down to the mineral soil.



ϕ_v = height of piezometric head of groundwater in the peat

$\phi_{z(1)}$ = height of piezometric head of groundwater in mineral subsoil above the peat base

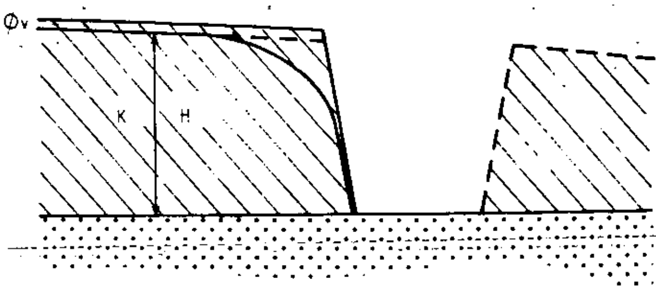
$\phi_{z(2)}$ = height of piezometric of groundwater in the mineral sub-soil below the peat base

The resistance of these remnants of peat layers is usually very small which causes the piezometric head of groundwater in the peat (ϕ_v) to fall sharply in dry periods. The peat dries out frequently, when the piezometric head of groundwater table in the sandy subsoil falls far below the base of the peat or even lower. In this last case the intensity of downwards seepage is maximal. Ombrotrophic peat formation is not possible under these conditions, because the buffering of the water capacity in the peat deposit is to small.

Peat-cutting ditches and the cutting of the edge zones of a raised bog

The hydrological effects of these actions are practically identical. In these situations the peat is dug away up to the mineral sub-soil in the one case in the central part of a bog (peat-cutting ditches) and in the other case at the edge. This was discussed in section 6.1.3. and it is represented in figure 35. The water table in the peat falls sharply in the edge zone of the bog. At the site of peat cutting the peat is strongly drained. The width of the zone, over which the water table will fall, can be approximated by calculation.
Van der Molen (1984) has designed a formula for this purpose, which is as follows below.

Figure 35. Sketch of a bog hole or cut away at edge of raised bog.



$$W = \frac{2.20 \times KH\ (t + \mu H / g D)}{\mu}$$

W = width of the zone in which the water table falls

k - permeability of the peat
H - the maximum height of the water table in the peat at the edge of the zone of drainage
t - the time, over which the lowering of the water table in the peat can occur effectively
μ - coefficient of storage
D - horizontal discharge from the raised bog

The peat shrinks locally and dries irreversibly because of drainage of the edge of the bog. This means that it can not take up water again. Because of the cutting the stability of the remaining body of the bog can decrease considerably, which often results in the formation of cracks up to a great depth in the peat. The formation of can occur over great distances in the bog. Examples of can be seen in the Deurnse Peel (The Netherlands) and in Mongan Bog (Ireland). The presense of tears causes strong aeration of the peat: it dries out heavily.

<u>Some examples from practical experience</u>

In the first example it is shown that with various differences in resistances and heights of rise also different orders of magnitude of downwards seepage can be calculated in a model study of the Bargerveen for uncut areas (A), partly cut areas (B) and practically completely cut areas (C). These differences may lead to different measures of management. The results of these calculation are represented in table 19.

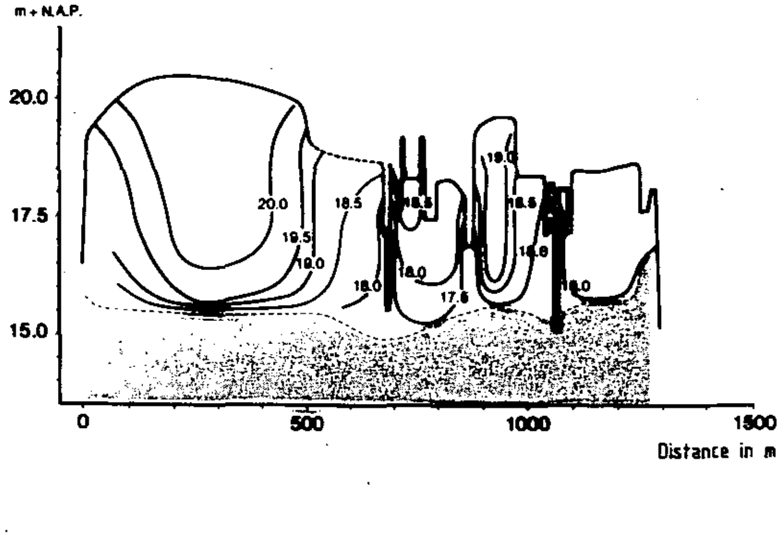
Table 19. The vertical resistance of an uncut, partly cut and practically completely cut area of the Bargerveen and the respective changes in difference of height of rise and quantity of downwards seepage.

	A uncut	B partly cut	C practically completely cut
- thickness (t) of peat in m	3	1	0,2
- resistance (c) in days	35,000	12.000	2,300
- difference in height of			
- piezometric head $\Delta\phi$ in m	2,5	0,9	0,4
- infiltration (D_v) in mm/d	0,07	0,08	0,17
- infiltration in (D_v) mm/y	26	27	63

The height of rise of the ground water of the sandy subsoil (ϕ_z) is higher in A and B than at the base of the peat in situation C. From the table it can be seen that less than 30 mm of water per year disappears to the subsoil in the first two areas, while the downwards to the subsoil is very high in the last area, as was noted earlier (section 5.6.). In the latter case the height of rise of the groundwater in the sandy subsoil (ϕ_z) would have to be increased up to within or near the peat surface if the downwards seepage is to be reduced sufficiently.

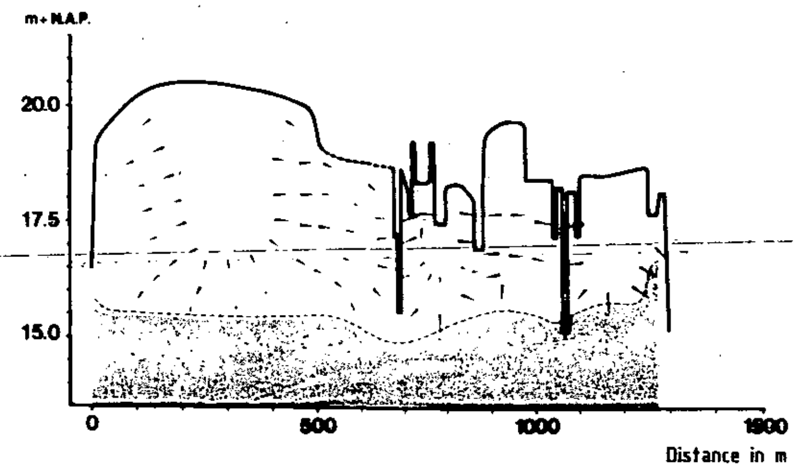
The second example concerns the hydrological influence of two main peat-cutting ditches in the Meerstalblok, which is a raised bog complex which is part of the Bargerveen reserve in Southeast Drenthe. The cuttings reach about the mineral subsoil. This situation is drawn in figures 36 and 37.

Figure 36. Pattern of lines of equal potential in a peat deposit, as a consequence of the presence of ditches.



In order to trace the effects of this type of intervention on the remnant of raised bog a transect of tubes to measure height of rise is layed out to traverse the cutting ditches for each measuring point several tubes are placed and are provided with a filter at different depths below the peat surface. Lines of equal potential are constructed based on the heights of rise in the transect. These are lines of equal heights of rise.

Figure 37. Pattern of flow in the same peat deposit.



The flow of the bog water occurs at right angles to the lines of equal potential. In this way the direction of discharge can be determined in the peat, as is shown in the figure. The influence of the cutting ditches is clearly seen; they discharge water from the raised bog and are thus draining the area of raised bog.

9.3.3. Summary of the problematics of the Dutch raised bogs

Following the previous sections the hydrological problems of the raised bog areas can be summed up as follows:

- The bogs are characterised in their present form by a strong fragmentation caused by peat cutting, which causes increased discharge and the areas show locally features of drying out and eutrophication;
- The deposit of poorly humified peat has been dug away for the most part, only in a few places are some areas with this type of peat still present;
- Drainage and cutting has caused structural changes in the surface of the bog in the top layer of the peat, the degree of humification has become higher; this results in a smaller coefficient of storage, also as a result of the smaller pore volume which goes hand in hand with more humification. The peat can dry out strongly, because the smaller coefficient of storage leads to a strong decrease of the water table in the peat in dry periods of the year;
- Because of this type of intervention in the natural system chemical processes take place in the peat, which results in an increase of the amount of nutrients in the bog.

Concrete measures of management will be further discussed in the next section.

9.4. REGENERATION OF RAISED BOG; THE CREATION OF CONDITIONS FOR THE GROWTH OF OLIGOTROPHIC PEAT

The restoration of the growth of natural raised bog is called raised bog regeneration. It has become clear from section 9.3. that growth of raised bog does not occur automatically on substrates which were drained or cut away. Without suitable management measures the growth of ombrotrophic vegetations, which create raised bog peat, can not take place. In the Netherlands measures are taken by managers to stimulate the regrowth of raised bog. The different aspects of the hydrological management will be discussed further.

9.4.1. The regeneration of still surviving, dried out raised bog remnants

Discussed are here raised bog remnants in which the peat deposit is practically intact as far as its thickness is concerned; in any case they are not cut away. The peat deposits still retain their natural resistance against vertical water loss and the infiltration into the subsoil is only increased because of drainage of the surroundings, where the level of the ground water table has been lowered in the mineral subsoil. If the infiltration stays within acceptable limits (section 8.3.2.) the catotelm conditions can be considered as reasonably optimal. The raised bog reserve at Fochteloërveen is considered in some detail as an example of a concrete case of improvement of catotelm conditions. The reserve is situated at the border of the provinces Friesland and Drenthe, near the village of Veenhuizen.

The water balance of this raised bog reserve would look as follows at optimal growth of peat.

precipitation (P)	830 mm/year	(measured)
evaporation (E)	550 mm/year	(estimated)
surplus of precipitation (P - E)	280 mm/year	
laderal and downwards seepage (L+D)	100 mm/year	(calculated)
surface runoff (R)	180 mm/year	(balance)

($\Delta St=0$, after all the mean change of storage over the hydrological year is equal to about zero; section 5.2.).

The total discharge D_t from the area would be 280 mm per year in this situation. This raised bog area was drained by surface ditches before management measures were taken. The area was dried out, with the result that vegetations had become established, which evaporate less than the peat-moss vegetation, e.g. heather and Molinia caerulea. According to Ernst (1979) a surface runoff of about 250 mm/year occurred via ditches and low areas of the terrain. In relation to the optimal situation for the growth of peat mosses as shown above, this amounts to a deficite of moisture of 70 mm.

To counteract the shortage of moisture, the manager had to decrease the surface runoff from the area. This was achieved in the following way. The ground water table in the sandy subsoil has to be increased in order to decrease the vertical water loss. Increasing the water table in the peat by the installation of certain water levels in the ditches present at the edges of the reserve was not sufficient. Downwards seepage decreased only by 10%, or 10 mm per year. Complete elimination of the vertical discharge would only be possible if the surrounding farmland was flooded by 2 to 3 meters of water. Therefore in this area the choice was made to decrease the surface runoff, by the construction of dykes and dams. During long periods of the year the surplus of precipitation is contained in the area as open water in low lying basins. The first signs of the development of Sphagnum peat growth are visible after a number of years (be it to a limited extent).

Apart from the creation of optimal conditions for the catotelm, as was shown in the examples above, acrotelm conditions can be adversely affected also by:

a. fire;
b. surface drainage;
c. drainage of the edges;
d. side effects of the management measures mentioned under c.

These measures and the possibilities for regeneration of the ombrotrophic peat growth will be discussed further below.

a. Burning of the peaty top layer and possibilities for regeneration

A raised bog can be damaged by fire from natural causes (strike of lightning) or antropogenic agents. The drier parts of the bog are obviously the most prone to burning; especially the system of hummocks. The hollows are in general too wet and the burning of this top layer only happens in extremely dry years under natural conditions, which causes the bog to dry out strongly in part. In the latter case the vegetation is almost completely destroyed by fire and for the first few years bog growth is practically impossible: first a new peat moss vegetation has to be established. When circumstances are not so extreme the system of hollows and the more isolated wet places remain intact. Acrotelm conditions are not destroyed in those places. Although as a result of fire temporary enrichment takes place, the released nutrients are discharged with the surplus water from precipitation and a nutrient poor, acid environment continues to exist because of the dominating influence of the rain. The ombrotrophic peat growth can start once more, because Sphagna migrate from hollows and isolated places of the bog.

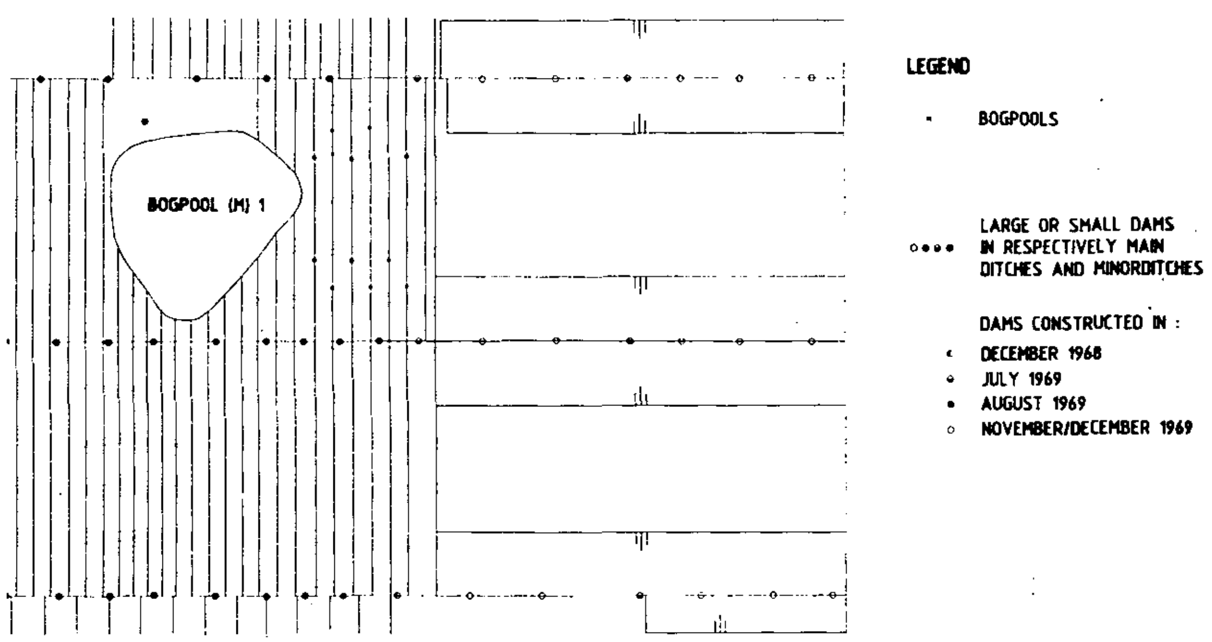
b. Surface drainage and possibilities for regeneration

Drainage causes changes in the physical conditions of the peat as a result of mineralisation, which results in permanent changes in the top layer of the peat. The coefficient of storage becomes smaller and because of this the water table in the peat sinks deeper in dry periods of the year. Only in wet depressions in the peat surface (for example bog pools and larger hollows) can the growth of raised bog peat continue. Drainage is less effective in these places at first, and the specific substrate properties are damaged hardly at all, or they are only damaged at a later stage. These are the places were active peat growth remains for longer periods, while the drained parts of the raised bog do not grow any more and are in a state of rest. This situation occurred in the Meerstalblok in the Bargerveen. However, the surface water table was lowered here somewhat, which caused the originally open water of the pools to be invaded by raised bog vegetation.
Starting from these depressions the organisms of the raised bog can disperse again over the bog complex, if the acrotelm conditions are restored and the nutrients are discharged so that oligotrophic conditions prevail once more and possibilities for ombrotrophic peat growth develop.
Creation of these conditions is not an easy task in practice. Managers know that damming of buckwheat ditches results in a rise in the water table in the peat, which in turn results in a wetter peat surface.

As a result of the reduced storage coefficient the water table becomes still to low to supply Sphagna sufficiently at negative changes of storage, and so ombrotrophic peat growth does not take place. In general in this situation ombrotrophic peat growth occurs only on a micro-scale along the dammed up ditches or permanently inundated situations in the peat surface (Jansen and Oosterveld, 1987). The acrotelm conditions are optimal in these wet places only, because sufficient water is present there for the Sphagna. In addition the surplus nutrients are discharged from these mini raised bogs via ditches, or low areas in the peat surface. To create acrotelm conditions over larger areas a permanent wet situation is necessary. The area has to be designed in such a way that discharge of nutrients takes place via low areas in the relief of the peat.

The creation of water stores as high up as possible on the peat surface, the discharge of which takes place by overflow, function as restored bog lakes, which can establish the required situation of water surplus at the surface of the peat and can enhance this situation. If the peat surface still has so much relief that the water is discharged too quickly, than the construction of dams made out of poorly humified peat can be considered. Surface runoff will than proceed slower. The above is shown in figure 38.

Figure 38. Over-view of dams made out of poorly humified peat in the Meerstalblok in the Bargerveen of Southeast Drenthe.

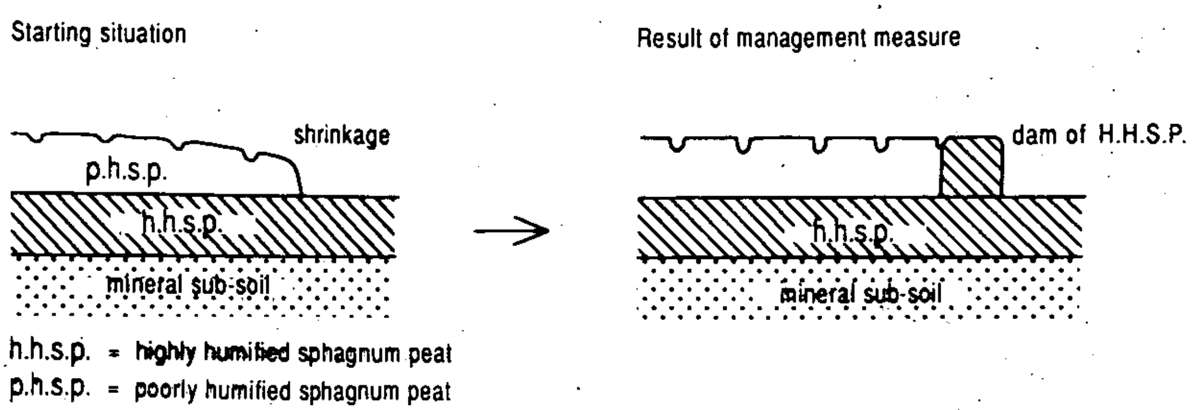


c. <u>Drainage of the marginal zone of raised bogs and possibilities for regeneration</u>

Drainage of the border zones of the raised bog remnants takes place via the large drainage ditches or as a result of the edge of the bog being cut away, as was indicated in section 9.3. Because of this intervention the edges dry out and the peat shrinks. The slope of the bog surface increases and the superficial discharge increases also, which causes the peat to shrink and dry out further, until a new equilibrium has been reached. The surface runoff can be reduced by the application of certain management measures, which can improve the supply of water for the bog. These measures and their inpacts will now be discussed.

1. Cutting away of the edges of raised bog and the measures that can be implemented against drying out. In the figures below is portrayed the starting situation and the results of management.

Figure 39. Sketch of the construction of a highly humified peat dam on highly humified peat along a cut away edge of a raised bog.

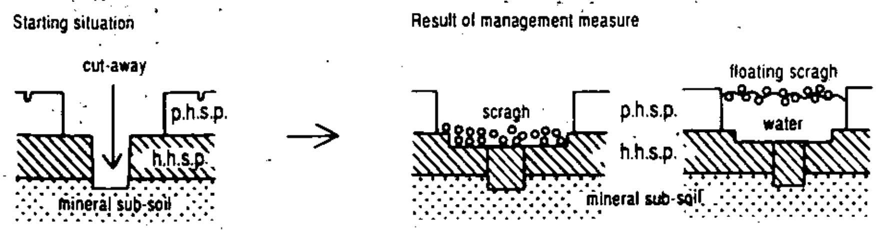


Along the edge of the cut away raised bog a dam of higly humified peat is constructed (see figure 39). The base of this dam rests on higly humified peat. A barrier is formed because the higly humified peat has very low permeability. The water which flows in the direction of the dam is impounded. The water table in the peat increases and the poorly humified peat expands (swells). The surface of the peat rises and the fall in discharge of water decreases because of this measure with the result that the superficial discharge is retarded considerably. The water surplus condition in the bog is therefore improved and better possibilities for the growth of raised bog peat are created. The swollen poorly humified peat deposit will remain just below the top of the dam, because the surplus of water has to be discharged about 0.30 m below the top of the dam. This is necessary to maintain the dam itself. If the top layer of the dam becomes too wet this causes problems (pers. comm. R.J. Zandstra, manager of the "Bargerveen").
Plastic sheating can be used also as material for the dams if higly humified peat is not available. This sheating is inserted vertically in the peat profile and on the peat surface a dam is constructed, in which the sheating is incorporated.

2. Main drainage ditches and the management measures against drying out.

The starting situation and the results of the management measures are indicated in the figure below.

Figure 40. Sketch of sealing of the large cutting ditch with higly humified peat, on a subsoil of sand.



The drainage-ditch has been dug out up to the mineral subsoil. The hydrological problems are the same as in the situation described earlier, i.e. drying out, shrinkage, increase in surface discharge caused by the greater slope of the peat surface. Management measures consist here of the construction of a dam of highly humified peat (or plastic sheating) on the mineral subsoil in order to decrease vertical water loss. In this way an impermeable layer is introduced. If the ditch is closed off with a dam of higly humified peat, the area enclosed will fill up with water from precipitation and run-off from the bog surface. In this way quite amazing results can be obtained, and the water level in the previous drainage ditch may rise several meters. The collection of water in the ditches is of great importance. These waters have the function of contact zone.

The mass of water maintains the water pressure in the bog (reconstruction of catotelm condition); the fall in the peat surface becomes less and this can keep the speed of the water flow low, which is discharged from the surface. Now the "Mooratmung" can develop again. Discharge of these water basins takes also place via overflow, in order to prevent nutrient rich conditions and flooding of the peat surface.

d. Side effects of the measures mentioned under c. above

The two management measures mentioned under c above can give rise to an important side effect. Evaporation of a damaged raised bog partly invaded by trees (e.g. birches) is usually considerably higher than evaporation of a living raised bog. This is not a positive feature, from a water management point of view. An important part of the evaporated water does not derive from the upper centimetres of the peat, but comes from deeper layers. Therefore it causes aeration, irreversible drying out and decomposition. Because the water level in the bog is increased by means of the dams, the trees die off and the bog regains its natural openness. The unwanted enrichment with nutrients and organic material from below which occurs temporarily because of the increase in water table, can be counteracted by discharging these nutrients with the surplus of water from precipitation or by simulating a bog burst, which removes a large quantity of nutrients from the system. This improves the oligotrophic conditions.

9.4.2. <u>The regeneration of raised bog on partly cut away remnants of raised bog</u>

In this situation a layer of higly humified peat (or a rest layer of several decimeters) remained after cutting. The substrate is reasonably poor in nutrients and is a favourable starting situation for the development of oligotrophic peat growth, if further suitable management measures are taken. The latter will be discussed later. Because the peat deposit is thin the resistance to vertical water loss to the subsoil is small. Because of drainage of the surroundings the height of rise in the mineral subsoil is lower and this in turn increases the vertical losses of water. The remnants of peat are vulnerable in this respect. Sufficient water is permanently available for the growth of peat-mosses only when no more than the difference between the mean yearly surplus of precipitation and the necessary system-linked discharge of about 110 mm/year is allowed to seep away to the subsoil.

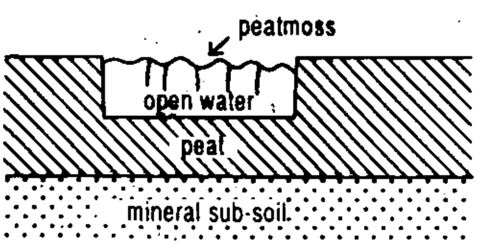
In order to create acrotelm conditions the water table in the peat must reach permanently to the surface-vegetation; only in this situation is the supply of water to the Sphagna sufficient. The acrotelm system also takes care of the discharge of a surplus in nutrients (via the system-linked discharge). Three different possibilities for peat regeneration are available i.e.:

a. the open water situation;
b. the floating vegetation situation;
c. between tussock vegetation.

The different starting situations will now be discussed. Figures 41, 42 end 43 represent these options.

a. <u>The regeneration of raised bog starting from an open water situation</u>

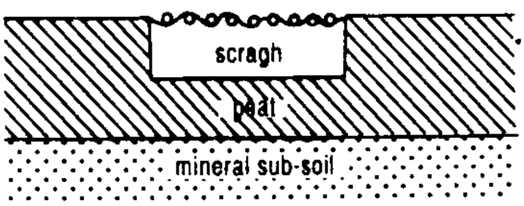
Figure 41.



In this situation a remnant peat layer is all that is left, of an arbritrary thickness, see figure 41. The blocks of the upper peat layer have not been returned to the site and therefore only open water is left on the peat substrate. In the open water Sphagna can develop, if the water on the peat substrate is sufficiently acid (pH<6, section 4.3.1.) and nutrient-poor (conductivity 15 m Sm^{-1}, section 4.3.4.). Initially Sphagnum cuspidatum will grow, as it develops well in open water. When the lake or ditch grows full of the submerse form of this species, floating mats will develop, creating a somewhat dryer situation, just above the water table. In the raised bog reserves Bargerveen, Deurnse Peel, Engbertsdijksvenen and Fochterloërveen this development takes place. These conditions also create possibilities for the growth of species of Sphagna of a somewhat less wet and possibly somewhat less oligotrophic environment, e.g. Sphagnum recurvum and in the long run a mat develops which provides an environment sufficiently acid and nutrient poor so that the real raised bog Sphagna (like Sphagnum papillosum and S. magellanicum) can establish themselves. Especially in the Bargerveen, where management measures were taken some years ago, this development can be seen (Jansen and Oosterveld, 1987). Finally the open water can be filled completely. The depth of water fills up gradually also because of an increase in weight of the floating vegetation and over the surface the lake will have filled in already earlier and thus a peat forming situation develops on a substrate which is still floating. This vegetation can have the character of a quaking moor ("Schwingrasen"). A condition is that the level of the water is hardly fluctuating; preferably the water is no deeper than about 1 to 1.5 m. Especially the influence of the wind will have to be limited, in order to make possible the formation of floating mats. In practice areas of about 200 m^2 are suitable. When the mats develop this in itself will restrict the action of waves and flow by the wind, in which case the compartments may be larger at a later stage.

b. <u>The regeneration of raised bog from a situation of floating scragh</u>

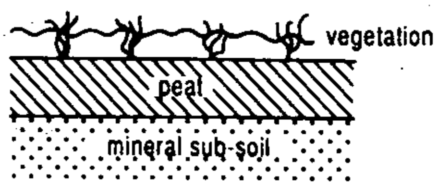
Figure 42.



This situation is hydrologically comparable to the last situation, only the starting material is different, as the peat blocks of the upper layer have been returned to the site. When the water table rises these block start to float. When this peat is rewetted (originally poorly humified peat) favourable situations are created for peat producing Sphagna as far as moisture supply is concerned. The stadia of development to ombrogenous bog mosses is generally the same as described under a. above, i.e. a succession of Sphagnum cuspidatum to S. recurvum, S. papillosum, S. magellanicum and other ombrotrophic vegetations which form peat. The reserve Bargerveen, where this measure has been carried out, shows a comparable development of the vegetation (Jansen and Oosterveld, 1987). An important advantage of this way of management is that right from the start a floating mat is present, which simulates acrotelm conditions normally present on ombrotrophic peat substrates, which means that management can be carried out on a large scale, with compartments of up to 2000 m^2. In this way less compartments are necessary.

c. Regeneration of ombrogenous peat between tussock vegetation

Figure 43.



This situation is different from the previous methods, as here the starting point is a vegetation development which takes place on a substrate which is not wetted, e.g. a vegetation of Molinia caerulea, or Eriophorum. After that the peat surface is flooded and the intention is that the tussock vegetation grows in tandem with the rewetting. In between and on the tussocks Sphagna can develop in an environment undisturbed by wind action, as can be seen in the Lichtenmoor (Germany), (Eggelsmann and Klose; 1982).
This is a method full of risks and large questions remain about the correctness of the ecological points of departure. Tussock forming species (especially Molinia) keep growing on as long as the water table is unstable and on average too low. Sphagna do establish, but usually these are minerotrophic species. In any case acrotelm conditions do not exist between the tussocks. Eriophorum vaginatum disappears rather quickly at stable water levels (Jansen and Oosterveld, 1987). Succession to real raised bog vegetation does not take place as long as the tussocks remain in existance, after all this means that the fluctuations in level are too large. The growth conditions are clearly different from those required for true raised bog Sphagna.
Of great importance, and at the same time a disadvantage of this method, is that the water level must be managed up to the centimeter exact. Drowning as well as drying out of the tussock vegetation is very harmfull, while the chance is large interference takes place because of the setting of seed and dispersal of the present vegetation. However the influence of the wind can be strongly curbed in this way, if the substrate has been leveled properly.

9.4.3. Growing-in with vegetation of lakes in a more nutrient rich environment

In general the start of raised bog formation in a more nutrient-rich environment only happens at a far advanced stadium of the succession process of growing-in of a water body. The storage of water in the floating mat increases more when the succession progresses. The floating mat becomes a succeedingly thick floating deposit of dead plant material and becomes more compact in composition. The plant communities become more oligotrophic the more the water in the top layer begins to resemble rain water in its compositions. In the table below the values for conductivity are listed, as they were measured in the reserve De Rottige Meente, in various places.

Table 20. Increase in poverty of nutrients in systems of peat-digging ditches systems, as a result of the filling-in of open water with vegetation.

Place of measurement	Site of measerement	Conductivity (EC ^{25})
- canals little isolated in relation to water inlet system	- in the canal	- 40 to 60
- peat-digging ditches which are in direct contact with inlet system	- in peat-digging ditches	- 25 to 20
- poor pastures	- near ground level	- 16 to 27
- more isolated canals, woods or reedlands	- in canals or near ground level	- 20 to 30
- older scragh with peat moss	- near ground level	- 8.5 to 15
- precipitation	- at measuring station	- 6 to 8

As the floating mat of vegetation fluctuates somewhat with the water level, the water level can not sink more than about 0.10 m below the vegetation cover. The top layer is generally well saturated with water, while the coefficient of storage reaches values of 0.8 to 0.9. Apart from the condition of oligotrophy for the water quality this hydrological property is an important enviramental factor for the formation of raised bog.
The largest threat for a nutrient poor development of the floating vegetation system is the supply with water of different ecological quality, often applied after drainage of the surroundings, which causes the level of the ground water to fall.
A first priority in taking management measures is to improve the water quality, which should have as much as possible a character like that of the water from the reserve area. One should aim at reconstruction of the original system of water supply.

The largest threat to the formation of raised bog in quantitative terms occurs when the floating mat of vegetation gets contact with the bottom and the fluctuations of the water-table becomes two large as a result.
Nutrient-rich wet situations in small scale peat remnants, as described in section 6.2., almost all originated after cutting of turf or after drainage. Measures that aim at the reconstruction of the base conditions are the lessening of drainage by the construction of dams in the drainage canals, so that only the surplus of water is discharged; the lessening of eutrophication by making sure that drainage ditches of the surrounding agricultural land do not discharge into the peat remnants; discouraging the dumping of rubish and sealing off of the subsoil in order to reduce vertical water losses are important measures. In order to improve the water quality a well adapted water management plan must be designed, in cooperation with the surrounding land owners, so that the bog remnants can be supplied solely with rain water. Maintenance measures are strongly dependent on the specific local circumstances. Reconstruction of the original relief could be considered, as

well as the cleaning up of the fen or bog and the transport of nutrients out of the system by mowing and removal of the material from immediate surroundings and banks.
The removal of trees is necessary from the point of view of reduction of evaporation, but also to prevent pucturing of the hard iron pan and downwards seepage to the subsoil and to preserve the gradient rich bank zonation.

Management of reed lands by flooding is not good from the point of view of water quality and the development of nutrient-poor conditions. Reeds are often cut by machines and the water table is lowered in winter to create a workable situation. This involves discharge of the nutrient poor rain water (Fahner, 1985). If the spring is dry, nutrient-rich water of different ecological quality is often put into the reserve to counter unacceptable vertical discharge or to stimulate reed growth. This is not benificial for the water quality of the area and counteracts the formation of raised bog.

10. SUMMARY

The hydrological management of raised bog remnants is the central theme of this report. The hydrological regime of raised bog systems is analyzed in relation to the mechanisms of raised bog growth, as they are known from peat stratigraphical research.
Raised bogs can be considered as ecosystems, in which nutrition as well as water supply takes place solely by direct precipitation. Typical of raised bog growth is the oligotrophy of the system, the low pH (between about 3.2 and 4.5), a surplus of water in the vegetation cover and a water saturated peat deposit (or: subsoil). Following Ingram (1983) two concepts can be distinguished in the hydrological regime: the <u>acrotelm</u>, the system of living Sphagna including the necessary hydrological provisions and special structures, in which the actual peat formation takes place; and the <u>catotelm</u>, under which is understood the water saturated body of peat, in which biological processes do not or almost not take place, and in which very little movement of water takes place.

Only when both of these systems function properly one can speak about raised bog formation. Raised bog formation is possible within rather broad climatological limits and geographical boundaries. Raised bog formation is possible in Europe at a mean yearly precipitation of at least 500 mm and a mean yearly temperature below 11 ^{o}C, depending on the prevailing climatological circumstances. For the Netherlands this is precipitation of on average 700 mm or more per year at a mean yearly temperature of a maximum of 9.5 ^{o}C. The formation of raised bog can begin or restart on various substrates. Conditional is in general hydrological isolation from the influence of too many nutrients, from an insufficient degree of acidity and from (sub-surface) discharge. The Dutch raised bogs belong to the plateau or lens raised bogs with a domed surface (convex relief) and a surface runoff in periferal direction.

In raised bog formation the evaporation is the most important part of discharge; (infiltration to the subsoil) is very small and superficial discharge is necessary to maintain the conditions for ombrogenous peat formation. The latter is called system-linked discharge. For the Netherlands the evaporation is on average 550 mm/year and the downwards seepage is about 30 mm/year (if the precipitation is on average 700 mm/year). The system-linked part of the surface discharge is about 110 mm or more per year. Discharge of truely superfluous water increases strongly with increasing precipitation. Climatological conditions in most parts of the Netherlands have been favourable for the formation of raised bog since about 5,000 B.C., although not optimal. The determining conditions were probably not always present in the province of Limburg; in Noord-Brabant the formation of raised bog was only just possible. In this area, but also in areas where large raised bogs did develop, the formation of peat could stall to a greater or lesser extend in dry years or in periods of dry years.

The present day rarity of raised bogs in the Netherlands is solely due to antropogenic influences since the 17th century A.D.: drainage, peat cutting and at present possibly also air pollution.
In the Middle Ages about 230,000 ha of raised bog was present in the Netherlands. Of this about 8,000 ha remains, of which about 6,000 ha is managed by nature conservation organisations. These are all damaged remnants, and their peat deposits are only partly present (seriously affected, resting, partly or

nearly completely dug away). In those reserves where the aim of management is the formation of ombrogenous peat, within the climatoligal restrains of precipitation and temperature, hydrological management measures are proposed, which are meant to create or maintain the necessary conditions for the formation of raised bog in these reserves. The hydrological management involves the recreation of acrotelm and catotelm conditions in such a way that water surplus situation are recreated on a water saturated substrate by a maximal retention of precipitation, strong reduction of vertical water losses and the retardation of the surface runoff.

Which problems does a manager of a raised bog reserve encounter? The evaporation of, usually somewhat dried out, is often somewhat less than 550 mm per year; this is not the main problem. The downwards seepage especially in our well drained country, is always much larger than the 30 to 40 mm it would be in a living raised bog, usually it is well over 100 mm. It is a huge problem for the manager to decrease this. He has to seal the subsoil or to increase the height of rise of the ground-water in the sandy soil of the lands surrounding the raised bog reserve. This is not easy in practice, but is often necessary to give the reserve some chance of renewed peat growth.

Two serious problems are connected with surface runoff. Often about 200 to 300 mm disappears via ditches and canals; this is more than the system can sustain. This water also disappears much to quickly. Often it has gone from the system in a few days, especially in the winter period or in early spring. This results in a lack of water at the surface during the growth period of the peat mosses. When the water table falls too much the peat mosses are replaced by other vegetations, like Molinia caerulea, Juncus effusus and birches, which removes the manager further from his goal. These species will cause the peat to oxydise.

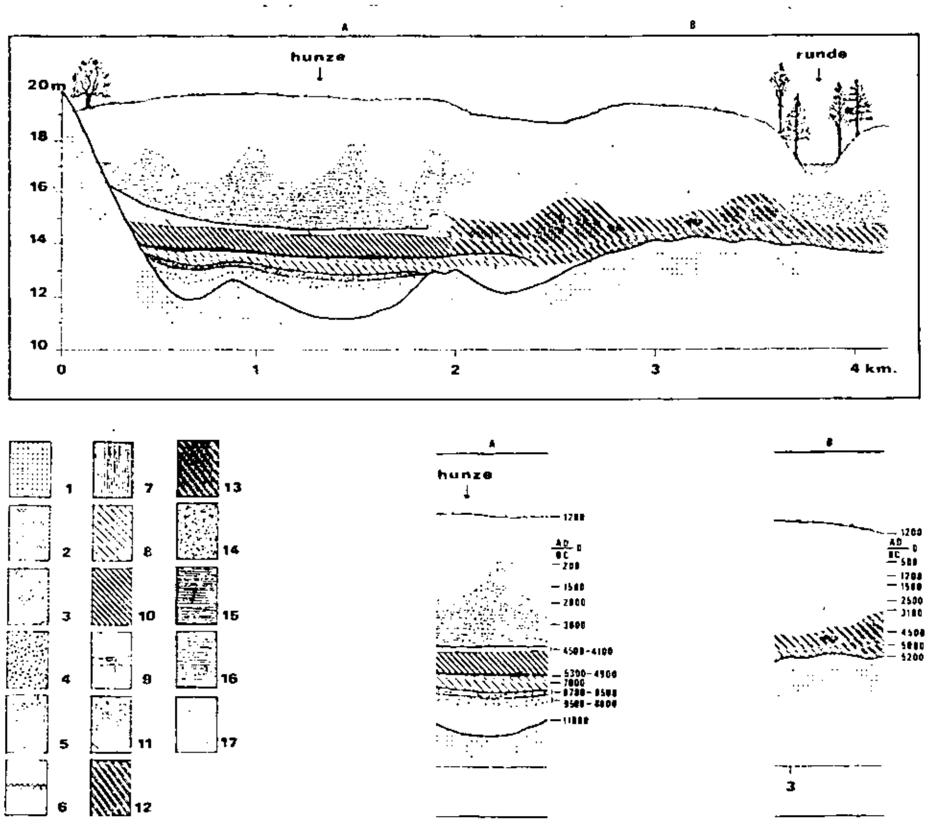
What can the manager do to create ombrogenous peat formation in his reserve? Water balance studies of raised bog, peat stratigraphy and ecological research show clearly that the manager must make sure that water from outside his raised bog reserve can not come in contact with the reserve. Direct precipitation is the only source of water that he should use. Precipitation must be retained so that evaporation, and downwards seepage can be compensated for and so that the system-linked discharge can take place. This can be done by the construction of systems of dams. Under infavourable circumstances the total discharge may be as high as 350 mm per year and this has to be reduced to about 150 to 200 mm per year in the ways described above.

This is not all that needs to be done. The system-linked discharge has to be implemented. This means: water has to flow over the surface of the peat during a large part of the year and preferably during the whole year. This can be done only in one way: by closing off all means of discharge at the peat surface and constructing water reservoirs at the peat surface, which can contain water for a sufficiently long time. This can also be done by a system of dams on the bog. Via a system of overflows water saturated conditions can be generated, in which the formation of raised bog can start again.

Appendix 1

Strongly simplified record of the peat deposits at the Bourtangerveen east of Emmen, with the time scales on two places: A and B. Heights are in meters above NAP (=Dutch datum level). This transect represents the situation at the end of the Middle Ages; well before drainage. The vertical scale has been expanded by 125x.

1. sand
2. fluvial loam
3. Hypnaceae peat("Braummoos Torf"), formed between 11,000-9,500 B.C.
4. löss layer, deposited between 9,500-8,800 B.C.
5. thin layer of birchwood peat, formed around 8,500 B.C.
6. open water, in this case the bog stream Runde.
7. gyttja (lake bottom sediment), deposited between 6,800-5,300 B.C.
8. strongly humified birchwood peat, formed between 8,300-5,300 B.C.
9. charcoal layer, remnant of a pine forest between 5,300-4,900 B.C.
10. moderately humified alder wood peat, formed between 5,000-4,500 B.C.
11. pine stump layer, remnant of a pine forest between 4,500-4,100 B.C.
12. Ferruginous Hypnaceae peat, developed in an iron-rich upwards seepage environment between 5,200-3,100 B.C.
13. bog-iron or deposits in the seepage peat, developed between 4,500-3,100 B.C
14. birchwood peat, formed between two raised bog complexes between 3,100-1,900 B.C.
15. brown-black highly humified moss peat, formed between 4,500-2,000 B.C.
16. blue-black highly humified moss peat, formed between 3,100-1,500 B.C.
17. poorly humified moss peat, formed from 2,000 B.C. in the hollows of the brown-black complex (15) and from 1,500 B.C. in the hollows of the blue-black complex (16). Around 200 B.C. the area was for the greater part overgrown with poorly humified moss peat.



Appendix 2

Degrees of humification following Von Post and Granlund (so-called degrees of squeeze)

H 1 Completely unhumified plant remains, from which by hand only almost colourless water can be squeezed.
H 2 Almost unhumified plant remains; the squeeze water is light brown and almost clear.
H 3 Very poorly humified plant remains; the squeeze water is cloudy and brown.
H 4 Poorly humified plant remains; peaty substance does not escape from between the fingers by squeezing.
H 5 Moderately humified plant remains; the structure is however still clearly visible; the squeeze water is dark brown and very cloudy, while some peat escapes between the fingers.
H 6 Fairly highly humified plant remains; the structure (texture) is unclear. About a third part of the peat escapes through the fingers. The part remaining in the hand has a more clear plant structure than the part that was squeezed out.
H 7 Highly humified plant remains; about half of the material escapes when squeezed. The water which may escape is dark brown in colour.
H 8 Very highly humified plant remains; two-thirths escapes through the fingers. The remainder consists mainly of resistant bits of roots, wood etc.
H 9 Almost completely humified plant remains; almost all the peat escapes through the fingers. Structure is almost absent.
H10 Totally humified plant remains; amorphous peat; all the peat escapes the fingers without any water being squeezed out.

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