Subsidence of Clara Bog West and acrotelm development of Raheenmore Bog and Clara Bog East

A comparison of 1991-1992 and 2002-2003

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SUMMARY

Introduction

This report deals with changes on Clara Bog and Raheenmore Bog, Co. Offaly from 1989-1993, when the fieldwork in the framework of the Irish-Dutch peatland project was conducted and the winter of 2002/03. On Clara Bog West the object of study was the subsidence that has occurred mainly in its southern part. On Clara Bog East and Raheenmore Bog the work focused on the development of the acrotelm since the blocking of internal drains around 1995/96.

Clara Bog West

In a part of the cut-away zone along the southern margin of Clara Bog West, in Co. Offaly Ireland, turf-cutting activities have increased since the early 1990s. In this part of the cut-away zone drains have been deepened and some new ones have been made, resulting in a lowering of the groundwater table to a level below the bottom of the peat. A comparison of bog surface levels measured in 1991 and 2002 showed subsidence values of up to a little over 1 m in the southern part of the bog, decreasing northwards, but still measurable at distances up to 600 m from the southern margin. This suggested that drainage of the bog had intensified. A comparison of volume fractions of organic matter in samples taken in 2002/03 and in 1991/92 showed that subsidence is mostly related to shrinkage of deep peat layers. Hence the subsidence must be attributed to a decrease in pore water pressure in the lower peat layers, resulting from the propagation of the lowering of the groundwater level in the cut-away zone *via* the underlying mineral soil (till). The effect has most likely been enhanced by the continued expansion of the cut-away zone into the bog in recent times as a result of turf cutting.

This conclusion is supported by the pattern of subsidence, which shows that the most severe subsidence occurs at the southern bog margin and gradually decreases northwards, but extends far into the bog, as mentioned in the previous paragraph.

Local spatial differences in subsidence have occurred on Clara Bog West. These differences, which have caused drier and wetter spots and even pools and small lakes, may probably be attributed to spatial variation of the hydraulic resistance of the underlying mineral layers (lacustrine clay and till). Differences in vertical resistance of the peat itself may also have played a certain role, but this could not be confirmed from the available data.

Results of the fieldwork done in 1991-93 show a considerable decrease of the hydraulic conductivity of peat with increasing volume fraction of organic matter. Although no additional measurements of the hydraulic conductivity have been made during 2002/03, these earlier results are a strong indication that the compaction of the peat, as found from the data, has caused a decrease in the horizontal and vertical hydraulic conductivity and hence an increased vertical resistance of the lower peat. This process can be called self-sealing of a peat body.

The identification of a possible self-sealing process, however, does not mean that subsidence will not cause long-term damage to a bog. Subsidence has changed the surface slope and the flow pattern on Clara Bog West, causing less favourable or even adverse conditions for acrotelm growth in large parts because they are drained more effectively. Better conditions caused by increased inflow of water from other parts of the bog will occur in minor parts only. One effect of increased internal drainage is a decreased flow towards the soak system of Shanley's Lough, which may decrease even more if continued subsidence in the part of the bog that is affected most will eventually result in loss of the western soak. Because subsidence is a delayed response to the changes that cause it, it is unlikely that the present process has already come to an end. In addition, it may eventually cause indirect additional

subsidence, resulting from damage to the acrotelm and subsequent loss of regulating properties.

Hence the subsidence may have a long-term impact on the ecological conditions on Clara Bog West. Therefore measures to remove the cause of the subsidence, such as a water level management in the cut-away zone that brings water tables at least close to or at the present land surface (which is mostly above the bottom of the peat), are urgently needed.

Clara Bog East

During the survey in 1992/93 it was found that Clara Bog East had suffered severely and from the internal drainage installed in the early 1980's. The results of the transmissivity measurements showed an even larger average difference between theoretical and actual transmissivity than those of Raheenmore Bog. The provisional drain blocking of 1989 may have slowed down the deterioration, but was probably insufficient to cause an improvement. In 1996 the drains were blocked effectively and already at the end of the growing season of 1997 *Sphagnum* species showed a large expansion in many areas (observation by Sake van der Schaaf). On Clara Bog East only acrotelm transmissivity measurements were carried out. The values measured in 2003 showed a considerable improvement over those of 1992, because the average actual values were much closer to the theoretical ones. This means that the restoration measures carried out on Clara Bog East have been effective and that the acrotelm of Clara Bog East is recovering from damage inflicted in the 1980's albeit with restrictions in areas with a relatively steep slope and/or a short flow path length.

Raheenmore Bog

Raheenmore Bog has suffered from internal drainage and peat cutting along the bog margins. In 1990/91 an acrotelm survey on Raheenmore Bog, including transmissivity measurements and acrotelm depth, showed that conditions were considerably below the potential situation, based on a theoretical relationship of transmissivity, flow pattern and surface slope. The drains have been blocked around 1995. To investigate how the acrotelm had developed since, a new acrotelm survey was carried out. The results showed that the average of measured transmissivities was closer to the potential situation than in the early 1990's and that the transition from subsurface acrotelm flow to surface flow occurred at larger specific discharge values, which indicates that the hydrological regulation function of the acrotelm had improved. The overall acrotelm depth also showed a significant increase since 1990/91. Therefore it can be concluded that the acrotelm of Raheenmore Bog has developed positively during the last decade.

PREFACE

This report is a reworked version of an earlier report by three students of Wageningen University, who did part of their MSc-work on the bogs described (Ten Heggeler *et al.*, 2003). The text in italics below is the preface by the original authors.

The work described in this paper was funded by National Parks and Wildlife, Department of Environment, Heritage and Local Government, Dublin.

Sake van der Schaaf

In the period 1989-1993 research was done on two bogs in the Irish Midlands: Raheenmore Bog and Clara Bog. This research was done in the framework of the Irish-Dutch Raised Bog project. Since then the bogs have been developing (positively or negatively). To investigate the development of both bogs, research was carried out from November 2002 until April 2003. In this report the results of the fieldwork are described.

Without the help of a number of people, this research would not have been possible. First of all we would like to thank Sake van der Schaaf, our supervisor. He introduced us to the bogs, supervised and assisted in the field. He gave answers to all our questions. He also introduced us to Irish life, pubs, Guinness and whiskey.

We are very grateful to Jim Ryan of NPWS, without whom this whole project would never have been started in the first place. Besides he facilitated us in a great way, e.g. he arranged an oven and a balance at the beginning of the project.

We want to thank Michael Jacob of Peatland World who lent us the oven and the balance.

Further, we would like to thank the Quinn family, for their hospitality and especially Joe and Anthony for helping on the bog.

Bob Hammond was so generous to lend us his Hiller auger and Colm Malone helped with constructing the discharge point at Raheenmore Bog.

Hennie Gertsen assisted us the first week with the fieldwork and the people of Rabbitte's showed us that time is relative.

Most Irish we have met, taught us to have a different look at the weather and we always have a special feeling now when the sun is shining.

To all these people we express our sincere thanks.

Martine van der Ploeg

Menno ten Heggeler

Saskia Vuurens

CONTENTS

1. INTRODUCTION

1.1. Scope and problem description

Once large parts of Europe were covered with peat. In past centuries most of these peatlands have been drained and used as a source of fuel and/or reclaimed for agriculture and forestry. The first country in northwestern Europe that fully exploited its peatlands was The Netherlands. Ireland, on the contrary, still has 50% of the remaining area of uncut raised bogs in northwestern Europe (excluding Scandinavia), despite the fact that 94% already has been exploited for fuel and garden peat production. In contrast to the Netherlands, large-scale commercial peat cutting started in Ireland only in the middle of the 20th century (Schouten *et al*., 2002).

In the last decades of the 20th century awareness grew that conservation and restoration of bogs was important from several points of view, such as uniqueness, preservation of biodiversity, the global carbon cycle, national heritage, etc.

In 1989 the co-operation of Ireland and the Netherlands, countries with different backgrounds in peat exploitation, began. The Irish National Parks and Wildlife Service (NPWS), the Geological Survey of Ireland and the Dutch National Forestry Service (Staatsbosbeheer) initiated this study.

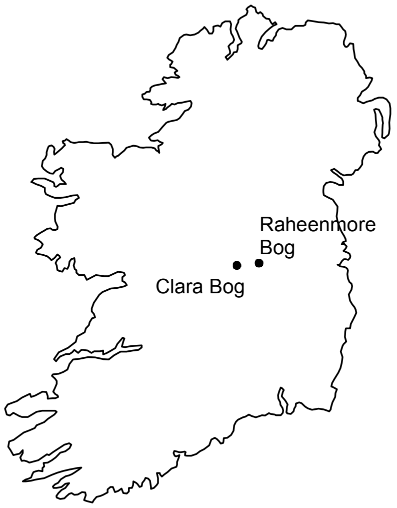

Figure 1.1. Location of Clara Bog and Raheenmore Bog in Ireland.

The objective of this large project was to improve the understanding of bog ecosystems in Ireland and to develop strategies for the restoration of bog remnants and regeneration of bog growth in the Netherlands. The research programme was interdisciplinary; hydrology, geology and ecology were the main fields of interest. The project focused primarily on the interaction between the peat forming bog ecosystem and hydrology, and on the disturbing effects of turf cutting along bog margins and drainage of the bog.

The research work concentrated on two raised bogs in the Irish Midlands, Clara Bog and Raheenmore Bog (positions shown in Figure 1.1). Clara Bog, bisected into a western and eastern part by a road, was chosen for its valuable soak systems, for example Shanley's Lough on the western half and Lough Roe on the eastern half. Soak systems are natural features of raised bogs, but as a result of peat exploitation almost all Irish soak systems have been lost (Schouten *et al*., 2002). Raheenmore Bog, a typical Irish Midland dome-shaped bog, suffered from marginal turf cutting and damage from drainage; however, it was deemed to be only moderately disturbed.

The fieldwork part of the research covered 1989-1993 and resulted in the further development of theory on bog hydrology and its interaction with the vegetation. The theory is based on the concept of diplotelmy, i.e. the subdivision of the peat into two layers: the acrotelm and catotelm. The acrotelm is the thin top layer of the bog peat and the catotelm usually comprises the bulk of the peat in a raised bog (Van der Schaaf, 1999).

Since 1989–1993, Clara Bog West has subsided. From visual observations the acrotelm on Raheenmore Bog and Clara Bog East seems to develop positively. NPWS, Department of the Environment, Heritage and Local Government, Ireland is interested to know the cause of these changes for reasons of future preservation and management of the bog and started a new research project on both Clara Bog and Raheenmore Bog, which has resulted in this report. Below, further introductions to the bogs are given and research questions are formulated.

1.2. Research questions

1.2.1. Subsidence on Clara Bog West

Clara Bog has suffered severe damage during the last two centuries. About one third of its original size has been lost. The bog subsided extensively over the past 150-200 years, mainly as an effect of the bog road and its associated drains, not only those immediately alongside the road, but also the double and triple drains on the bog parallel to the bog road (Figure 1.2). The double and triple drains were blocked around 1995. In the early 1990s, peat extraction increased at the southern and southwestern bog margin outside the nature reserve. In 1995/96 the drains at the southern cut-away were deepened well into the mineral subsoil.

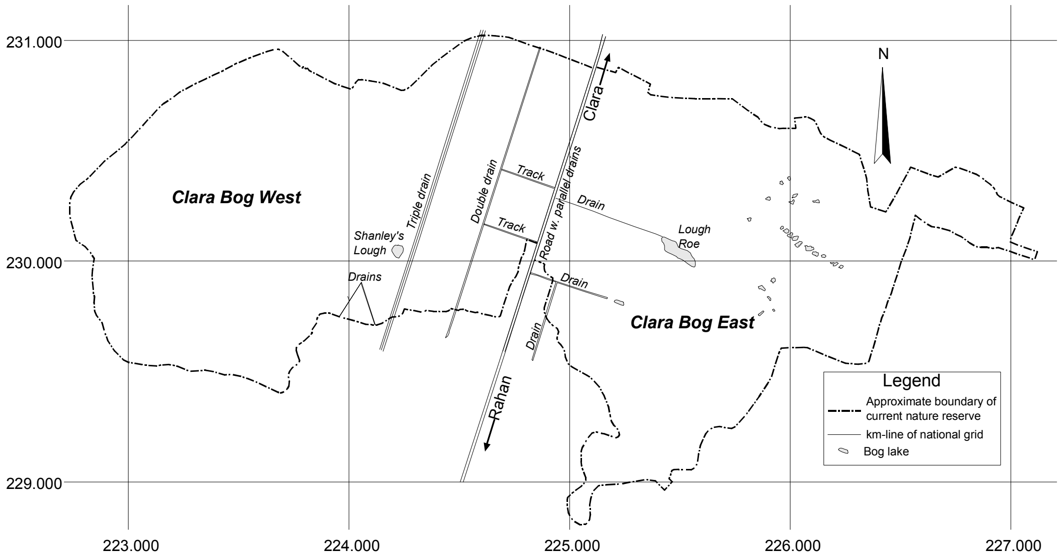

Figure 1.2 Outline of Clara Bog in 1991 with national grid coordinates (Van der Schaaf, 1999).

During 1991-2002 severe subsidence occurred in the southern and southeastern part of Clara Bog West. Also two small lakes and some pools formed. The subsidence and lake formation, possibly caused by the deep drainage, can have far-reaching ecological consequences. Now, the three main research questions are:

1) What caused the subsidence in the period 1991 – 2002?
2) Which processes are involved?
3) Which ecological consequences of the subsidence may be expected?

1.2.2. Acrotelm development on Clara Bog East and Raheenmore Bog

Clara Bog East

In 1983/84 Bord na Móna had cut a dense network of surface drains, about 0.6 m deep and spaced 18 to 20 m, to prepare the bog for industrial peat extraction. Also smaller cutting activities were undertaken at the often privately owned bog margins. In 1987-1989 the drains were blocked provisionally and more effectively in 1996. The drainage caused much damage to the acrotelm. Acrotelm transmissivity measurements in 1992 showed that the actual transmissivity was on average only one fifth of the theoretical value, which indicated a severe degradation of the acrotelm (Van der Schaaf, 1999). Now, the main research questions can be formulated:

1) Has the acrotelm on Clara Bog East developed positively since the research in 1991-1992?

2) Is transmissivity a useful indicator to quantify acrotelm development, when compared with the 1991/92 data?

Raheenmore Bog

Raheenmore Bog suffered from marginal turf cutting and surface drainage in the (north-) eastern part of the bog. As a result of a drainage system, which is probably over 100 years old and has now partly terrestrialised, this part of the bog has subsided gradually, causing the highest point to shift towards the southwest. This has affected the flow pattern on the bog and the southwestern part became dryer as a result of shorter flow paths, whereas the flow path lengths to the northeast of the highest point have increased, causing more water to discharge at the northeastern margin. In 1995 the drains were blocked in an attempt to stimulate acrotelm growth. Some old face banks near the northern dam (Figure 1.3) were regraded.

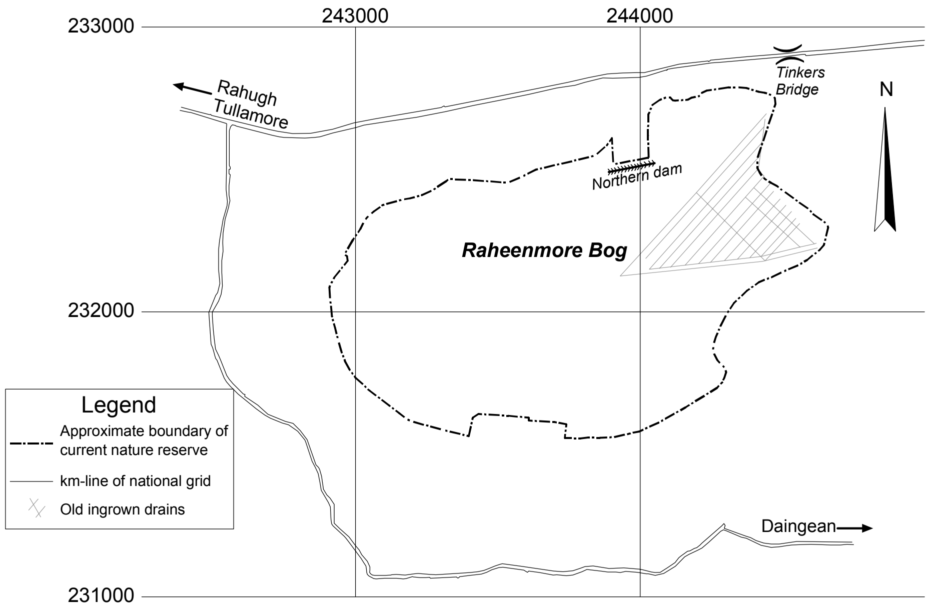

Figure 1.3. Outline of Raheenmore Bog with coordinates of the national grid in 1991 (Van der Schaaf, 1999). Position of northern dam (constructed after 1993) added.

As mentioned, a survey of acrotelm depth and transmissivity was carried out around 1991 by Van 't Hullenaar and Ten Kate (1991). Their results were later compared with the potential situation (Van der Schaaf, 1999). The comparison indicated a rather poor condition of the acrotelm. Around 1995 the drains on Raheenmore Bog were blocked in an attempt to stimulate acrotelm growth. Since the blocking of the drains the acrotelm seems to develop well. The main research questions are:

1) Has the acrotelm on Raheenmore Bog developed positively since the research in 1991-1992?
2) Are transmissivity and the depth of the acrotelm useful indicators to quantify acrotelm development, when compared with the 1991/92 data?

The latter question is the same as for Clara Bog East.

1.3. Structure of the report

Chapter 2 gives a description of concepts and terminology. In chapter 3, Clara Bog and Raheenmore will be looked at in detail. The subsidence of Clara Bog West and the research questions concerning that part will be described in Chapter 4. In Chapter 5, the acrotelm transmissivity measurements are described and discussed and the question whether the acrotelm of Raheenmore Bog and of Clara Bog East have developed positively, is discussed. Chapter 6 gives conclusions and recommendations.

2. CONCEPTS AND TERMINOLOGY

In this chapter concepts and terms used in this report are explained and discussed. The position of raised bog in the general concept of mires is given in section 2.1. In section 2.2, the development of raised bogs in general and specific in Ireland are discussed. Thereafter, in section 2.3, some characteristics of peat bog are given and in section 2.4 the hydrology of raised bogs is described.

2.1. Introduction to raised bogs

Mires in general are characterised by accumulation of organic matter under waterlogged conditions. Different types of mires can be distinguished by various characteristics. One of the most widely used distinguishing features is the nature of the water supply. A division can be made into three types of mires: ombrogeneous, topogeneous and soligeneous mires (Wheeler and Shaw, 1995).

Ombrogeneous peatlands are those where water logging is maintained solely by precipitation (ombrotrophic). Topogeneous peatlands occur in basins, floodplains etc., where water accumulates as a result of the topography of the landscape, whilst soligeneous examples are those where laterally mobile water maintains wet conditions, most typically on sloping sites. Although both topogeneous and soligenous peatlands are partly fed by precipitation, they also receive inputs of telluric water (*i.e.* water from the soil, which has been in contact with mineral substrata. They are often referred to as minerotrophic (groundwater-fed) mires (or fens). Bogs are exclusively ombrotrophic (rain-fed) mires (Wheeler and Shaw, 1995).

In Ireland two types of bogs can be distinguished: blanket bogs and raised bogs. Blanket bogs follow the contours of the underlying surface and are up to 3 m in thickness. They occur where the annual precipitation exceeds 1250 mm and the average number of rain days is 225 or more. In Ireland blanket bogs occur at sea level in the most western part of the country. Further inland they occur only in mountainous regions (Hammond, 1981; Van der Schaaf, 2002a).

Raised bogs in northwestern Europe are primarily (but not exclusively) lowland peatlands, which can occupy the bottoms of broad, flat valleys, the heads of estuaries or shallow basins and the peat may be over 10 m deep. Their development requires a sufficiently high rate of precipitation input (800 – 1000 mm per year in the Irish Midlands), not restricted to a single season, i.e. divided reasonably evenly over the year. Besides, the precipitation sum exceeds the potential evapotranspiration sum in almost every year. These conditions are required to permit peat to accumulate above the level of the mineral ground or the influence of telluric water (Leene and Tiebosch, 1993; Van der Schaaf, 2002a).

By their nature, raised bogs form as a peat deposit above the regional groundwater level in their immediate surroundings, the underlying fen peat and mineral deposits. In their most distinctive development raised bogs form shallow domes of ombrogenous peat delimited by mineral ground, fen or water courses (Wheeler and Shaw, 1995).

2.2. Development of raised bogs

At the end of the last glaciation, some 10,000 years ago, glaciers in Ireland retreated northwards and the permafrost disappeared. In central Ireland, ridges up to about 100 m wide and 20 m high in west-east direction were formed, commonly known as eskers. On top of the limestone bedrock ground moraine (till) was formed. Between the eskers and till mounds, lakes and lake systems formed. Surface sediments were easily washed into the lake basins. These sediments, with a low hydraulic conductivity, contained clay with fine sand and pebbles, know as glacio-lacustrine clay. In some areas lake marl was deposited on top of the clay. Lake marl is a deposit with a high content of calcium carbonate (Ten Dam and Spieksma, 1993; Van der Cruijsen *et al.*, 1993; Warren *et al*., 2002).

Some 8.000 years ago, fen peat started to develop in the lakes (Figure 2.1 A and B). Fen peat is mainly composed of layers of reed, various sedge species and (birch or alder) trees (eutrophic species). As the lakes were overgrown in time, the influence of nutrient-rich water gradually declined and a mesotrophic environment (transitional stage) developed (Figure 2.1 C). As a result plants invaded, which were able to grow in a mineral poor habitat. In time the plants became solely dependent on the nutrient-poor precipitation (ombrotrophic stage), and plants typical of raised bogs, such as *Sphagnum* and heather developed on the bog. As a result the peat surface became dome shaped (Figure 2.1 D and E). From approximately the beginning of the Atlantic, some 7.000 years ago, the climate in Ireland became suitable for ombrogenous peat growth (Cross, 1989; Van der Cruijsen *et al*., 1993).

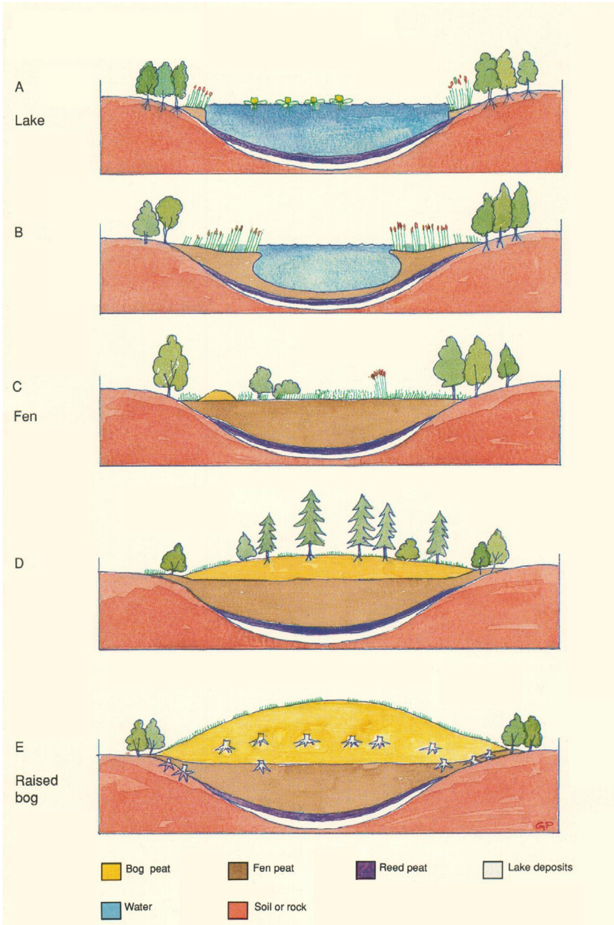

Figure 2.1. Stages in the development of a raised bog (Cross, 1989). A: Lake with open water and marginal reed beds; B: Lake filled with fen reed peat; C: Fen stage; D: Raised bog with woodland phase; E: Present raised bog.

2.3. Characteristics of bog peat

Vegetation

The most important producers of organic matter in a raised bog are *Sphagnum* species. These *Sphagnum* species only grow in situations with small seasonal fluctuations of the phreatic level and a mean phreatic level near or at the surface. The *Sphagnum* species help to create the characteristically low pH environment of bogs and they can store a large volume of water (Wheeler and Shaw, 1995).

Healthy bogs show a microtopographical structure, in which *hummocks* and *hollows* can be recognised. The shallow depressions in the bog surface where water collects, or where the water table reaches ground level or lies above ground level, depending on the seasonal fluctuations, are called hollows. Pools are deeper depressions where the water table remains above surface level all year round. Hummocks are mounds on the bog surface that can elevate from a few centimetres to more than 75 centimetres in height. The *Sphagnum* species that form the hollows differ from those forming the hummocks (Kelly and Schouten, 2002).

The surface of a raised bog is typically waterlogged and the highest part of the bog, often being the wettest and showing the most developed pattern in hollows and hummocks. The wet conditions are caused by accumulation of precipitation. Therefore, the chemical composition of the bog water is nutrient poor and is influenced by processes within the peat (Wheeler and Shaw, 1995).

Humification

Fresh biomass of *Sphagnum* is produced at the surface level of the bog and is overgrown by new organic material in the next year. Alternating drying and wetting of the bog surface and exposure to atmospheric oxygen cause decay of the young material. When the material is totally waterlogged in time, the decay rate decreases to a low level. A safe maximum value of subsidence caused by oxidation seems to be 2 mm a^{-1} in an uncultivated raised bog (Van der Schaaf, 1999).

The process of decay is usually called humification. The process breaks down the fibres and the weight of the overgrowing younger material causes a certain degree of collapse, which is reflected in the porosity and pore size distribution of the peat. The porosity in loose *Sphagnum* peat in the upper part of the bog normally exceeds the porosity in strongly humified peat (Wheeler and Shaw, 1995). The volume fraction occupied by the larger pores decreases particularly during the process of humification, which causes a strong decrease of the hydraulic conductivity of the material.

A practical and widely used field method to estimate the degree of humification is the Von Post scale (Appendix A) (Von Post, 1922; Von Post and Granlund, 1926).

Organic matter

The volume fraction of organic matter in profiles of undisturbed bogs lies approximately between 0.02 and 0.08. Peat is buried gradually deeper as a result of continuing production of new peat material at the surface. The pressure exerted by the overlying material increases with ageing and the gradual loss of elasticity resulting from the humification process continues. Hence, a positive correlation between the peat depth and the fraction of organic matter may be expected. One should realise that seemingly small changes if the volume fraction of pores, may mean a large compaction of the peat. For example, decrease of the volume fraction of pores from 0.98 to 0.96 means a volume reduction by 50%.

2.4. Hydrology of raised bogs

Hydrological characteristics

Mire systems differ hydrologically from mineral soils in a number of ways, caused by genesis and soil material. The most important characteristics that are typical for raised bogs and distinguish them in a hydrological sense from mineral soils are discussed below (Van der Schaaf, 1999; Van der Schaaf, 2002b).

1) A relatively large storage coefficient. The storage coefficient in mineral soils usually varies between 0.05-0.10. In raised bogs this value is larger (0.30 or higher), which is caused by the high porosity and the high proportion of large pores in the young *Sphagnum* material in the surface layer.
2) The discharge regulating properties of the surface layer, caused by the strong decrease of the hydraulic conductivity with depth. This causes the outflow to increase rapidly with a

rising water table when the water can flow through the highly permeable to layer, but in times of lowering of the water table, the opposite occurs.

3) Small temporal fluctuations in time of the phreatic level. Seasonal fluctuations of the phreatic level in NW-Europe in mineral soils are 0.50-1.50 m. In undisturbed bogs the fluctuations are up to 0.2-0.3 m. This difference is caused by the processes mentioned in 1) and 2).
4) Vertical oscillation of the surface, related to wet and dry seasons (*Mooratmung*). Mooratmung is a result of the flexible peat matrix and water tablel fluctuation. The volume of the peat mass and thus the bog's surface level vary slightly with the phreatic level, whose fluctuation in turn is caused by evapotranspiration and precipitation. The lowest levels occur at the end of the summer and the highest level at the end of the winter. The seasonal fluctuation of the bog's surface level caused by *Mooratmung* is usually only a few cm, but may be more in years with large seasonal differences in wetness (Uhden, 1956).

In the following sections, the properties of the acrotelm, based on the concept of diplotelmy, and the hydraulic conductivity of raised bogs are discussed.

The concept of diplotelmy

Hydrologically, raised bogs can be considered as two-layered (diplotelmic) systems comprising an uppermost layer or acrotelm and a catotelm, which comprises the entire peat body below the acrotelm (Figure 2.2).

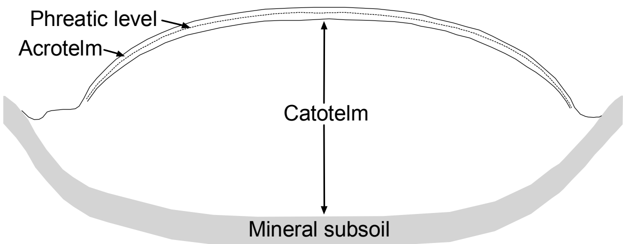

Figure 2.2. Schematic section through a raised bog with mineral subsoil, catotelm, acrotelm and phreatic level (Van der Schaaf, 1999).

The acrotelm comprises the fluctuating water table and is the functional horizon for plant growth. It is composed of living vegetation cover at the top, with underlying recently produced dead plant material and fresh peat. The acrotelm is usually thin (< 50 cm) because the peat gradually decays and eventually gets incorporated into the catotelm as the upper level of the permanent water table is follows the upward growth of the surface level. The acrotelm has a high hydraulic conductivity near the surface, but becomes less permeable with depth as the peat becomes more consolidated and decomposed or humified, which results in a decrease of the average pore size. The acrotelm can be regarded as an integrated combination of plants (especially *Sphagnum* species), peat and water. Plant growth contributes to the formation of a microtopographical structure which has a capacity for regulating water movement and discharge and which helps to maintain the growth and survival conditions of the plants (Wheeler and Shaw, 1995; Van der Schaaf, 2002b). Thus the acrotelm is not only the (one and only) aquifer of a raised bog, but also the layer, which largely regulates the bog's hydrological system, as outlined in the previous section.

The catotelm usually comprises the bulk of the peat in a raised bog. It is built up of former acrotelm peat. The catotelm peat is to some extent consolidated and moderately to strongly humified. It has a much lower hydraulic conductivity than the acrotelm and correspondingly slower rates of water movement within it. In case of an undamaged bog, the catotelm is the water-saturated anaerobic base to the acrotelm (Wheeler and Shaw, 1995) and the aquitard underlying the acrotelm aquifer. However, downward vertical flow through and from the catotelm may in time affect the catotelm's own volume and thus the cross-sectional shape of a raised bog.

For an understanding of the flow through the catotelm, the vertical water losses and the hydraulic conductivity are discussed below.

Water losses

Vertical water losses in the catotelm depend on the vertical hydraulic conductivity k_v [LT^{-1}] and the vertical hydraulic gradient over (a part of) the peat profile:

$$v_v \approx -k_v \frac{\Delta h}{\Delta z} \approx \frac{(h_1 - h_2)}{C_c(z_1, z_2)} \tag{2.1}$$

where

v_v = vertical component of flow rate density in the catotelm [LT^{-1}]

z = vertical position [L]; $z_1 < z_2$; *i.e.* z_1 is the deepest position.

h_1 = piezometric level at vertical position z_1 [L]

h_2 = piezometric level at vertical position z_2 [L]

$C_c(z_1,z_2)$ = vertical resistance of the catotelm between vertical positions z_1 and z_2 [T]

The vertical water losses exceed the horizontal water losses in the catotelm, because the vertical hydraulic gradient in a bog usually exceeds the horizontal by more than an order of magnitude. The horizontal gradient is approximately equal to the surface slope in the direction of flow.

Hydraulic conductivity of the catotelm

Peat in raised bogs often shows substantial spatial variability laterally as well as vertically. The properties of bog peat, such as humification, the volume fraction of organic matter and the microstructure differ between types of *Sphagnum* peat. These properties cause differences in the hydraulic conductivity k [LT^{-1}] in the horizontal (k_h) as well as in the vertical (k_v) direction. The average layering in the catotelm is approximately horizontal. Van der Schaaf (1999) noted that k often varies by half an order of magnitude or less over horizontal distances of a few metres and over vertical distances of a decimetre in the upper part of the profile. Anisotropy of k, related to layering, decreases with depth.

A statistical relationship exists between k and the volume fraction of organic matter. This relationship is useful, because the volume fraction of organic matter can be measured more easily than the hydraulic conductivity. Figure 2.3 shows that k_h generally decreases with increasing volume fraction of organic matter for Clara Bog West as a result of compaction that reduces average pore size, mostly at the expense of the large pores.

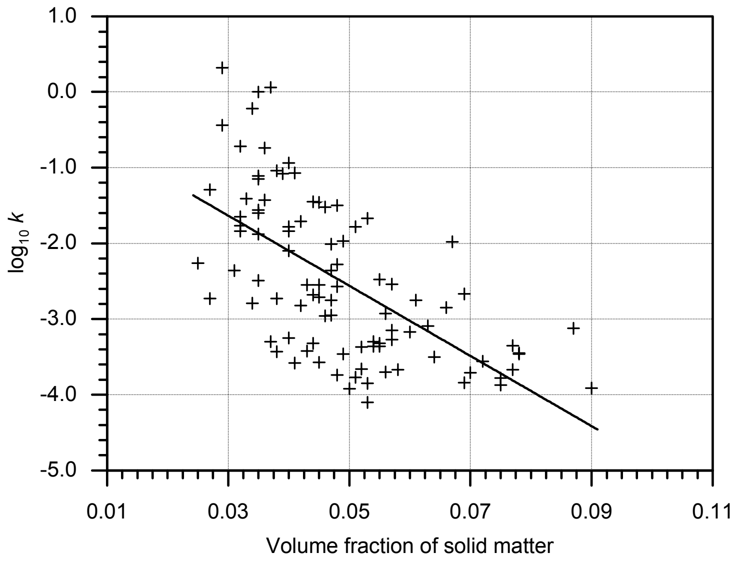

Figure 2.3. Measured horizontal hydraulic conductivity expressed as $\log_{10} k$ (k in m d^{-1}) versus the volume fraction of organic matter with fitted straight line for Clara Bog West (Van der Schaaf, 1999).

3. AREA DESCRIPTION

3.1. Clara Bog

Size and surface levels

In the north, Clara Bog is bounded by an esker and to the south, west and east by a glacial till landscape with remnants of the cut-away zone of the bog in the lower parts and small farms and meadows in the higher. Clara Bog has been a nature reserve since 1987. The size of the bog is around 665 ha. This includes cut-away sections and privately owned parts; the nature reserve itself comprises 465 ha. It is one of the largest uncut Irish Midlands raised bog remnants (Figure 1.2). The surface level of the high bog lies between 57 and 62 m above sea level. The bog surface slopes downwards to the road, shown in Figure 1.2. The eastern part of Clara Bog is slightly convex, which is the normal shape of Irish Midland bogs. However, the western part is slightly concave, with the highest surface levels close to the northern, western and southwestern margins.

Geology

For a better understanding of the following chapters a short description of the geology of Clara Bog is given below.

The geological base in the Clara Bog region is composed of Lower Carboniferous limestone. On top of the bedrock glacial till is found. Till is a mixture of sand and clay with varying texture and structure varying from clayey/loamy till to gravely, often with a high content of boulders. The till generally varies in thickness between 2 and 6 m. In the middle and southwestern part of Clara Bog the deposits exceed 10 m in thickness (Warren *et al*., 2002). The hydraulic conductivity of the till varies between 10^0–10^{-3} m d^{-1} (Van der Schaaf, 1999, Van der Schaaf *et al.*, 2002). The till is covered with glacio-lacustrine clay. The content of the lacustrine clay differs substantially. It ranges from gravely sandy clay (in the auger similar to till) to rather stiff clay. A large variation of the clay content occurs between sites on Clara Bog over distances. The variation in clay content influences the permeability of the clay. The hydraulic conductivity of the glacio-lacustrine clay lies in the order of 10^{-4} m d^{-1} (Rodgers, 1993; Van der Schaaf, 1999). In the Clara Bog basin this clay covers the till. It has a thickness up to 6 – 7 m. The deepest deposits lie in the central part of the bog and become shallower towards the margin. At several locations lake marl has been deposited on top of the clay, primarily in the central and deepest part of he bog basin. This deposit is generally no more than 40 –50 cm thick (Bloetjes and Van der Meer, 1992; Warren *et al*., 2002).

The fen peat of Clara Bog ranges between 1 and 3.5 m in thickness. The bog peat thickness varies in thickness from several meters up to 9 m in the low-lying parts of the bog (Bloetjes and Van der Meer, 1992). The average volume fraction of organic matter in the peat profiles lies around 0.04-0.07, depending on position. The vertical water losses through the peat are estimated around 5-15 mm a^{-1} (Van der Schaaf, 1999).

3.2. Raheenmore Bog

Size and surface levels

Raheenmore Bog was the first raised bog nature reserve in Ireland. It is a good example of a raised bog with a typically well-developed dome. It is a slightly asymmetric bog in a basin. The surface level of the bog lies between 3 and 7 m above the immediately surrounding land. The highest point lies about 107 m above mean sea level. The peat depth in some places is 14 - 15 m. The size of the bog including the cut-away is about 162 ha (Figure 1.3) (Sijtsma & Veldhuizen, 1992; Van der Schaaf, 1999).

Geology

The Raheenmore Bog basin is entirely underlain by a dark, muddy, well-bedded chert-rich limestone, commonly known as Calp. This Calp has an extremely irregular bedrock surface, with two major deep depressions. Similar to Clara Bog, the basin of Raheenmore Bog is filled with glacial deposits below the peat. Two 'till' units can be recognised. Directly overlying the bedrock, a sandy, gravely till is found, generally with a thickness more than 10 m, but thin at the bog margins. The second till layer consists of gravely clay or clayey gravel, with a thickness from 1 to 10 m, averaging about 4 m. On top of the till layers, lake clays are deposited. The clay contains more sand, and is therefore coarser than the clay found in de Clara Bog basin. In the Raheenmore Bog basin no lake marl has been found (Warren *et al*., 2002).

The process of peat formation in the Raheenmore Bog basin are similar to those in the Clara Bog basin, but the available information on the Raheenmore Bog basin is less detailed. (Warren *et al*., 2002).

4. SUBSIDENCE ON CLARA BOG WEST

4.1. Introduction

Between 1992 and 2002 severe subsidence occurred on southern and southwestern parts of Clara Bog West, threatening the soak system of Shanley's Lough and possibly also the western soak (Figure 4.1). Both soak systems are of the rheotrophic type (Kelly and Schouten, 2002), which makes them vulnerable to changes in the bog's flow system, which may be a result of changes in surface topography, in this case caused by subsidence. In 1992 and in 2002 topographic surveys of the bog surface level have been carried out. Figure 4.1 shows the surface levels of Clara Bog West in 1992.

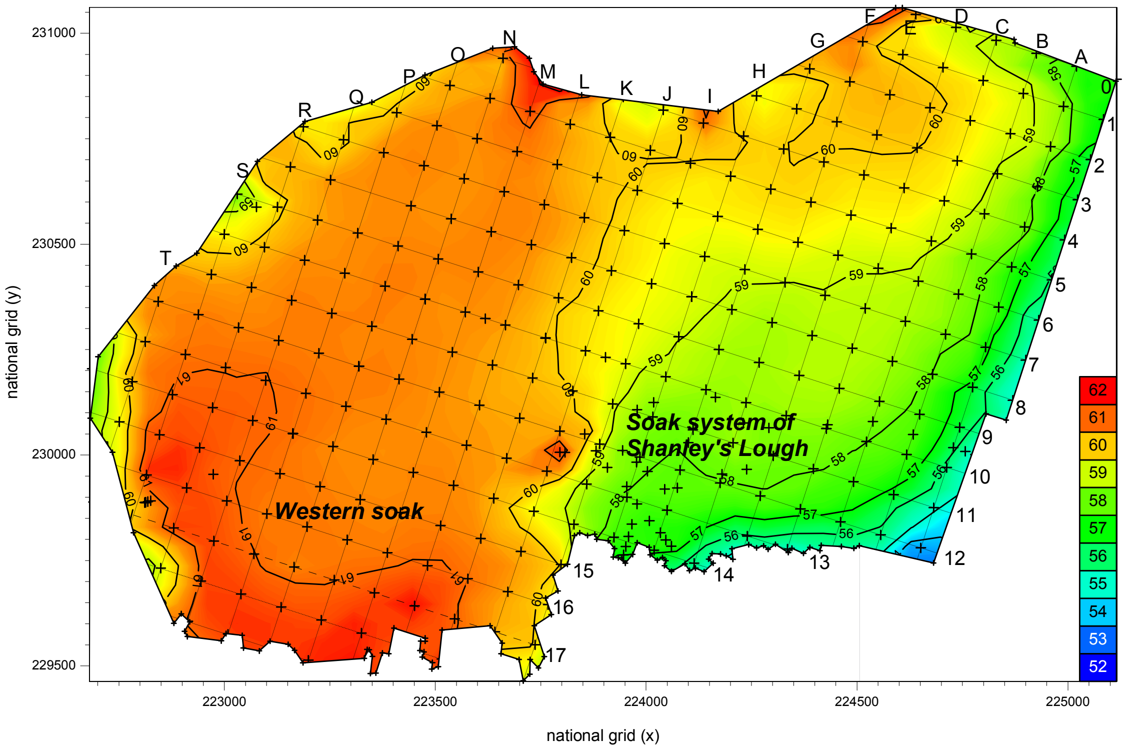

Figure 4.1 Surface levels of Clara Bog West in 1992 (m above sea level) with the coordinates of the national grid and soak areas. The 100 * 100 m levelling grid is shown as dotted lines with '+' marks as grid points. Grid lines are marked with numbers (app. E-W) and characters (app. N-S). Other '+' marks show positions of the dip well network observed during 1990-1993. The eastern border of the outline from '0' to '8' marks the road from Clara to Rahan.

The surface levels of 2002 were measured with a GPS-controlled laser system. Because bogs do not have a rigid peat matrix and the bog surface is uneven, an uncertainty of a few cm in the measuring results is inevitable. When using these maps, one must also consider that the surface level of bogs has a seasonal fluctuation, because it fluctuates to some extent with the phreatic level (*Mooratmung*, Chapter 2).

Figure 4.2 shows the subsidence on Clara Bog West in the period 1992-2002, as calculated from the levelling data. In the south it is locally more than a metre, whilst other areas, in the northwest and northeast in particular, show no significant lowering of the surface level. It shows that both rheotrophic soak systems are in or near the area with the largest subsidence.

Section 4.2 deals with the expected answers to the research questions on Clara West as formulated in 1.2. The measuring sites, materials and methods used during this project are discussed in section 4.3; section 4.4 deals with the results and conclusions.

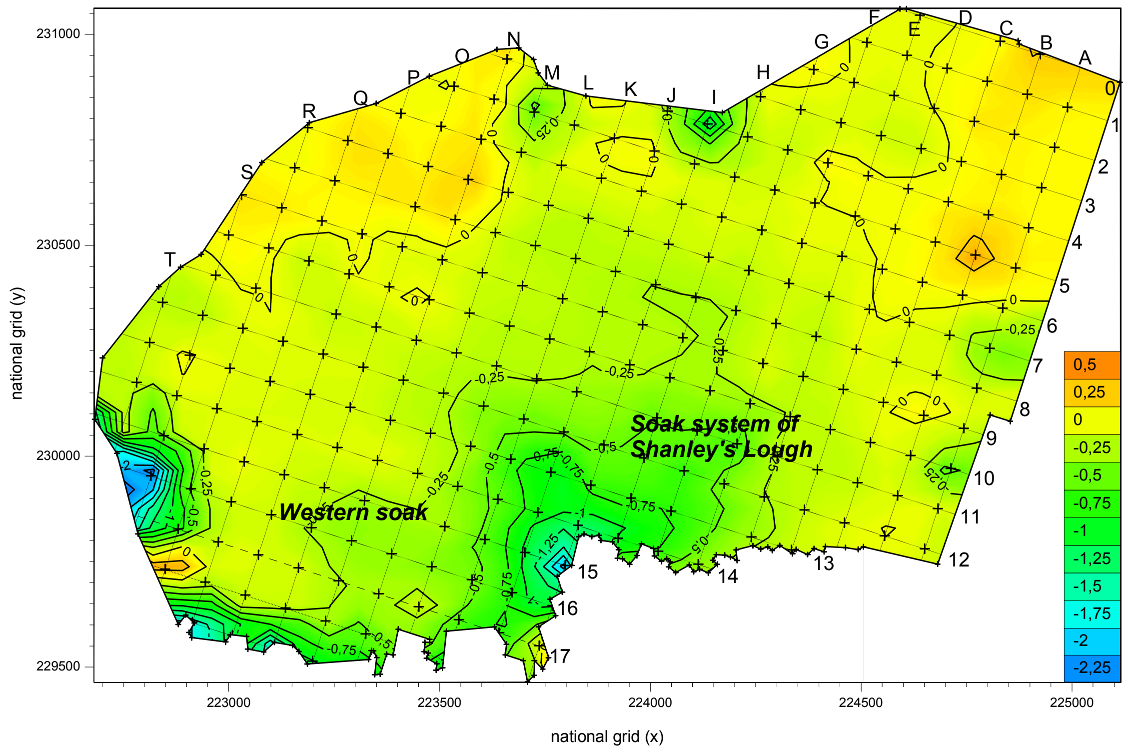

Figure 4.2 Subsidence between 1991 and 2002 in m with coordinates of the national and the local grid. The values >1.50 m in the South and Southwest are caused by two grid points, which lay on the bog in 1991 and in the cut-away in 2002.

4.2. Possible causes and consequences of subsidence on Clara Bog West

Water loss from the peat, burning or oxidation can cause subsidence. Clara Bog West has been damaged by burning in the past decade. Burning may cause a subsidence of up to 3 cm for each fire. Subsidence caused by oxidation probably does not exceed a rate of 2 mm a^{-1} (Van der Schaaf, 1999). Hence loss of water from the peat is by far the most likely cause of subsidence as occurred at Clara Bog West over the last decade.

Turf cutting activities had increased since the early 1990s and open drains were deepened into the till during 1995/96 by peat exploiters to facilitate the peat extraction on the southern margin of Clara Bog West. Drainage in the cut-away is likely to lower the piezometric head in the mineral layers subjacent to the peat, especially if the drainage level is below the surface of the underlying, relatively permeable till. Subsidence caused by such a process is likely to affect the lower part of peat profiles more than their upper part, whereas internal drainage, which is mostly relatively shallow, affects the upper rather than the deeper layers of the peat (Uhden, 1960; Van der Schaaf, 2000).

The effect in the peat profile itself would be an increase of the vertical hydraulic gradient over the peat profile. This reduces pore pressure and causes compaction of the flexible peat matrix. Compaction of the peat implies an increase of the volume fraction of organic matter and a decrease of the vertical hydraulic conductivity, which in turn means an increase of the hydraulic resistance of the peat. An increasing hydraulic resistance in the lower part of the catotelm and/or clay under the bog will eventually reduce the effect of the decreased piezometric head in the underlying mineral soil, thus effectively protecting the bog from future subsidence.

Lateral effects of subsidence may also have an impact. Subsidence causes a change in surface slopes, affecting the flow pattern. This may affect the bog's ecosystem because of a change in the actual acrotelm capacity due to an increase in the slope or the shortening of flow paths, due to a redirection or water flows (Van der Schaaf, 2000a; Van der Schaaf and Streefkerk, 2002).

4.3. Methods, materials and measuring sites

The volume fraction of organic matter ϕ_o, degree of humification H, peat depth D_p, piezometric head and phreatic level are important quantities to understand the processes involved in subsidence. Data of these quantities from the research period 1991/92 are available (Bloetjes and Van der Meer, 1992; Ten Dam and Spieksma, 1993; Van der Schaaf, 1999). In 2002/03 measurements on these quantities were done in the area of largest subsidence at the same measuring sites as in 1991/92 to allow an effective comparison. The comparison was expected to allow a quantification of changes over the last decade. In addition, some new sites were sampled in areas of large subsidence. In the sections below, the measurements and measuring sites are presented.

4.3.1. Volume fraction of organic matter and degree of humification

To find ϕ_o, samples were taken at depth intervals of 0.5 m. The comparison with the data of 1991/92 was expected to give information whether the shrinkage was concentrated in a specific part of the profile. A Russian type peat corer was used to take half-cylindrical samples with a diameter of 5 cm. From the middle of each core of 0.5 m, a 5 cm long sample was cut and stored in an aluminium box, which was closed immediately after filling. H (Von Post scale) of adjacent and similar material in the same core was determined on the spot. The sample was identified as fen peat when reed, sedge or pieces of wood (mostly alder or birch), not being heather, were identified. The samples were weighed on the same day and dried at 105°C until all the water had evaporated. This took about 24 hours. The samples were then weighed again. The result gave the weight of the organic matter and from this weight the weight of water could be derived. ϕ_o can be derived directly from the mass fraction if the mass density of organic matter in peat is known and the sample does not contain substantial amounts of other components but organic matter and water. Data of Galvin (1976) and Hammond (1981) show that peat of Irish Midland bogs contains negligible amounts of mineral matter (Van der Schaaf, 1999). Therefore, organic matter was assumed to be identical to solid matter. Galvin (1976) found a value of 1.38 g cm^{-3} for the mass density of organic matter ρ_o in Irish bog peat.

The equations used to calculate the volume of water in a sample and volume fraction of organic matter are given below (Van der Schaaf, 1999). The volume of water (V_w) in a sample is calculated from:

$$V_w = \frac{m_w - m_d}{\rho_w} \tag{4.1}$$

where

V_w = volume of water [L^3]

m_w = wet mass [M]

m_d = dry mass [M]

ρ_w = density of water [ML^{-3}], assumed to be equal to 1 g cm^{-3}

The volume of the dry matter (V_o) was calculated from:

$$V_o = \frac{m_d}{\rho_o} \tag{4.2}$$

where

V_o = volume of the organic matter [L^3]

ρ_o = mass density of the organic matter [M L^{-3}]

The volume of the sample (V_s) is found by adding V_w and V_o:

$$V_s = V_w + V_o \tag{4.3}$$

The volume fraction organic matter (ϕ_o) is derived from:

$$\phi_o = \frac{V_o}{V_w + V_o} \tag{4.4}$$

This technique can only be used under the assumption that the peat is saturated. Therefore, samples were only taken below the phreatic level. The process of decay produces gas, which can be entrapped in the peat. This percentage, 1-8 % (Ivanov, 1981), was neglected as it was also neglected in 1991/92.

If subsidence has occurred and it can be assumed that only the volume of water in the peat has decreased, the relationship between volume fractions of organic matter before and after subsidence can be written as (Van der Schaaf, 1999):

$$\frac{V_{s0}}{V_{s1}} = \frac{\phi_{o1}}{\phi_{o0}} \tag{4.5}$$

where

V_{s0} = volume of the sample before subsidence [L^3]

V_{s1} = actual volume of the sample as it was taken [L^3]

ϕ_{o0} = volume fraction of organic matter before subsidence [-]

ϕ_{o1} = actual volume fraction of organic matter [-]

Because shrinkage of peat in a bog means mainly shrinkage in the vertical direction, the symbols for volume in Eq. 4.5 can be replaced by symbols for layer thickness D:

$$\frac{D_0}{D_1} \approx \frac{\phi_{o1}}{\phi_{o0}} \tag{4.6}$$

where

D_0 = original layer thickness [L]

D_1 = actual layer thickness [L]

Equation 4.6 is the basic equation to estimate subsidence caused by water loss, as long as other causes such as losses by methane production due to decay of plant species can be neglected. This seems a reasonable assumption for a short period of 10 years.

4.3.2. Fractional depth

The sampling depths in different profiles cannot be compared directly, because the thickness of the peat differs considerably between the sampled spots. Therefore, in some comparisons between profiles with different depths, the sampling depth was transformed to a dimensionless fractional depth (d_f), defined as:

$$d_f = \frac{d_s}{D_p} \tag{4.7}$$

where

d_f = fractional depth [-]

d_s = sampling depth below the surface [L]

D_p = thickness of the total peat profile at the sampling site [L]

4.3.3. Piezometric head and phreatic level

Piezometers with filter screens of 20 cm long were installed with their lower end 0-10 cm above the bottom of the peat to measure differences between deep piezometric and phreatic levels in the peat. Phreatic levels were measured outside the tube. Some piezometers were later pushed down into the underlying mineral layer to measure piezometric heads immediately below the peat.

Phreatic and piezometric levels were measured occasionally in early 2003. Piezometers of the 1991 network, which still worked, were also used. Piezometers consisted of plastic tubes of 1” outer and 0.9” inner diameter.

4.3.4. Peat thickness and composition of the mineral subsoil

To assess only peat type and peat thickness without sampling for ϕ_o, a Hiller auger was used. To create a representative map of the level of the mineral subsoil, the peat thickness was required. The surface level of the peat was known at the grid points. When measuring the peat thickness, the composition of the subsoil was also described.

4.3.5. Measuring site positions

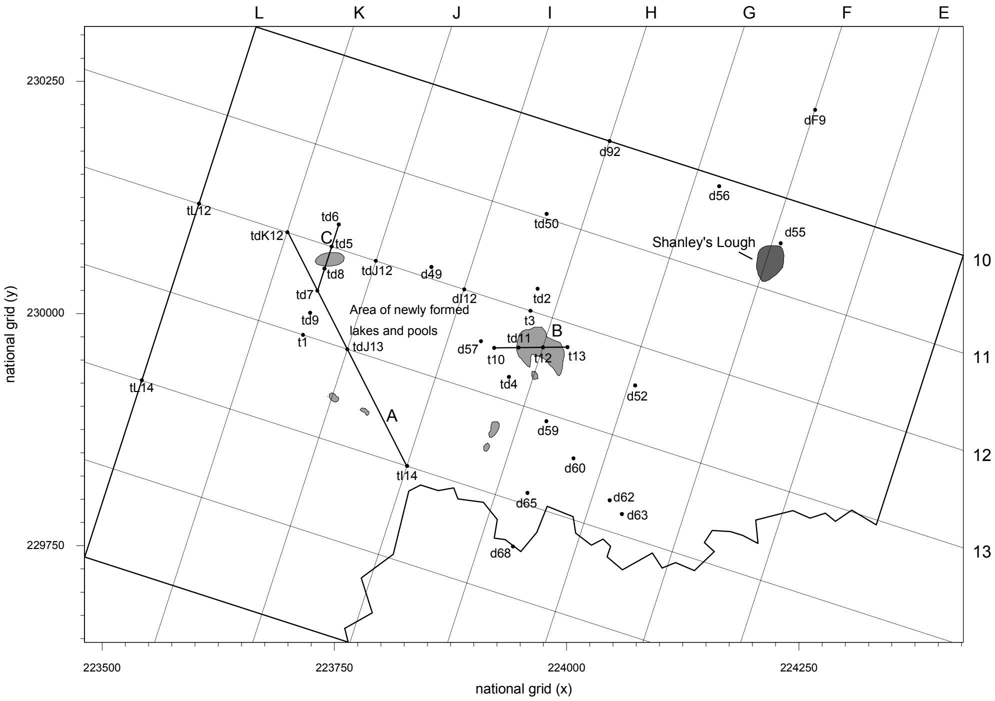

Figure 4.3 Measuring sites with lines of the 100 * 100 m local grid and coordinates of the national grid (see also Figure 4.1) and subsidence contour lines (1991-2002). Sites on a grid point show grid coordinates (e.g. dF9), others a number (e.g. td50). The lines of piezometers ‘A’, ‘B’ and ‘C’ were installed to measure deep piezometric heads.

The measuring sites were chosen to coincide as much as possible with those of the 1991/92 research (Bloetjes and Van der Meer, 1992; Ten Dam and Spieksma, 1993; Van der Schaaf, 1999). Additional measurements were made to obtain some extra results. Measuring site positions are shown in Figure 4.3.

On sites shown with a ‘d’ (drilling), peat samples were taken as described to determine ϕ. The measuring sites with a ‘t’ (tube), were installed to measure hydraulic heads at the bottom of the peat profile, just above the mineral subsoil. The tubes, tdK12, td5, td7, tdJ13 and tI14 were pushed down during the project to measure piezometric heads immediately below the peat. Tube td7 broke during this operation. Lakes are also shown in figure 4.3. The lakes at the sites td5 and t12 have developed over the last decade. The lake near d55 (*Shanley's Lough*) is older. The pools to the south of the new lakes have developed in the last 10 years.

4.4. Results and conclusions

4.4.1. Volume fraction of organic matter versus fractional depth

As mentioned in chapter 2, ϕ_o was expected to increase with depth. The data of 1991/92 confirmed this. The comparison between 1991/92 and 2002/03 gave remarkable results. At sites without subsidence, no increase in organic matter was expected. Small differences may occur due small differences in drilling position and sampling depth between 1991/92 and 2002/03. According to the levelling data, the surface level at coordinate point F9 has not changed. Figure 4.4 shows the distribution of ϕ_o over the profile at F9 as determined in 1991/92 and 2002/03.

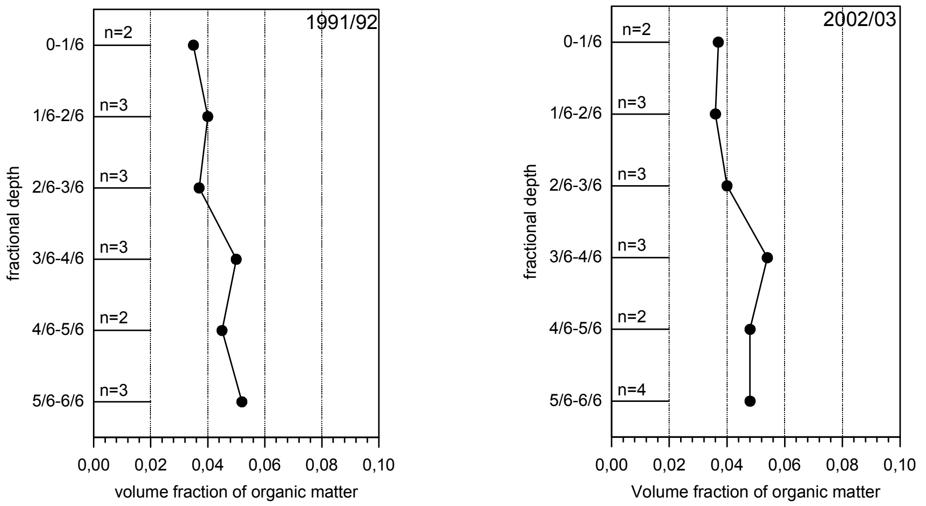

Figure 4.4. The volume fraction of organic matter and fractional depth for respectively 1991/92 and 2002/03 for peg F9 only; *n* is the number of measurements. The results are based on only 2 to 4 measurements at each fractional depth. Therefore confidence intervals are not shown.

Figure 4.5 shows a similar plot of average ϕ_o versus d_f of eleven sites in the subsided area. with 5% confidence intervals of the averages.

The confidence intervals in Figure 4.5 (and al others applied in this report) were calculated from (Snedecor and Cochran, 1989):

$$\bar{x} - t_{n-1;0.05}\frac{s}{\sqrt{n}} < \bar{x} < \bar{x} + t_{n-1;0.05}\frac{s}{\sqrt{n}} \qquad (4.8)$$

where

$\bar{x}$ = Arithmetic mean of x

$t_{n\text{-}1,0.95}$ = Student's two-tailed t-variate with n-1 degrees of freedom and a probability of 0.05 [-]

s = Estimated sample standard deviation of x

n = The number of data values within the class [-]

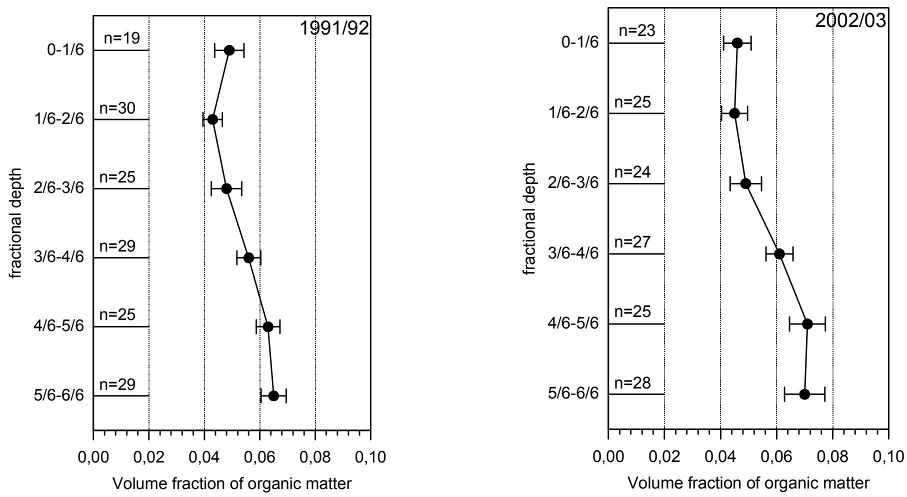

Figure 4.5. Profiles of mean volume fraction of organic matter with 5% confidence interval versus the fractional depth for 1991 and 2002 for the same measuring sites; *n* is the number of measurements.

It should be noted that equation (4.8) assumes x to be normally distributed, which is probably not the case for ϕ_o. However, (4.8) is assumed to give a reasonable indication.

Figure 4.5 shows a significant increase of ϕ_o in the deepest half of the profile from 1991/92 to 2002/03, whilst ϕ_o did not increase significantly at the 'reference' peg F9 (Figure 4.4). The effect becomes even more distinct if only the means of the five measuring sites with a subsidence >10% of the total peat depth of 1991 are included (Figure 4.6).

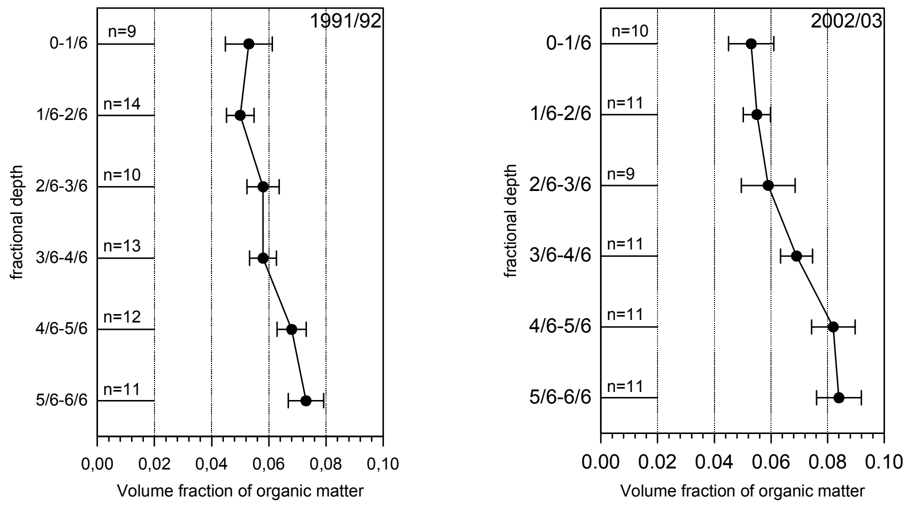

Figure 4.6 The volume fraction of organic matter with 5% confidence intervals versus fractional depth for respectively 1991/92 and 2002/03 for measuring sites with a subsidence of >10% of the peat depth since 1991 (d57, d59, d60, d62, d65, in Figure 4.3); *n* is the number of measurements.

The relationship between the increase in ϕ_o and subsidence is given in Eq. (4.6). Table 4.1 shows the result of this equation. The subsidence is in agreement with the increase of ϕ_o.

Table 4.1. Averages of the peat thickness and the volume fraction of organic matter in 1991/92 and 2002/03 (see also equation 4.6).

Sites d57, d59, d60, d62, d65	1991 ($_0$)	2002 ($_1$)
Average peat thickness D (m)	7,02	6,18
Average ϕ_o (-)	0,0599	0,0674
Number of measurements n (-)	69	63
5% confidence interval of ϕ_o (-)	±0,0028	±0,0041
$\phi_1/\ \phi_0$ (-)	1,125	
D_0/D_1 (-)	1,136	

4.4.2. Degree of humification versus fractional depth

Although the degree of humification was not included as an assessment parameter for the subsidence problem, an effort was undertaken to find, to what extent it might be useful. The parameter was the humification degree *H* as estimated using Von Post's 10-class scale (Von Post, 1922), specified in Appendix A. *H* was estimated in the field during sampling.

Humification is a slow process. Catotelm peat is expected to lose an average in the order of 0.01% of its mass each year (Clymo, 1992). This percentage decreases with increasing age of the peat. From this information, no substantial differences in humification values *H* can be expected between 1991/92 and 2002/03. The comparison between both periods might give information about the accuracy of *H*-estimates and the influence of compaction on the data.

Two graphs were plotted, one with the data of 1991/92 (figure 4.7, left hand graph) and one with those of 2002/03, all from the sites that were sampled in both periods (figure 4.7, right hand graph). The data have all been derived from measuring sites in the area of the new lake at 'B' (Figure 4.3). At the sites to the west of this lake, near the new lake at 'C', no samples were taken in 1991/92. Equation 4.8 was used to derive the confidence intervals. In the right hand graph of figure 4.7, no confidence interval could be given for the fractional depth of *H9*, for this degree was found only once.

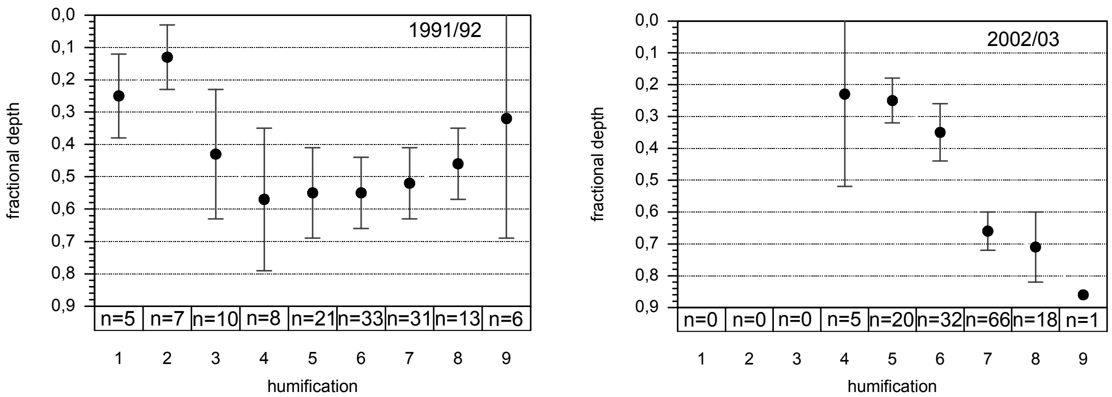

Figure 4.7 Degree of humification versus fractional depth, relative to the peat thickness in 1991 (left hand graph) and the peat thickness in 2002 (right hand graph), for measurements in 2002/03 and 1991/92 at the same measuring sites, 'n' is the number of measurements.

Figure 4.7 shows a rather different pattern in 2002/03 compared to 1991/92. *H1*, *H2* and *H3* were not found and the top of the graph of 2002/03 lies at higher degrees. Another difference is that *H7* was measured relatively often in 2002/03.

The measurements of 1991/92 and 2002/03 were not carried out on exact the same places and fractional depth. The large spatial variability of *H*-values may have caused some variation in results, but the large differences between both graphs suggest that it is more likely that the method, although originally intended for a reliable estimation in the field by relatively inexperienced workers (Von Post, 1922), is not as reproducible in practical situations as it was intended to be. Therefore conclusions drawn from differences in *H* should be interpreted with great care and should preferably be cross-checked using one or more different methods.

The picture for 2003/03 in Figure 4.7 looks more like what one would expect – a distinct increase of *H* with depth- than the one of 1991/92.

4.4.3. Degree of humification versus fractional depth; horizontal and vertical hydraulic conductivity

As mentioned, the horizontal hydraulic conductivity k_h probably does not differ substantially from the vertical hydraulic conductivity k_v at high *H*-values or, in other words, anisotropy resulting from horizontal layering of the peat, is likely to decrease with depth. This decrease also seems likely from results obtained by Van der Schaaf (1999), when the average downward seepage rate from the bog was estimated from k_h and vertical gradients of the piezometric head. However, such a decrease might also be related to the transition from bog peat to fen peat, because remnants of vertical roots in fen peat may create a relationship of k_v and k_h that differes from bog peat where such vertical roots are far less common.

Therefore, to estimate changes in k_v from ϕ_o, one must know in which part of the profile relatively high *H*-values occur to be able to apply Figure 2.3 on k_v. In general, the highest *H*-values can be expected in the oldest and thus in the deepest part of the profile. In figure 4.8 all 2002/03 estimated values of *H* versus d_f are shown for the whole profile (left hand graph) and for bog peat only (right hand graph).

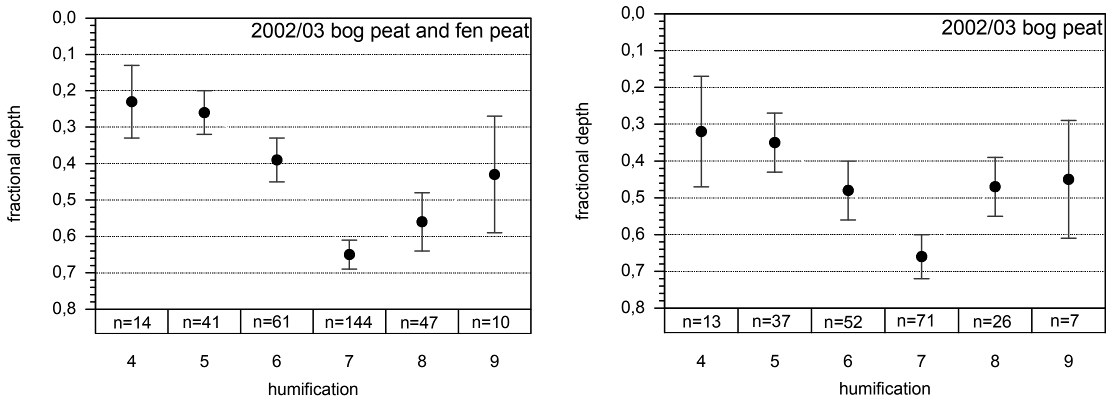

Figure 4.8. Degree of humification *H* versus fractional depth d_f; d_f relative to the full peat depth in the left hand graph and relative to bog peat depth only in the right hand graph. Averages and 5% confidence intervals calculated for all drillings of 2002/03. *n* is the number of measurements. The thickness of the fen peat layer on Clara Bog West is between 1/2-1/6 of the peat profile.

A downward peak was found at *H7* for bog peat as well as for the whole peat profile. *H6* to *H9* occurs in the deepest part of the whole profile and in bog peat only. *H7* was the most common degree of humification in the fen peat. Therefore the assumption that k_h and k_v do not differ substantially in the lowest part of the peat profile seems reasonable.

4.4.4. The vertical hydraulic gradient

Drainage in the cut-away beneath the peat base, in the relatively permeable till, may be assumed to have induced a decrease of the piezometric head in the mineral layers immediately below the peat. This will have increased the difference between the phreatic level and the piezometric head at the bottom of the peat profile and thus an increase of the average vertical hydraulic gradient. Subsidence tends to reduce the effect to some degree, because the phreatic level decreases as surface subsidence progresses.

An increase in vertical gradient over the peat profile was derived from still reliable tubes installed in 1991/92 at the sites d55, d59 and d63 (Figure 4.3). The hydraulic gradient was derived from 1991 measurements at a phreatic tube and a deep tube. In 2003 the same deep tubes were used to measure the deep hydraulic head, the phreatic level was measured outside the deep tube. Results are shown in Table 4.2.

Table 4.2 Peat thickness, subsidence and vertical hydraulic gradients. The data of the vertical hydraulic gradient (1990-1993) are based on 2 or 3 measurements each month. Data of the period 1990-1993 were derived from Van der Schaaf (1999). Site positions shown in Figure 4.3.

Sites	d55	d59	d63
Peat depth 1991 (m)	8.25	7.65	6.70
Subsidence 1991-2002 (m)	0.40	0.72	0.72
Average vertical hydraulic gradient Aug. 1990 - July 1991 ($m\ m^{-1}$)	0.041	0.102	0.320
Average vertical hydraulic gradient Aug. 1991 - July 1992 ($m\ m^{-1}$)	0.043	0.110	0.362
Average vertical hydraulic gradient Aug. 1992 - July 1993 ($m\ m^{-1}$)	0.044	0.121	0.388
Vertical hydraulic gradient on 10th and 12th April 2003 ($m\ m^{-1}$)	0.049	0.139	0.357

It must be taken into account that the measurements in April 2003 were carried out during an exceptionally dry period. The average vertical hydraulic gradient in 2003 is likely to be higher.

From table 4.2 it can be inferred that the vertical hydraulic gradient increased in the period 1991-2003 at sites d55 and d59, in spite of the subsidence. The subsidence has caused a decrease in phreatic level, but the deep hydraulic head has even decreased more. Even in the period 1990-1993 the vertical hydraulic gradients have increased. Thus, the lowering of the deep piezometric head at the bottom of the peat was already going on in the early 1990s. At site 63, near the bog margin, there is no clear difference with the early 1990's. This might indicate that a new equilibrium at this margin site –where the process may be expected to proceed faster than more inside the bog- has been reached.

4.4.5. Deep piezometric heads

Piezometric heads were measured along the line marked ‘A’ in Figure 4.3, approximately perpendicular to the pattern of subsidence. Figure 4.9 shows a decrease of the deep piezometric level towards the southern margin. The horizontal gradient of about 10 $m\ km^{-1}$ demonstrates the lowering effect of the drainage in the cutaway area on the piezometric head in the subsoil.

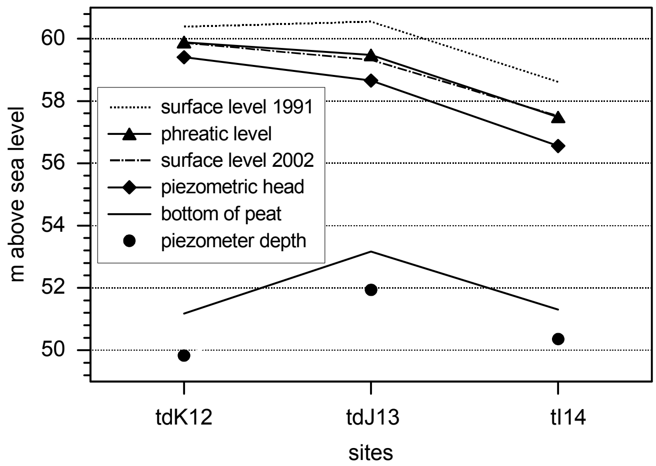

Figure 4.9. Phreatic levels and piezometric heads just below the peat on 14th April 2003. Site I14 lies at the bog margin. Distance between sites is 141 m. Site positions shown in Figure 4.3.

4.4.6. Influence of the mineral subsoil on subsidence

The thickness and k_v determine the vertical hydraulic resistance of the (anisotropic) lacustrine clay layer (C_c in Eq. 2.1). This hydraulic resistance may affect the change in piezometric head at the bottom of the peat that results from the decreased piezometric head in the till. Figure 4.10 shows the phreatic and deep hydraulic heads in the peat at the transects marked 'B' and 'C' in Figure 4.3.

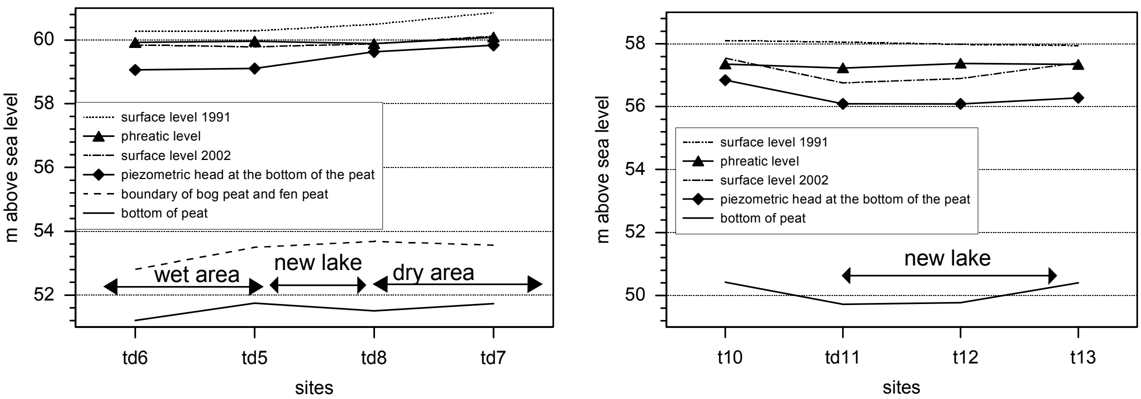

Figure 4.10. Deep and phreatic levels of the largest new lakes on 10th of March 2003. Left hand diagram: transect marked 'C' in figure 4.3. Right hand diagram: transect marked 'B' in figure 4.3.

The material immediately below the peat at sites td6, td5, td11 and t12 is gravelly and sandy clay (till) whilst the other sites in Figure 4.10 have a subsoil of rather stiff (lacustrine) clay. The piezometric heads at the bottom of the peat where the subsoil is sandy or gravelly, are lower than where it is more clayey. This shows that the effect of the deep drainage on the deep hydraulic head at the peat base is probably stronger where the hydraulic resistance of the subsoil is smaller. The spatial variability of the composition of the mineral subsoil seems to be substantial over rather short distances. The influence of the deep drainage on the peat profile may vary accordingly.

Figure 4.11 shows the level of the mineral subsoil or clay level. From this figure, it seems that the new lakes other than B (Figure 4.3), which lies just North of a ridge of unclear origin in the bog surface, could develop just to the north of elevations of the mineral subsoil. Where the lacustrine clay is thin or absent, depressions were able to form. From the available information, this is the most likely explanation of the development of the new lakes.

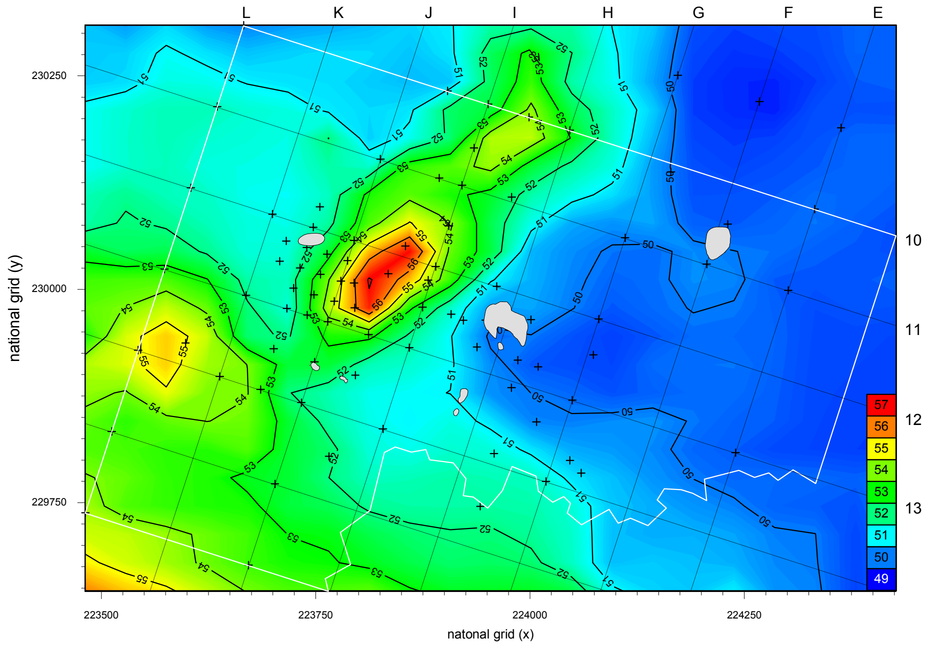

Figure 4.11. Level of the mineral subsoil, clay or till (m above sea level) and small lakes and pools in 2002 with local coordinates and coordinates of the national grid.

4.4.7. Spatial variability of the vertical hydraulic conductivity of peat

In chapter 2 it was stated that both k_h and k_v of the peat may vary substantially over short horizontal distances. Because no k-values have been measured during the field work of 2002-03, volume fractions of organic matter ϕ_o can be used as a replacing quantity in a comparison between neighbouring measuring sites. Sites td8 and td7 have had a larger subsidence in the period 1991-2002 than td5 and td6 (Figure 4.10). The measured hydraulic gradient across the peat profile at td5 and td6, sites with almost equal peat depths, exceeds the gradient at sites td8 and td7. According to Eq. (2.1), k_v of the latter two sites should exceed k_v of td5 and td6 to explain the subsidence at td8 and td7. k_h does not differ much from k_v at high H-values. Hence it can also be related to ϕ_o. Unfortunately, no ϕ_o have been measured here in 1991/92. In Table 4.3 values of ϕ_o measured in 2003 are shown for these four measuring sites.

Table 4.3. Averaged volume fraction of organic matter (ϕ_o) for measuring sites td6, td5, td8 and td7 (figure 4.3) for the deepest part, in fractional depth (d_f), of the peat profile, where most of the compaction has occurred. The data are based on 2 or 3 measurements at each interval of fraction depth.

d_f	td6 (ϕ_o)	td5 (ϕ_o)	td8 (ϕ_o)	td7 (ϕ_o)
3/6-4/6	0,045	0,053	0,041	0,038
4/6-5/6	0,047	0,053	0,050	0,052
5/6-6/6	0,068	0,073	0,060	0,059

The values of ϕ_o at td6 and td5 exceed those at td8 and td7. Figure 2.3 suggests that k_h and probably also k_v in td8 and td7 must be larger than in td6 and td5. This might explain the relatively large subsidence at td8 at td7, with a relatively low hydraulic gradient over the peat profile, but the available data do not permit a hard conclusion.

4.4.8. Surface slopes and flow pattern

Subsidence changes the flow pattern due to changing surface slopes. The mineral subsoil has an influence on the subsidence pattern of a bog.

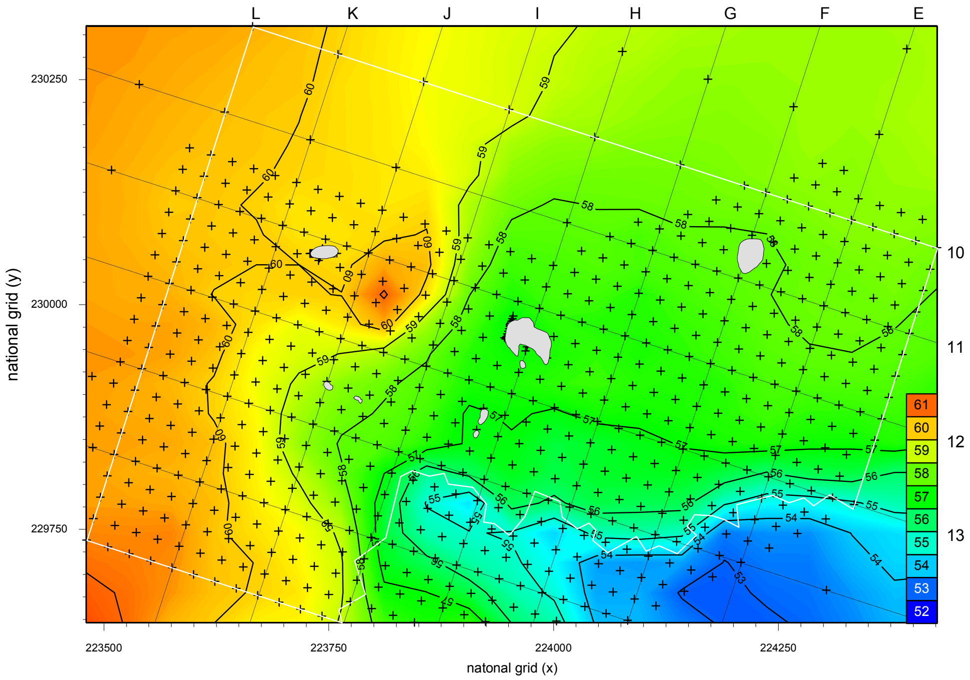

Figure 4.12 Surface levels in 2002 of Clara Bog West in detail (m above sea level), lakes and waterlogged sites in 2002, with local coordinates and coordinates of national grid.

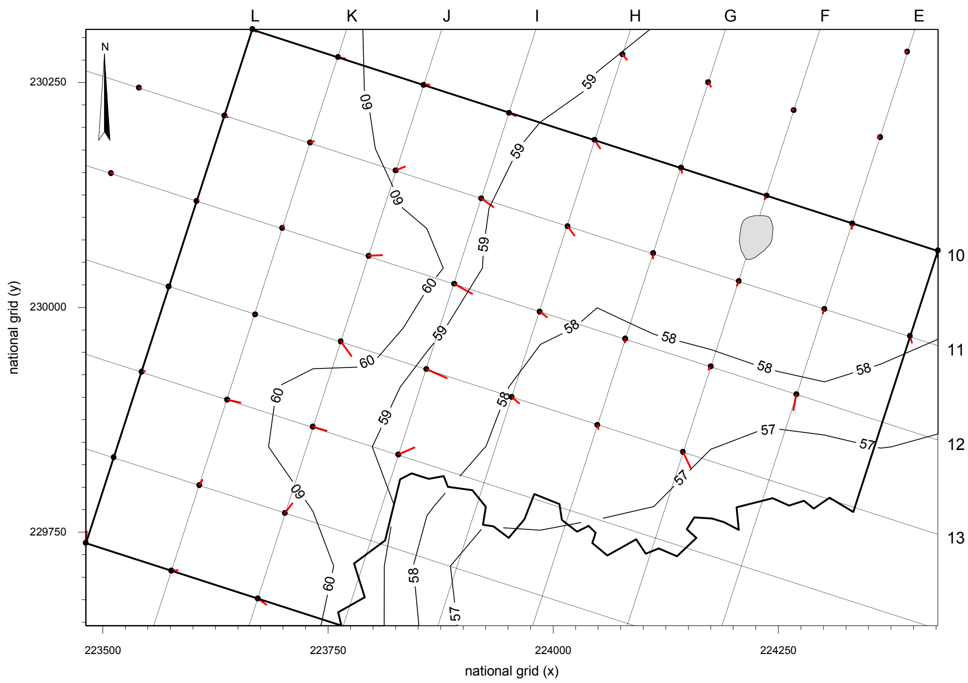

Figure 4.13. Surface slopes, slope directions and surface level contours in m above sea level, based on data of the local 100*100 m grid levelled in 1991. The red lines at the grid points show the slopes and their direction. The length of the lines indicates steepness, the direction of the line the slope direction, with the grid point at the upslope end. National and local grid coordinates are shown on the axes.

Especially the shape of the mineral mound (centre of Figure 4.11, square of local coordinates I12-J13), has influenced the bog surface and with it the flow pattern on the bog (Figure 4.12). In Figure 4.13 and 4.14 the surface contour lines and the slopes and their direction are shown for both 2002 and 1991.

The surface slope directions in the area of subsidence have changed substantially in only a few places during 1991-2002, such as the local coordinate points J12, G12 and F12. However, the slopes have generally become steeper. Surface contour lines have moved to the

West and Northwest (compare Figure 4.13 and Figure 4.14). These changes have affected the flow pattern. The change in slopes and the disappearance of the regulating effect of the acrotelm at dried-out areas have almost certainly decreased the residence time of the water in the surface layer of the bog.

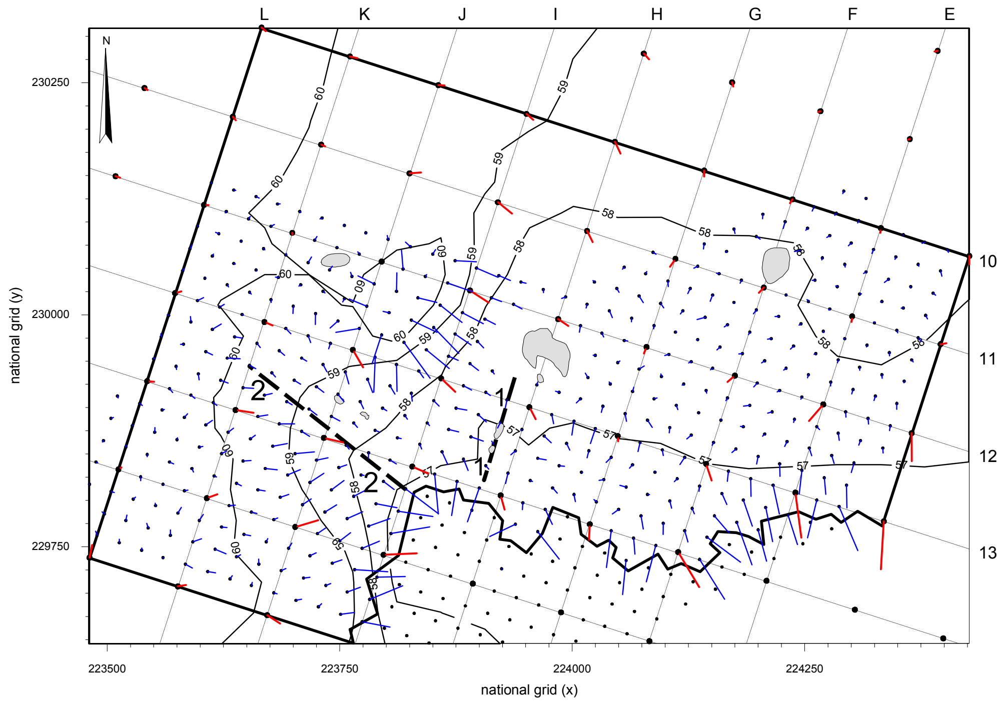

Figure 4.14. Surface slopes, slope directions and surface level contours in m above sea level, based on data of the local 25*25 m grid levelled in 2002. The red lines at the grid points show the slopes and their direction. The length of the lines indicates steepness, the direction of the line the slope direction, with the grid point at the upslope end. National and local grid coordinates are shown on the axes.

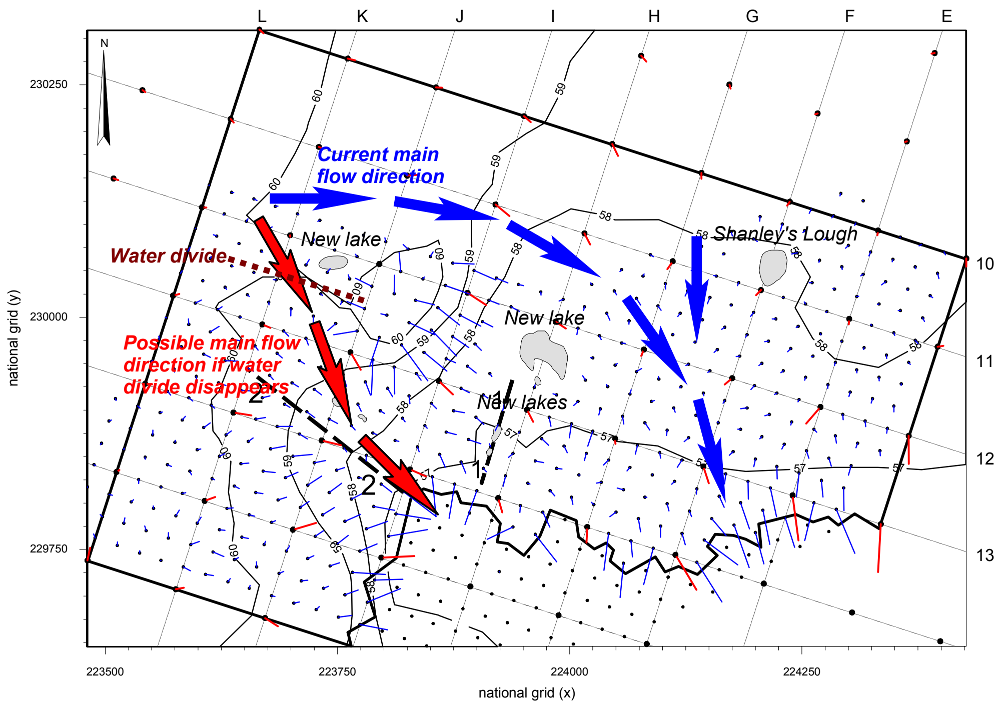

Figure 4.15. Current main flow direction (blue) and possible flow direction (red) if water divide (brown) disappears.

In 2002, the 60 m surface level contour line almost encircled the part of the bog overlying the mineral mound (Figure 4.14). A small water divide has developed to the south of the smallest new lake (at ‘C’ in figure 4.3 and marked in Figure 4.15) in the western part of the bog. Water from the Northwest of this lake still flows more northwards around the elevation in the bog surface level.

The development of the small lake may be attributed to this water divide. The phreatic level to the south of it has been lowered by the cessation of local inflow of water from the Northwest. This probably has decreased the vertical hydraulic gradient over the peat profile at td8 and td7 (Figure 4.10).

If this water divide disappears, it may cause a considerable part of the existing flow system around the northern slope of the mineral mound to be short-circuited towards the cut-away in the south, which will not be without consequence to the soak system of Shanley's Lough (Figure 4.15).

Unequal subsidence has caused a small V-shaped ‘valley’ perpendicular to the edge in which water prefers to flow towards the edge (near line ‘1’ in Figure 4.14). In such depressions an acrotelm mainly consisting of loose *Sphagnum* species, such as *Sphagnum cuspidatum*, occurs, whilst at higher parts the acrotelm is mostly absent.

Line ‘2’ represents an almost straight line of vegetation with birch, *Calluna vulgaris* and *Scirpus caespitosus,* indicating disturbance (‘richer’ water conditions or lower water levels). Some holes of 2 m in depth and with an area around 2 m^2 in the peat can be found along this line. At the bottom of these holes, sometimes referred to as ‘swallow holes’, one can see and hear the flow of water. The straight line may suggest a human induced origin. This watercourse probably contributes to a relatively easy outflow of water from the western soak in times of high water levels.

4.4.9. Ecological consequences

Subsidence changes the surface slopes and thus the flow patterns in the acrotelm. This will lead to lower water levels, a faster runoff and thus a deterioration of the conditions for sustaining and/or development of the acrotelm. The destruction of the acrotelm by the bog fire of some years ago has caused a further deterioration. Where the acrotelm has been destroyed, its the regulating effect on runoff has disappeared. This may eventually lead to additional subsidence as a result of compaction of the upper part of the peat (Van der Schaaf, 2000).

Where water levels are lowered and/or the acrotelm has disappeared, the water table fluctuation may be expected to increase due to the effects mentioned and to a decreased storage coefficient. This, in turn, affects the ecology of the bog. Lower water levels are likely to stimulate processes of oxidation and mineralisation. This may stimulate the growth of species such as *Calluna vulgaris*, *Scirpus caespitosus*, birch and other species, typical for disturbed bog conditions, and probably make a recovery of the acrotelm a very slow process.

The two rheotrophic soak systems depend on long flow paths and small local slopes. The current subsidence process on Clara West has already disturbed this situation to some extent, mainly as a result of increasing surface slopes. A continuing subsidence process could eventually lead to the disappearance of the subtle water divides (such as the one at grid points L12, K12, L13 and K13), which now maintain the newly formed small lakes. Whether these newly formed patterns are permanent phenomena is uncertain. If the newly formed water divides disappear, the western soak will eventually suffer from increased drainage and the flow that feeds the system of Shanley's Lough will partly be drained towards the southern bog margin. This would mean an even more serious danger to the rheotrophic soak features that make Clara Bog West such a highly interesting system.

4.5. Discussion and conclusions

In the area with the most severe subsidence, ϕ_o has increased mainly in the deepest part of the profile. Because it is known since a long time that internal superficial drainage in a bog causes shrinkage in the upper layers of the peat rather than in the lower parts (Uhden, 1960; Eggelsmann 1990a, 1990b), this is hard evidence that the related loss of water is caused by a change in piezometric head in the till underlying the peat. Such a change can only have been induced by a substantial lowering of the groundwater table or piezometric head in the near surroundings of the bog. In the last fifteen years, such a lowering has only occurred in the southern cut-away zone. Hence, this must have caused the subsidence. This conclusion is supported by the subsidence pattern, which shows an increasing subsidence towards the southern margin.

The horizontal and vertical hydraulic conductivity values k_h and k_v in the deepest part of the profiles can be quantitatively related to the volumetric fraction of solid matter ϕ_o (Figure 2.3 and section 4.4.7). From the increase of ϕ_o over the last decade it may be concluded that both hydraulic conductivity values have decreased considerably in the deepest part of the profile in the subsidence area in the south and will continue to do so as shrinkage of the lower peat continues. However, this process may slow down the water loss from the deeper peat and possibly eventually cause a new equilibrium with the piezometric head in the till. Hence this process may eventually imply self-sealing of the catotelm.

Piezometric heads at the bottom of the catotelm have decreased and thus caused an increase of the average vertical hydraulic gradient over the peat profile during the last decade as a result of deep drainage at the southern edge in the cut-away sections. This supports the first conclusion that the subsidence has been caused by lowered piezometric heads below the peat. The subsidence process was already going on in the early 1990's when turf cutting activities had intensified. The deepening of the open drains into the mineral subsoil in 1995/96 has probably contributed to these effects. The pattern of subsidence, with increasing values towards the southern margin mentioned in the first paragraph of this section, is yet another piece of evidence of the effect of this deep drainage on the bog surface levels.

Another, yet unproven process may be that the small valley along line '2' in Figure 4.14 may eventually extend westwards, thus draining the western soak or a part of it. The flow direction at the corresponding grid points already suggests such a development.

Within the general trend of increasing effects of the deep drainage in the cut-away on the deep piezometric head below the peat and the increasing subsidence towards the southern bog margin, difference in subsidence in subsidence over short distances occur. This may often be attributed to differences in hydraulic resistance of either the peat, the underlying (lacustrine) clay or its local absence, or all of the above. Such differences over relatively short distances have resulted in the forming of some new bog lakes, pools and local wet spots, even though the overall picture is one of drying rather than (re)wetting.

The slopes of the peat surface and its direction have changed in the area of subsidence during the period 1991-2002. Existing surface contour lines have moved to the west and northwest. This has caused an increase in the average surface slope, a decrease of the residence time of water in the acrotelm, affected the flow pattern and the discharge behaviour on Clara Bog West. This change may eventually cause flows from the western soak and the area to the north of it to be partially diverted to the southern bog margin, thus causing considerable ecological damage to both systems.

5. ACROTELM SURVEY RAHEENMORE BOG AND CLARA BOG EAST

5.1. Introduction

In this chapter the acrotelm transmissivity and thickness of Raheenmore Bog and the transmissivity of Clara Bog East are discussed.

The flow rate in an acrotelm is determined by its transmissivity T_a [L^2T^{-1}] and the surface slope [-]. Water does not only flow through the acrotelm, but the outflow through the catotelm in raised bogs is usually a negligible fraction of the total lateral outflow (Van der Schaaf, 1999).

It is possible to derive a potential T_a (Van der Schaaf, 1999). This T_a would theoretically occur when the acrotelm on a bog is in good health.

In 1991/92 transmissivity measurements were done on Raheenmore Bog and Clara Bog. The results showed that conditions were considerably below the potential situation. The difference was attributed to internal drainage and peat cutting along the margins. Drains have been blocked since. New transmissivity measurements were done in 2002/03 to quantify whether there is a positive development of the acrotelm on both Raheenmore Bog and Clara Bog East.

In section 5.2 the concept of potential transmissivity and the transmissivity measurements will be explained, in 5.3 and 5.4 the results of these transmissivity measurements are described for Raheenmore Bog and Clara Bog East respectively.

Conditions for peat forming processes are not only likely to be reflected in acrotelm transmissivity, but also in acrotelm depth (Van der Schaaf, 1999). As mentioned in the first chapter, investigating the acrotelm thickness and its spatial variability of Raheenmore Bog is expected to yield information about the health of the bog and the drainage pattern. Section 5.5 deals with the acrotelm thickness of Raheenmore Bog.

5.2. Potential transmissivity and transmissivity measurements

5.2.1. Theory of the potential acrotelm transmissivity

The acrotelm transmissivity can be written as a function of surface slope and flow pattern (Ivanov, 1965, 1975, 1981). It is based on the assumption that the acrotelm regulates itself, i.e. the production and decay of fresh organic material control the growth of the acrotelm.

For a flow path between two streamlines (Fig. 5.1) on a bog a steady state equation can be derived that describes the flux at the downstream end of the flow path:

$$\overline{Q}_{aL} = \overline{Q}_{a0} + \int_0^L \overline{U}_v w(s) ds \tag{5.1}$$

where

$\overline{Q}_{aL}$	=	long term mean of the flux at the downstream end of the flow path [L^3T^{-1}]
$\overline{Q}_{a0}$	=	long term mean of the flux at the upstream end of the flow path [L^3T^{-1}]
$\overline{U}_v$	=	long term mean of the net supply rate to the acrotelm [LT^{-1}]
w	=	width of the path at the cross section [L]
s	=	distance along the middle of the path [L]
L	=	flow path length [L]

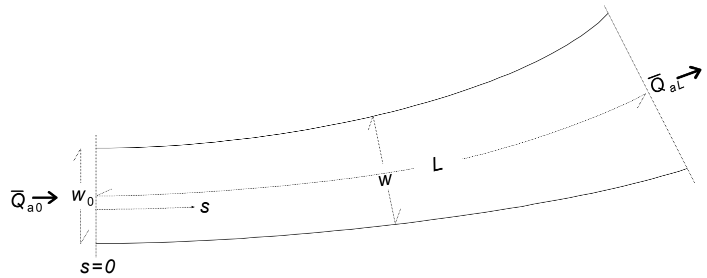

Figure 5.1. Flow path between two streamlines.

An implicit assumption is that $\overline{U}_v$ is independent of s, which is probably reasonable in relatively small areas such as Raheenmore and Clara Bog. For a position where $s = L$, after substituting $\overline{Q}_{aL} \approx -\overline{T}_a w_L \frac{dh}{ds}$ (Darcy's law), expressing $\overline{Q_{a0}}$ in flux q per width using $\overline{Q}_{a0} = w_0 \overline{q}_{a0}$, Eq. 5.1 yields:

$$\overline{T}_a = \frac{w_0 \overline{q}_{a0} + \int_0^L \overline{U}_v w(s)\,\mathrm{d}s}{w_L \frac{\mathrm{d}h}{\mathrm{d}s}} \quad (5.2)$$

where

$\overline{T}_a$	=	long term mean of acrotelm transmissivity [L^2T^{-1}]
w_0	=	width of the flow path at its upstream end [L]
w_L	=	width of the flow path where $s = L$ [L]
h	=	phreatic level [L]
$\overline{q}_{a0}$	=	long term mean of the flux per width, perpendicular to the flow direction [L^2T^{-1}]

Because $\overline{T}_a$ may be considered constant over time intervals of one or a few years if no major changes in the water regime occur (Van der Schaaf, 1999), T_a may replace $\overline{T}_a$. If the size of the upstream area A_u and the width w of the flow path at the point of T_a-measurement are known, $v_a = \frac{1}{A_u}\int_0^L \overline{U}_v w(s) ds$. If the flow path begins at the water divide where $\overline{q}_0 = 0$ and if $\frac{\mathrm{d}h}{\mathrm{d}s}$ is replaced by the surface slope I, the equation reduces to:

$$T_a = \frac{A_u v_a}{Iw} \quad (5.3)$$

where

A_u	=	size of the upstream area [L^2]
v_a	=	specific discharge [LT^{-1}]

However, it can be difficult to estimate the flow path areas and the width of a flow path is not necessarily 100 m. Therefore a different approach was used as well; using flow path lenght instead of flow path area.

When a flow path area is considered as a rectangle or a triangle, A can be substituted according to $A = wL$ or $A = \frac{wL}{2}$, respectively.

Then Eq. (5.3) becomes:

$$T_a = \frac{vL}{I} \tag{5.4}$$

if the flow path area is rectangular in shape (the stream lines are parallel to each other) and

$$T_a = \frac{vL}{2I} \tag{5.5}$$

if the flow path area is triangular-shaped (the streamlines are radially divergent). The flow path length approach does not work in case the streamlines are convergent; in that case the flow path area method must be applied.

5.2.2. Transmissivity measurements: The semi-steady state method

The semi-steady state method is based on the drawdown of the water level in a well (Figure 5.2). During the test water was pumped out using a pump with a capacity of 1-10 l/min until the drawdown did not change visibly during 15 to 60 s.

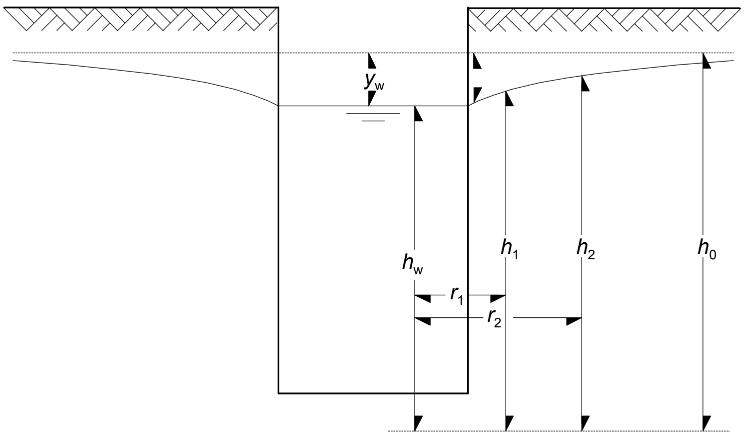

Figure 5.2. Acrotelm transmissivity test (schematised) (Van der Schaaf, 1999).

To calculate the transmissivity of the acrotelm, Van der Schaaf (1999) modified the Thiem equation

$$T_a = \frac{Q \ln n_w}{2\pi y_w} \tag{5.6}$$

where

T_a = acrotelm transmissivity [L^2T^{-1}]

Q = well discharge [L^3T^{-1}]

n_w = ratio between the radius of the depression cone r [L] and the effective radius of the well r_w [L]; ($\frac{r}{r_w}$) [-]

y_w = drawdown in the well caused by pumping [L]

Van der Schaaf (1999) gives some conditions at which Eq. 5.6 holds approximately:

1) The extent of the aquifer is much larger than the distance to which the phreatic level is noticeably affected by the drawdown in the well;
2) The aquifer is homogenous in the horizontal direction over the area in which the phreatic level is noticeably influenced by the drawdown in the well;
3) The phreatic level is approximately horizontal immediately before the test;
4) The discharge rate is constant;
5) The well fully penetrates the aquifer;
6) The flow is horizontal;
7) The saturated depth of the acrotelm aquifer is constant over the area in which the phreatic level is noticeably affected by the drawdown in the well.

Conditions 1, 3, 4 and 5 are normally satisfied. Condition 2 is mostly satisfied if the site is properly chosen. Conditions 6 and 7 are satisfied reasonably well if the drawdown in the well is kept small, preferably less than 5 % of the acrotelm depth (Van der Schaaf, 1999).

Because the horizontal cross-section of the pits was approximately square, an effective radius had to be found. It can be approximated from either the radius of a circle with the same area, which gives an underestimation, or one with the same circumference, which gives an overestimation. Averaging the two yields:

$$r_w \approx \frac{\frac{L}{\sqrt{\pi}} + \frac{2L}{\pi}}{2} \approx 0.6L \qquad (5.7)$$

where

r_w = radius of a well [L]

L = length of a side of the pit [L]

n_w can be calculated from:

$$t = \frac{\pi r_w^2 y_w}{Q}\left(1 + \frac{\mu\left(n_w^2 - 2\ln n_w - 1\right)}{2\ln n_w}\right) \qquad (5.8)$$

where

t = pumping time [T]

μ = storage coefficient [-]

The value of n_w is not found directly. However Eq. (5.8) can be solved by iteration:

1) estimate a value of n_w;
2) calculate the estimated pumping time t_{est} using Eq. 5.8.;
3) multiply the estimated value of n_w by $\frac{t_{real}}{t_{est}}$, where t_{real} is the real pumping time;
4) repeat step 2 and 3 until the difference between t_{est} and t_{real} has become sufficiently small.

5.2.3. Transmissivity measurements: The pit bailing method

The pit bailing method is based on the speed of recovery after lowering of the water level in a pit with the bottom below the phreatic level (Van der Schaaf, 1999). At the beginning of the measurement, water is removed from the pit. The rise of the water level in time is then recorded. The basic equation, which is also based on the Thiem equation, reads

$$k_{eff} = \frac{r_w^2 \ln n_w}{\left(h_0^2 - h_w^2\right)} \frac{\mathrm{d}h}{\mathrm{d}t} \tag{5.9}$$

where

k_{eff} = hydraulic conductivity [LT^{-1}]

h_0 = water level before water removal [L]

h_w = water level in the pit during the test [L]

In order to get comparable results with the piezometer method (described in section 5.2.4), the distance of the bottom of a pit to an underlying impervious layer should not be large compared to the pit diameter. In properly dug acrotelm pits this condition is always met, because the acrotelm is fully penetrated.

The depth D_a of the acrotelm can be approximated by

$$D_a \approx \frac{h_0 + h_w}{2} \tag{5.10}$$

if h_0 and h_w are taken relative to the level of the acrotelm bottom. Because $T_a=k_{eff}D_a$ and $y_w=h_0-h_w$, Eq. 5.9 can be reduced to

$$T_a = -\frac{r_w^2 \ln n_w}{2 y_w} \frac{\mathrm{d}y}{\mathrm{d}t} \tag{5.11}$$

If the test is done as a recovery after the semi-steady state test, the initial value of n_w is known from the latter. However, as the water level in the pit recovers, the depression cone expands laterally. Assuming a constant total emptied storage volume in the cone and the emptied part of the pit, n_w becomes a function of the discharged volume V [L^3], drawdown in the pumped pit y_w, r_w and μ. With Eq. 5.8 the equation yields:

$$V = \pi r_w^2 y_w \left(1 + \frac{\mu\left(n_w^2 - 2\ln n_w - 1\right)}{2\ln n_w}\right) \tag{5.12}$$

The transmissivity T_a can now be calculated over different time intervals during the recovery. The eventual value is then found by calculating the arithmetic mean of the results for individual time intervals.

In situations in which the transmissivity is too low to apply the semi-steady state test, the pit-bailing method is the only option. In those cases the semi-steady state method was applied to obtain n_w from the removed volume of water, but the semi-steady state method itself was not used to calculate transmissivity in such cases.

5.2.4. Transmissivity measurements: The piezometer method

The piezometer method was described by Kirkham (1945) and Luthin and Kirkham (1949). Normally it employs a cavity at the lower end of the tube as a filter. The hydraulic conductivity k of the surrounding soil is calculated from the speed of recovery of the water level in a piezometer after water has been removed (rising head variant). The equation is

$$k = \frac{\pi r_p^2}{A_p\left(t_{i+1} - t_i\right)} \ln \frac{y_i}{y_{i+1}} \tag{5.13}$$

where

k = hydraulic conductivity [LT^{-1}]

r_p = inner radius of the piezometer tube [L]

A_p = shape factor [L]

y_i = difference between the level in the tube at equilibrium and at the time t_i after the beginning of the test [L]

y_{i+1} = difference between the level in the tube at equilibrium and at the time t_{i+1} after the beginning of the test [L]

t_i = see y_i [T]

t_{i+1} = see y_{i+1} [T]

A_p is a function of the wetted length L_w of the piezometer, cavity length L_c , the cavity radius r_c and the vertical distance d_{imp} to an impervious layer below the cavity. Eq. (5.13) implies that the change of $\ln(y_i/y_{i+1})$ with time is constant, because k is assumed to be constant during the test. However, in peat soils this condition is often not met (Van der Schaaf, 1999). Hence Eq. 5.13 should be written as

$$k(t) = \frac{\pi r_p^2}{A_p} \frac{\mathrm{d}}{\mathrm{d}t} \ln \frac{y_0}{y(t)} \qquad (5.14)$$

where

$k(t)$ = apparent hydraulic conductivity at time lap t after the test was started [LT^{-1}]

y_0 = the value of y at t=0 [L]

$y(t)$ = the value of y at t>0 [L]

To use the piezometer method in calculating acrotelm transmissivities, Eq. 5.14 needs two modifications (Van der Schaaf, 1999):

1) The shape factor A_p has to be adjusted for the acrotelm pits that extend upwards to the phreatic level;
2) The piezometer method calculates the effective saturated hydraulic conductivity k_a over the saturated depth of the acrotelm instead of T_a. The obtained value of k_a must be multiplied by the acrotelm depth below the phreatic level in order to obtain an acrotelm transmissivity T_a; $T_a \approx k_a L_w$.

Although the piezometer method has an approximate 1:1 relationship with the pit bailing method when T_a is in the order of magnitude of 1 m^{2}d^{-1}, the method is likely to underestimate large T_a and overestimate small T_a (Van der Schaaf, 1999). Hence the piezometer method was only applied if the value of T_a was in the order of magnitude of 1 m^{2}d^{-1}.

5.2.5. Measurements

On Raheenmore Bog, a number of grid points were selected for acrotelm transmissivity measurements. In the 1991-measurement series the L- and the 6-transect were used (Figure 5.3). For reasons of comparability the same transects were taken.

On Clara Bog the measurements were done on cluster Aa, Ab, Bb, Bc, Cb and Cc (Figure 5.4) for the same reasons.

Two approximately rectangular pits were cut at every measuring site, *i.e.* one in a hollow and one in a hummock. In some cases it was not possible to find a hollow where the pit would not flow over; those sites only have a hummock pit. It was made sure that the pit depths exceeded the acrotelm depth. The sides of a pit were between 15 and 25 cm.

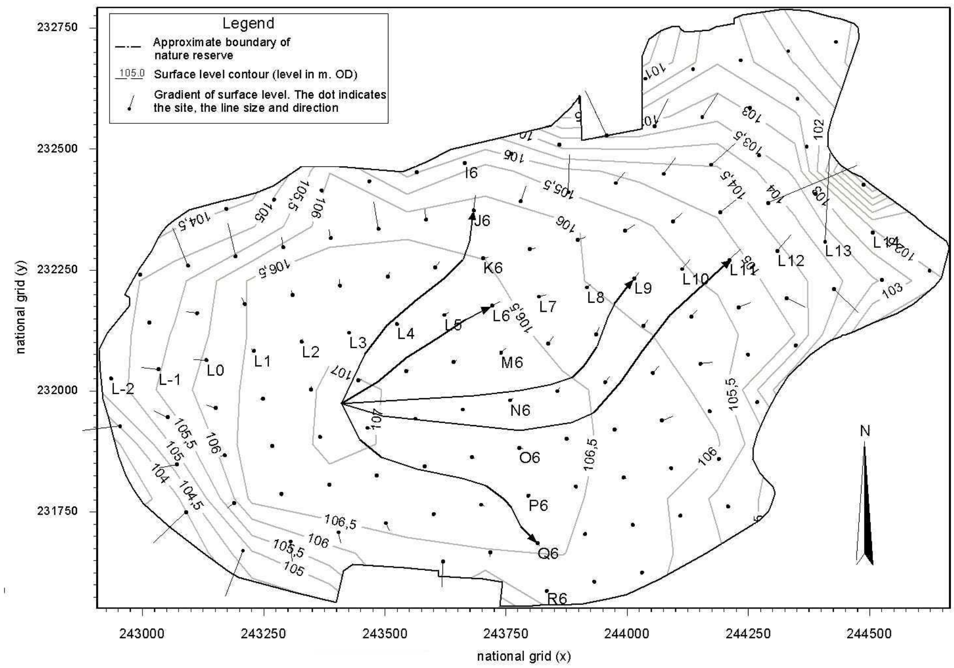

Figure 5.3. Contour lines, slopes and a number of schematised flow paths for Raheenmore Bog in 2002/03, with national grid coordinates.

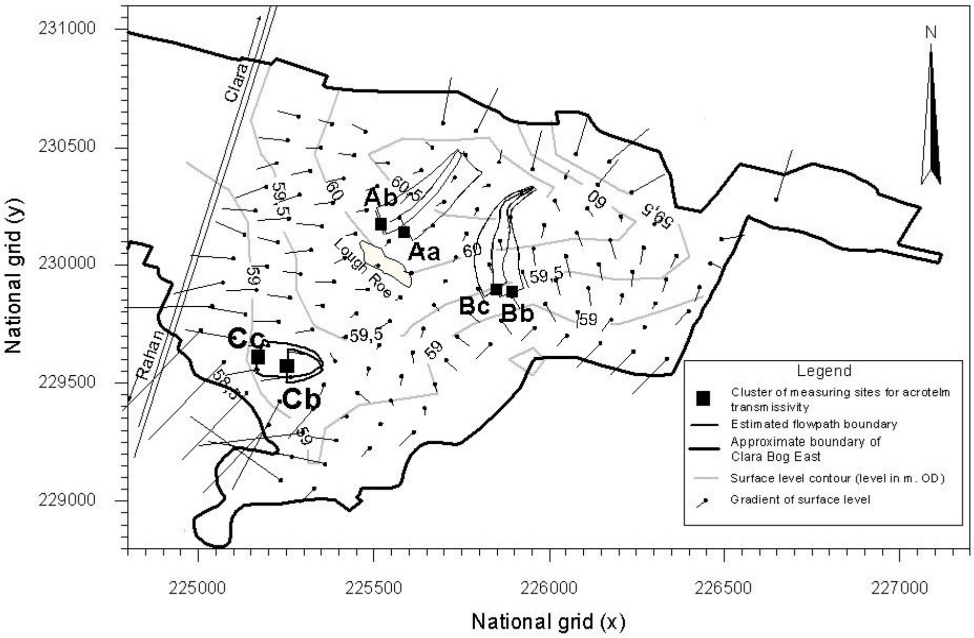

Figure 5.4 Contour lines, slopes and the schematised flow path areas for Clara Bog East in 2002/03, with the coordinates of the national grid.

During each measurement a 12 V battery powered centrifuge type pump (capacity 1-10 l/min) was used to remove water from the pit. Water was pumped out until the drawdown did not change visibly during 15 to 60 s. Then the pump was switched off and a recovery measurement was done.

A splatter screen folded to a sort of sieve around the pump was used to prevent coarse particles from disturbing pump discharge. Sometimes, however, the screen was not effective, which disturbed the measurement. Such measurements were discarded. On Clara Bog, pits did not always contain enough water to do a transmissivity test, because the series of tests there was performed during a relatively dry part of the winter of 2003.

All three methods described in 5.2.2 were applied where appropriate.

During a measurement the peat matrix may change its geometry. This can happen during both the pump test and the recovery. A deformed matrix yields lower transmissivities. Therefore the largest result of the applied methods was selected as it was assumed that this value would give a transmissivity closest to the one of the undeformed peat matrix.

With the potential and measured transmissivities a ratio $T_{a\ potential}/T_{a\ measured}$ can be calculated of each measuring spot. The ratio gives an indication of the condition of the bog. A bog with a healthy acrotelm will yield ratios around 1; a disturbed bog will give much higher values.

5.3. Results of the transmissivity measurements on Raheenmore Bog

5.3.1. Potential and measured transmissivity

To calculate potential transmissivity, the flow path area, the flow path length, the slope and the specific discharge are needed. In Table 5.1 the slopes for 1991/92 and 2002/03 are given.

No surface slope was known for L-1 for 2002/03, so when calculating the potential transmissivity in 2002/03, the slope value of 1991/92 was used. An estimation of flow path lengths and areas yielded equal values for 1991/92 and 2002/03 (Table 5.1).

Table 5.1. Surface slope, flow path area and length in 1991/92 and 2002/03 per measuring site for a flow path width at the site of 100 m.

Measuring site	Surface slope [-] 1991/92	2002/03	Flow path area [ha]	Flow path length [m]
L-1	0,0093	-	2,5	310
L0	0,0081	0,0072	2,3	200
L1	0,0058	0,0052	1,3	144
L2	0,0018	0,0014	0,7	133
L3	0,0031	0,0014	0,8	244
L4	0,0016	0,0008	1	267
L5	0,0012	0,0008	1	378
L6	0,0027	0,0023	2	456
L7	0,0043	0,0043	3	544
L8	0,0026	0,0031	4,5	656
L9	0,002	0,0021	6	800
L10	0,0032	0,0031	6	944
L11	0,0046	0,0054	6	1089
L12	0,0067	0,0067	7	678
L13	0,0089	0,0089	6	744
J6	0,0043	0,0045	2,5	544
K6	0,0039	0,0033	2	544
M6	0,0019	0,0016	2	456
N6	0,0013	0,001	2	456
O6	0,0008	0,0013	1,5	500
P6	0,0009	0,0016	2	567
Q6	0,0025	0,002	3	478

The specific discharge for the measuring dates is given in Appendix B. Data from 1991/92 were obtained from Van ‘t Hullenaar and Ten Kate (1991), Sijtsma and Veldhuizen (1992) and Van der Schaaf (1999).

In the 1991/92 data series no difference was made between hummocks and hollows. In 2002/03 measurements were done in both hummocks and hollows. To compare 2002/03 with 1991/92, the hummock and hollow data of each site were averaged. Later in this section this will be justified.

The measured transmissivity, the potential transmissivity and ratios $T_{potential}/T_{measured}$ of Raheenmore Bog are given in Table 5.2. Pegs I6, R6, L-2 and L14 are not listed, because it was not possible to measure a transmissivity with the methods described in section 5.2 as the phreatic levels in the pits were mostly in the catotelm.

Table 5.2. Measured transmissivity data, potential transmissivities and ratios between $T_{a\ potential}$ and $T_{a\ measured}$ for Raheenmore Bog in 1991/92 and 2002/03. Data are organised per grid point. The transmissivity values are composed of n data.

	1991/92						2002/03					
	Ta measured	n	Ta potential, based on flowpath area	**Ratio of Ta potential/ Ta measured**	Ta potential, based on flow path length	**Ratio of Ta potential/ Ta measured**	Ta measured	n	Ta potential, based on flowpath area	**Ratio of Ta potential/ Ta measured**	Ta potential, based on flow path length	**Ratio of Ta potential/ Ta measured**
Measuring site	[m^2/d]		[m^2/d]	**[-]**	[m^2/d]	**[-]**	[m^2/d]		[m^2/d]	**[-]**	[m^2/d]	**[-]**
L-1	21	3	57	**2,7**	36	**1,7**	33	10	29	**0,9**	18	**0,5**
L0	3,3	3	61	**18**	26	**7,9**	22	10	34	**1,5**	15	**0,7**
L1	4,4	3	48	**11**	26	**5,9**	327	10	27	**0,1**	15	**0,05**
L2	75	3	83	**1,1**	79	**1,1**	106	10	53	**0,5**	51	**0,5**
L3	133	3	55	**0,4**	84	**0,6**	8,9	10	61	**6,9**	93	**10**
L4	7,6	4	119	**16**	159	**21**	7,2	10	123	**17**	165	**23**
L5	277	4	158	**0,6**	299	**1,1**	90	10	125	**1,4**	236	**2,6**
L6	40	4	141	**3,5**	160	**4,0**	125	10	102	**0,8**	116	**0,9**
L7	5,2	4	133	**26**	120	**23**	73	10	81	**1,1**	74	**1,0**
L8	92	4	329	**3,6**	240	**2,6**	101	10	170	**1,7**	124	**1,2**
L9	980	4	570	**0,6**	380	**0,4**	2965	10	307	**0,1**	205	**0,1**
L10	59	1	281	**4,8**	221	**3,7**	96	10	226	**2,4**	178	**1,9**
L11	89	4	248	**2,8**	225	**2,5**	131	10	130	**1,0**	118	**0,9**
L12	61	3	171	**2,8**	83	**1,4**	172	10	122	**0,7**	59	**0,3**
L13	77,9	2	125	**1,6**	77	**1,0**	33	10	79	**2,4**	49	**1,5**
J6	12,3	3	124	**10**	135	**11**	50	10	56	**1,1**	61	**1,2**
K6	25	3	109	**4,4**	149	**6,0**	16	10	61	**3,8**	83	**5,2**
M6	133	3	225	**1,7**	256	**1,9**	32	10	114	**3,6**	129	**4,0**
N6	59	3	328	**5,6**	374	**6,3**	65	10	182	**2,8**	207	**3,2**
O6	131	3	400	**3,1**	667	**5,1**	39	10	105	**2,7**	175	**4,5**
P6	73	3	484	**6,6**	687	**9,4**	188	10	114	**0,6**	161	**0,9**
Q6	171	3	256	**1,5**	204	**1,2**	49	10	137	**2,8**	109	**2,2**

The transmissivity at each peg, measured on a number of days, was averaged in order to reduce the number of data. The complete data set is given in Appendices B and C. Appendix B gives the transmissivity data set of 2002/03 and Appendix C the one of 1991/92. Some ratios in Table 5.2 may differ from the ratios in Appendix B and C due to rounding. The data in Appendices B and C were used for statistical analysis.

The ratios in 1991/92 vary between 0.4 and 26; for 2002/03 between 0.05 and 23. As mentioned earlier in section 5.2, when the ratio is above 1, the bog is not optimally developed, when it equals 1, the bog is supposed to be optimally developed and below 1 the bog is developed better than expected from the theory developed in section 5.2.1. The bog does not have the same circumstances everywhere (flow path lengths, slopes etc.). This partly explains the large variation between the different sites.

Site L9 is positioned in an ingrown drain, and therefore this point was not considered in further analyses.

Table 5.2 also shows a large difference between 1991/92 and 2002/03. The two data sets were tested statistically to quantify whether there is a significant difference between the ratios of 1991/92 and 2002/03. Because of the probably non-normally distributed data, a non-parametric two related Wilcoxon sample test (Sachs, 1982) was used for the statistical analysis. The results of the Wilcoxon test tell whether two tested data sets differ significantly. The results of the statistical analyses for acrotelm transmissivity are given below.

The potential transmissivity was calculated using two different methods; flow path area and flow path length (both described in Section 5.2.1). With the Wilcoxon signed rank test it was tested whether the two approaches differed in results. For the test the ratios of $T_{a\ potential}/T_{a\ measured}$ in 1991/92 and 2002/03 listed in Appendices B and C were used. The result of the test indicate that results from flow path area (method 1) and flow path length (method 2) did not differ significantly for both 1991/92 and 2002/03 (α>0.05, see Appendix D).

For 2002/03 a distinction was made between hummocks and hollows. The question was whether this approach would yield different transmissivities for both. From the Wilcoxon test it is clear that the measured transmissivities of hummocks and hollows do not differ significantly (α>0.05, see Appendix E). This result justifies averaging hummocks and hollows to make it possible to compare 2002/03 with 1991/92 (when hummock and hollow sites were not distinguished).

Furthermore, the ratios $T_{a\ potential}/T_{a\ measured}$ of 1991/92 and 2002/03 were tested. Because the two methods of calculating potential transmissivity are not significantly different, the ratios $T_{a\ potential}/T_{a\ measured}$ of both methods can be used as duplicates (P. Torfs, pers. comm. 2003). In this way one data set of 1991/92 and one of 2002/03 is used, within each data set both methods; flow path area and flow path length. Using the Wilcoxon test the ratios $T_{\mathrm{a}\ potential}/T_{\mathrm{a}\ measured}$ of 1991/92 and 2002/03 differ significantly (α<0.05, see Appendix F), indicating a positive development of the acrotelm in the past decade.

5.3.2. Relationship between specific discharge and transmissivity

For 1991/92 and 2002/03 a relationship between v_a and T_a was determined. According to the assumptions underlying Eq. (5.3), the relationship of v_a and T_a should be linear. The reality of course can be different.

The problem with measured transmissivities is that they are not comparable, because there are differences between measuring sites. Therefore a normalised transmissivity, which cancels out these differences, is needed. To calculate a normalised transmissivity $T_a{'}_{measured}$, $T_{a\ measured}$ is divided by a reference T_a, measured on the date with the largest number of measurements and on the same site. The result is shown in Figure 5.5. Note the difference in vertical scale of the left and right graph, which is caused by the difference between the respective reference values of T_a.

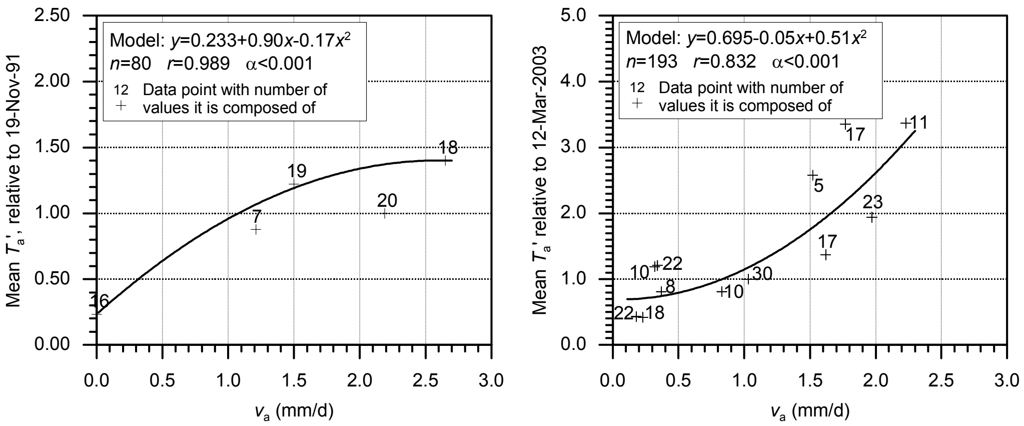

Figure 5.5. Relationship of v_a and T_a' in 1991/92 (left) (Van der Schaaf, 1999) and 2002/03 (right), where T_a' is acrotelm transmissivity expressed relative to T_a on a reference date.

In 1991/92 an approximately linear relationship was found for specific discharge v_a < 1.5 mm d^{-1}. At discharges >1.5 mm d^{-1}, hollows and pools interconnected, thus creating a flow via open water instead of the acrotelm (Van der Schaaf, 1999).

In 2002/03 a more or less linear part of the fitted curve was found to exist at v_a over 0.8 mm d^{-1}. The part of the curve for larger discharges lies therefore closer to the theoretical relationship of v_a and T_a. It also shows a greater role of the acrotelm in the discharge of water at high discharges.

At low discharges, water flows through the lower part of the acrotelm. The acrotelm in this part was formed when growth conditions varied largely due to damage of several kinds. Some flow barriers of more decayed material from the time damage was inflicted, may have subsisted in the acrotelm during the last decade, causing relatively low flow rates in newly developed acrotelm. This may have created an acrotelm with a more variable transmissivity than would have occurred under entirely natural conditions. This may explain why points in the graph between 0 and 0.5 mm d^{-1} with almost the same specific discharge vary so strongly in transmissivity, and why the fitted curve becomes relatively flat at specific discharges between 0 and 1 mm d^{-1}. Another possible cause is that the points in Figure 5.5 have not been calculated from exactly the same measuring sites. Measuring all sites on a single day was not possible.

5.4. Results of the transmissivity measurements on Clara Bog East

In 1992/93 T_a was measured on 3 plots on Clara Bog East. The plots were selected in 1989 to represent a wet, intermediate and dryer part of the bog (Plot A, B and C respectively, Figure 5.4). Each plot was subdivided into three clusters: a, b and c. In two out of three clusters, pits were made near tubes, 6 pits per cluster: Aa and Ab in plot A, Bb and Bc in plot B and Cb and Cc in plot C. In each cluster, three pits were made in hummock and three in hollow positions. The transmissivity data of 1992/93 were obtained from Van der Cruijsen *et al.* (1993) and Van der Schaaf (1999).

The drains cut in 1983/84 were provisionally blocked in 1987/89 and more effectively in 1996. In 1992/93 flow paths with a width of 100 m were estimated as they would have been without drains. The paths were based on the flow pattern that was derived from the 100x100 grid points and the contour map (Van der Schaaf, 1999).

From the levelling in 2003 it is clear that almost no subsidence had occurred on Clara Bog East since 1992. Only minor changes in surface slopes and directions occurred and an estimation of flow path lengths and areas yielded the same results for 2003 as in 1992/93. Also, due to better blocking of the drains, the present-day flow paths bear a closer resemblance to the flow paths as they existed before drainage.

No direct discharge measurements were available in both 1992/93 and 2003. In 1992/93 the discharge was estimated as the average of Raheenmore Bog and Clara West (Van der Schaaf, 1999). This approach could not be followed in 2003, since discharge on Clara Bog West could not be measured. Therefore, discharge was estimated from the data of Raheenmore Bog, using two approaches:

1) Comparing rainfall data on Raheenmore Bog and Clara Bog East, taking into account a reaction time of Raheenmore Bog between a rain peak and a discharge peak. From rainfall data and phreatic level data it can be derived that the reaction time between rain and surface water fluctuations is approximately equal on Raheenmore Bog and Clara Bog East. Therefore, it was assumed that the reaction time between rain and discharge on Clara Bog East would approximately equal the one of Raheenmore Bog.
2) Determining a linear relationship ($y=a+bx$) between surface water levels and discharge on Raheenmore. This yielded a slope (b) and it was assumed, that a linear relationship between surface water levels and discharge on Clara Bog East would have the same slope. The intercept a for the relation on Clara Bog East could be estimated from a simple water balance using data from Van der Schaaf (1999) (Van Lanen, pers. comm, 2003).

Both methods yielded approximately equal results (Appendix G). Method 2 uses point measurements (surface water levels were determined on 5 points on Raheenmore Bog and on 3 points on Clara Bog East) and these data may not represent the entire bogs. However, rainfall data from Raheenmore Bog and Clara Bog East are assumed to represent the entire bogs, since the areas are relatively small. Therefore the estimated discharge values from the first method were used.

The results of the calculated and measured T_a and the ratios $T_{potential}/T_{measured}$ are given in Tables 5.3 (1992/93) and 5.4 (2003). Measured data were averaged for each cluster. The full data set can be found in Appendix H. It shows that ratios of $T_{potential}/T_{measured}$ in 2003 are much lower compared to those of 1992/93. In 2003 the measured T_a was approximately 1.5 times the potential value, in 1992/93 the ratio was about 0.15. Statistical analysis using the Wilcoxon test showed a significant difference between 1992/93 and 2003 ($\alpha<0.05$, see Appendix I). There was no significant difference between the flow path area method and the flow path length method ($\alpha>>0.05$, see Appendix I). A comparison of the different plots shows that plot A has the lowest ratios, plot B is in between and plot C has the highest. This means that the differentiation in environments (wet, intermediate and dry) of the plots in 2002/03 is about the same as in 1991/92 as in 2002/03.

There was no significant difference between hollows and hummocks for Clara Bog East ($\alpha>0.05$, see Appendix J). Due to the low specific discharge (February and March 2003 were exceptionally dry) the potential transmissivities in 2003 are rather low. However, the actual transmissivity values remained high. This indicates that the drain blocking of 1996 was very effective and the acrotelm is developing well.

Table 5.3. Measured and potential transmissivities (using flow path area and flow path length) on Clara Bog East in 1992/93.

	Measured transmissivity (m^2/d)						
	Site	Aa	Ab	Bb	Bc	Cb	Cc
Date	va (mm/d)						
24-nov-92	3,30		51,0			5,6	11,1
25-nov-92	3,60	138,4		42,2	68,7		
09-dec-92	2,30	73,0	18,5	28,6	40,5	6,2	9,6
10-feb-93	0,58	33,2	9,0		7,2		
12-feb-93	0,53			14,1	6,3		
13-feb-93	0,50					1,0	
	Potential transmissivity (m^2/d), based on flow path length						
	Site	Aa	Ab	Bb	Bc	Cb	Cc
	Surface slope	0,0018	0,0031	0,003	0,002	0,0055	0,0061
	Flow path length (m)	354	250	521	458	104	208
Date	va (mm/d)						
24-nov-92	3,30		266,1			31,2	56,3
25-nov-92	3,60	708,0		312,6	412,2		
09-dec-92	2,30	452,3	185,5	199,7	263,4	21,7	39,2
10-feb-93	0,58	114,1	46,8		66,4		
12-feb-93	0,53			46,0	60,7		
13-feb-93	0,50					4,7	
Tpotential/Tmeasured		**5,2**	**6,3**	**6,6**	**6,5**	**4,5**	**4,6**
	Potential transmissivity (m^2/d), based on flow path area						
	Site	Aa	Ab	Bb	Bc	Cb	Cc
	Surface slope	0,0018	0,0031	0,003	0,002	0,0055	0,0061
	Flow path area (ha)	3,5	2,5	3	3,5	0,6	1,5
Date	va (mm/d)						
24-nov-92	3,30		266,13			36,00	81,15
25-nov-92	3,60	700,00		360,00	630,00		
09-dec-92	2,30	447,22	185,48	230,00	402,50	25,09	56,56
10-feb-93	0,58	112,78	46,77		101,50		
12-feb-93	0,53			53,00	92,75		
13-feb-93	0,50					5,45	
Tpotential/Tmeasured		**5,2**	**6,3**	**7,6**	**10,0**	**5,2**	**6,7**

Table 5.4. Measured and potential transmissivities (using flow path area and flow path length) on Clara Bog East in 2003.

	Measured transmissivity (m^2/d)						
	Site	Aa	Ab	Bb	Bc	Cb	Cc
Date	va (mm/d)						
13-feb-03	0,48	778,2	746,1				
14-feb-03	0,21			98,3	12,1	1,1	7,5
21-feb-03	0,34	82,7	79,6	60,9	35,7		
22-feb-03	0,34					0,9	1,2
06-mrt-03	1,01	624,1	630,8	129,3	147,1	4,6	21,0
22-mrt-03	0,20	72,5	69,9	94,9	75,0	1,0	2,7
	Potential transmissivity (m^2/d), based on flow path length						
	Site	Aa	Ab	Bb	Bc	Cb	Cc
	Surface slope	0,0027	0,0025	0,0039	0,0033	0,0076	0,008
	Flow path length (m)	354	250	521	458	104	208
Date	va (mm/d)						
13-feb-03	0,48	62,9	48,0				
14-feb-03	0,21			14,0	14,6	1,4	2,7
21-feb-03	0,34	44,6	34,0	22,7	23,6		
22-feb-03	0,34					2,3	4,4
06-mrt-03	1,01	132,4	101,0	67,5	70,1	6,9	13,1
22-mrt-03	0,20	26,2	20,0	13,4	13,9	1,4	2,6
Tpotential/Tmeasured		**0,2**	**0,1**	**0,3**	**0,5**	**1,6**	**0,7**
	Potential transmissivity (m^2/d), based on flow path area						
	Site	Aa	Ab	Bb	Bc	Cb	Cc
	Surface slope	0,0027	0,0025	0,0039	0,0033	0,0076	0,008
	Flow path area (ha)	3,5	2,5	3	3,5	0,6	1,5
Date	va (mm/d)						
13-feb-03	0,48	62,22	48,00				
14-feb-03	0,21			16,15	22,27	1,66	3,94
21-feb-03	0,34	44,07	34,00	26,15	36,06		
22-feb-03	0,34					2,68	6,38
06-mrt-03	1,01	130,93	101,00	77,69	107,12	7,97	18,94
22-mrt-03	0,20	25,93	20,00	15,38	21,21	1,58	3,75
Tpotential/Tmeasured		**0,2**	**0,1**	**0,4**	**0,7**	**1,9**	**1,0**

A comparison of the data of 1992/93 and those of 2003 makes it clear that major changes have occurred.The drain blocking has induced a renewed acrotelm growth and thus to an increased T_a. However, $T_{measured}$ in 2003 considerably exceeded $T_{potential}$ in a vast majority of the measurements. Why is the measured transmissivity so much larger than the potential one? It may be possible that the actual transmissivity is temporarily controlled by local changes and cannot be calculated using the potential transmissivity approach used in this report. The blocked drains may contribute locally in a positive way to the acrotelm transmissivity, by flowing over locally, thus creating longer flow paths than estimated from surface level data. Another possibility may –similar to Raheenmore Bog- be the uneven old bog surface that existed before the drain blocking, that may cause local flow obstacles to flow in the newly formed, but still shallow, acrotelm. Such obstacles may be more effective than on Raheenmore Bog, because the old top layer of the peat may have been compressed by the vehicle traffic during the drain blocking. In the winter of 1996, vehicle tracks were visible on almost any part of the bog.

Estimating discharge induces an error. Because the estimation procedures in 1992/93 and 2003 could not be the same, differences between the two data series were generated. The question remains, whether the different approaches provide an extra effect in the difference in ratios in 1992/93 and 2003. However, the differences between the results are so large that estimating errors cannot have caused them to such an extent.

5.5. Acrotelm thickness on Raheenmore Bog

5.5.1. Material and Methods

On Raheenmore Bog peat samples were taken to investigate the thickness of the acrotelm. The samples were investigated on humification degree (H), using the Von Post scale (Von Post, 1922, Von Post and Granlund, 1926). The depth of the acrotelm is defined as the depth over which $H \leq 3$ (Van der Schaaf, 1999), measured from the surface.

The sampling was carried out near all the points of the 100x100 grid (Figure 5.3) in February and March 2003. Near all the pegs both a hollow and a hummock were sampled. Using a spade, samples were taken at every 5 cm below surface down to a depth of circa 0.5 m (depending on the depth of the acrotelm). The thickness of the acrotelm was divided into classes of 0 cm, 0-5 cm, 5-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm and >50 cm. Near the grid points of the 100*100 m grid, hummocks and hollows, representative for the area were chosen for a better estimate of the acrotelm thickness. This means that e.g. when a high hummock occurred on the grid point, whose height was visually not representative for the area, a nearby lower one was selected. The same was done for hollows.

5.5.2. Results

The results of the acrotelm thickness sampling are given in figure 5.6 and 5.7. In figure 5.6 the acrotelm thickness of the hummocks is presented and in figure 5.7 the acrotelm thickness of the hollows. The average thickness of hummocks and hollows is given in figure 5.8 and figure 5.9 shows the acrotelm thickness in 1991. Data from 1991 from Van ‘t Hullenaar and Ten Kate, 1991)

The thickness of the acrotelm can vary considerably within a few meters. Therefore it is difficult to present the actual acrotelm thickness on every part of the bog with extrapolation of the acrotelm thickness per sample point (peg). Consequently the maps in figure 5.6- 5.8 are an indication rather than a real presentation of the entire bog surface.

Figure 5.6 shows the acrotelm thickness in the hummock positions. Close to the bog margin the thickness varied from 0 – 30 cm. Further to the centre of the bog the acrotelm became deeper. In the western part of the bog (left) hummocks occurred with an acrotelm thickness of 30 - >50 cm. In the north eastern part of the bog an old infilled drain system occurs, which was blocked around 1995. In the past these drains caused subsidence in this part of the bog. It is possible that blocking these drains influenced the development of hummocks in this part of the bog.

Figure 5.7 shows a map of the acrotelm thickness of Raheenmore Bog in hollow positions. In a large part of the bog margin there is no acrotelm. In the centre of the bog the acrotelm thickness varies from 0 to >50 cm. Comparing the acrotelm thickness of the hummocks with the hollows it can be seen that the variation in acrotelm thickness in the centre of the bog is higher for the hollows than for the hummocks. Therefore it seems that there is a better acrotelm development in the hummocks than in the hollows. It is possible that after drainage of the bog hummocks developed easier and better than hollows, therefore the differentiation between hummocks and hollows may not have reached a final stage.

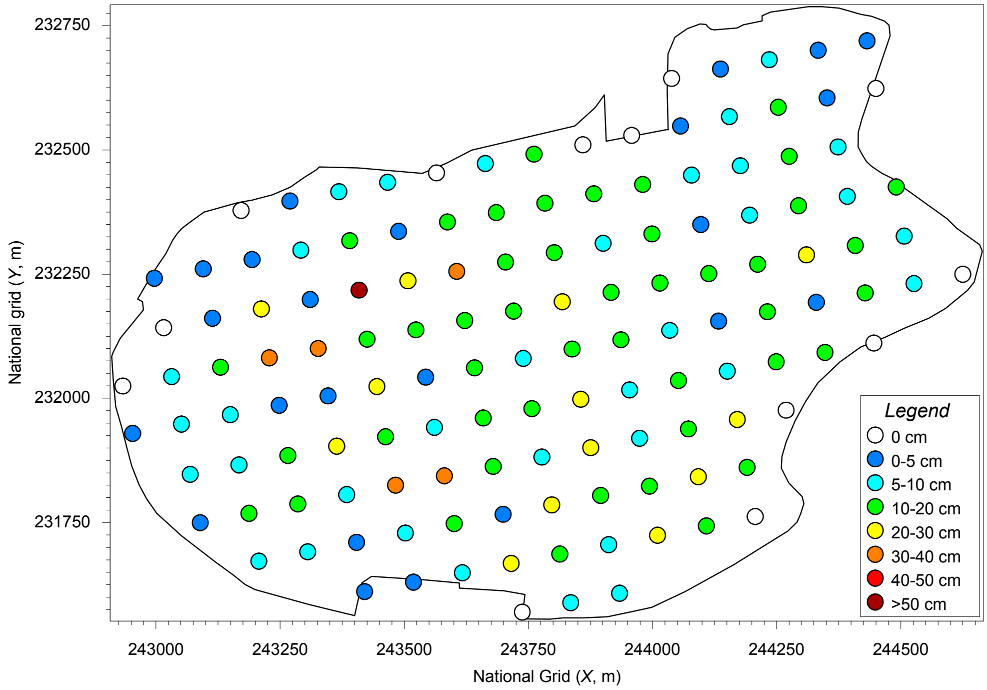

Figure 5.6. Acrotelm thickness on hummocks on Raheenmore Bog per grid point in 2003.

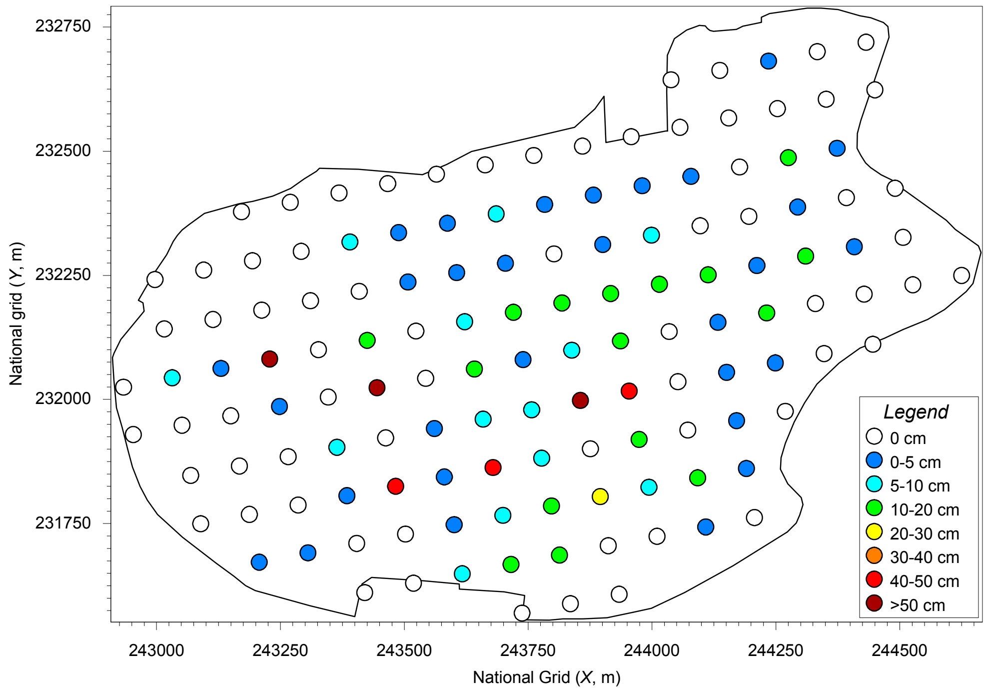

Figure 5.7. Acrotelm thickness in hollows on Raheenmore Bog per grid point in 2003.

To obtain an average indication for acrotelm development, the acrotelm thickness of the hummocks and hollows were averaged (Figure 5.8). The data presented by Van 't Hullenaar & Ten Kate (1991) are shown in Figure 5.9. The difference between the measurements in 1991 and 2003 is that in 1991 little was known about hummock/hollow complexes and sites were selected randomly per grid point. It is assumed that hummocks and hollows were approximately equally sampled. Around a grid point the random samples were taken in a place with an acrotelm in the sense of the definition of $H \leq 3$, else the acrotelm thickness was 0 (Van 't Hullenaar & Ten Kate, 1991). In 2003 hummock as well as hollows were sampled.

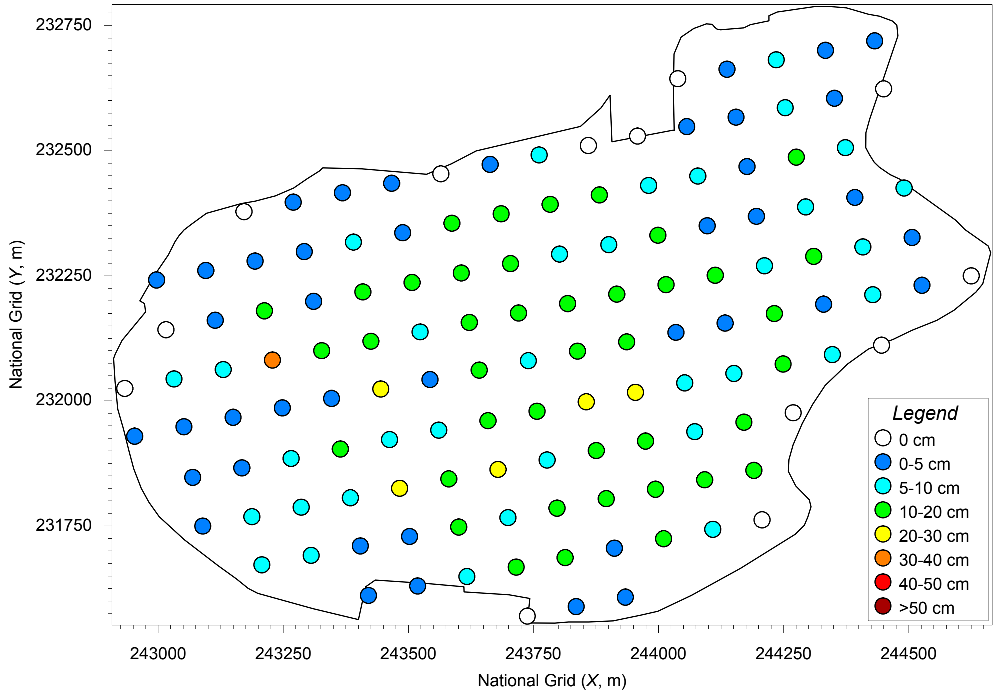

Figure 5.8. Average acrotelm thickness Raheenmore Bog per grid point in 2003.

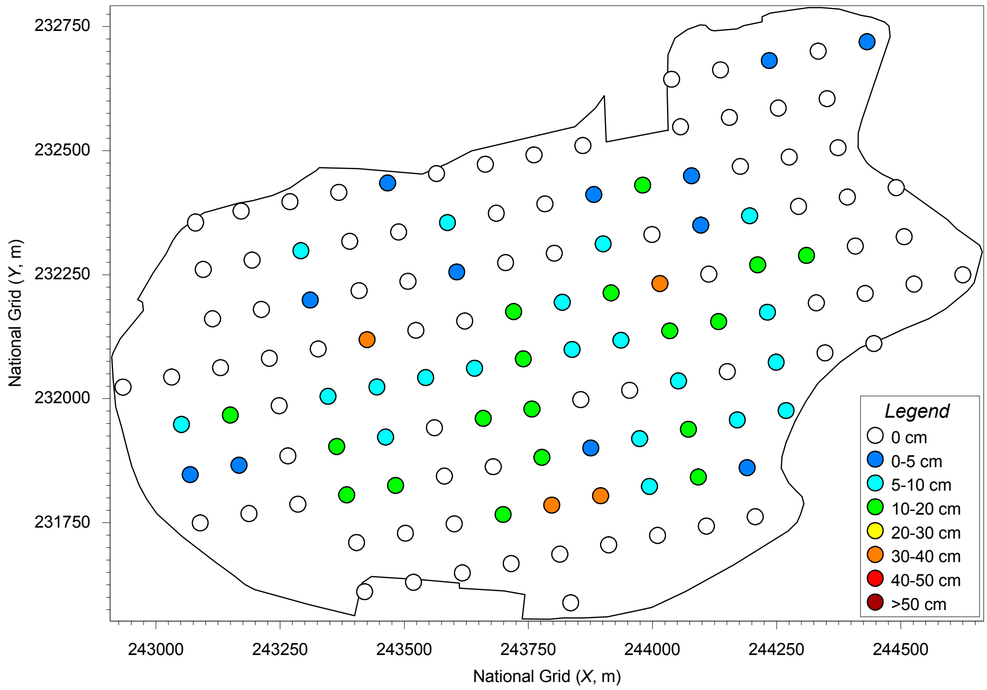

Figure 5.9. Approximate average acrotelm thickness Raheenmore Bog per grid point in 1991.

A comparison of Figure 5.8 and 5.9 shows that in 2003 both in the centre and on the margins of the bog the acrotelm is thicker than in 1991. Visually it also seemed that the acrotelm developed very well during the last 10 years, especially in the centre of the bog. Close to the bog margin the acrotelm seems to develop less quickly.

To test the statistical significance of the difference found between 1991 and 2003, the data sets were analysed with a Wilcoxon test. The test results in a statistically significant difference between the acrotelm thickness in 1991 and 2003 ($\alpha<0.05$, see Appendix K), which means a considerable positive development of the acrotelm over the last 12 years, probably mostly since the drains were blocked.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Introduction

In this chapter the conclusions of the research on Clara Bog and Raheenmore Bog will be given point by point. Section 6.2 deals with the subsidence of Clara Bog West, 6.3 and 6.4 with the acrotelm development on Raheenmore Bog and Clara Bog East respectively. Recommendations are also given in both sections.

6.2. Subsidence on Clara Bog West

In the period 1991-2002 severe subsidence occurred in the southern and southeastern part of Clara Bog West. The main research questions concerning the subsidence were:

1) Which process(es) is/are involved in the subsidence?
2) What caused the subsidence in the period 1991-2002?
3) What are the consequences of the subsidence?

1. Processes involved

- Loss of water, particularly in the lowest part of the peat profile, led to subsidence of the peat and an increase in the volume fraction of organic matter.
- Horizontal and vertical conductivity in the lowest part of the profile decreased. This process can be named as the self-sealing capacity of a bog.
- Local differences in subsidence may occur within short distances. This is caused by differences in the hydraulic resistance of the peat, the (lacustrine) clay and the till.

2.Causes of subsidence

- The drainage at the southern edge of Clara Bog West has lowered the piezometric head in the mineral layers subjacent to the peat and increased the hydraulic gradient over the peat in the period 1991-2003. This effect decreases with increasing distance to the bog margin.

3. Consequences

- Unequal subsidence has changed the surface slopes on Clara Bog West. This has resulted in a changing flow pattern on the bog. Changes in the flow pattern caused lakes, waterlogged areas and dryer areas.
- The subsidence lowered the phreatic level of Clara Bog West and partly destroyed the acrotelm. This affected and will affect the ecology of the bog.
- Owing to a changed flow pattern on Clara Bog West, the behaviour of the surface outflow has changed, resulting in shorter residence times of the water in the surface layer. In time this may lead to subsidence in the top layer of the bog.

Recommendations

- Turf cutting along the margins of Clara Bog should be stopped, especially at the southern margin. Besides, the government should acquire the area where the turf cutting activities still take place. Then, in order to prevent further subsidence, the water management in that area should be changed by increasing the water levels.
- Drains that are still open should be blocked effectively.

- Effects of changes in the water management should be monitored. More research is needed to estimate future subsidence and the effects on the flow pattern of Clara Bog West. Measurements of piezometric heads in the peat just above the mineral subsoil and in the mineral subsoil should be intensified.
- The development of a numerical subsidence model may give more information about the processes involved in subsidence.

6.3. Acrotelm development on Raheenmore Bog

Raheenmore Bog has suffered from different kinds of damage in the past, like turf cutting and drainage. In 1991/92 the results of the measurements indicated a rather poorly developed acrotelm. In 1995 drains were blocked. The main research question was:

Has the acrotelm on Raheenmore Bog developed positively since the research in 1991/92?

Conclusions

- The actual transmissivities improved, compared with the potential transmissivities.
- Statistical analysis showed a significant difference between ratios $T_{measured}/T_{calculated}$ in 1991/92 and 2002/03, indicating a positive development of the acrotelm in the last 12 years.
- The acrotelm has a greater influence on the discharge of water at large discharges in 2002/03, *i.e.* the hydrological regulation function has been enhanced since 1991/92.
- The overall acrotelm thickness has increased, not only in the centre of Raheenmore Bog but also towards the margins. Results from statistical analysis showed a significant difference between 1991/92 and 2003.
- When looking at the conclusions it can be said that the acrotelm on Raheenmore Bog has developed positively since 1991/92.

Recommendations

- An investigation of acrotelm thickness and transmissivity every 10 years will monitor the further development of the acrotelm on Raheenmore Bog.
- A vegetation survey would be useful, because it will give additional information on the development of the acrotelm.

6.4. Acrotelm development on Clara Bog East

Clara Bog East has also suffered from damage of draining in the past. This was confirmed during the 1992/93 research. In 1996 nearly all drains on Clara Bog East were blocked. The question here was rather the same as on Raheenmore Bog:

Has the acrotelm on Clara Bog East developed positively since research in 1992/93?

Conclusion

- The ratios of actual and potential transmissivities on Clara Bog East have improved considerably. A statistically significant difference between 1992/93 and 2003 was found. It should be noted that the potential transmissivities were based on estimated discharges in the measurement series of both 1991/92 and 2003.

Recommendations

- It would be useful to monitor the acrotelm development of Clara Bog East once per five or ten years and see if the actual transmissivity changes towards the potential.
- In 1992/93 and 2003 it was not possible to measure discharge on Clara Bog East. This is a problem since the potential transmissivity is based on the discharge of the bog. It would

therefore be good to try to measure a discharge on Clara East somehow or to develop a reliable estimation method.

- Investigation of the acrotelm thickness in about 5 years and a comparison with earlier measurements (Van der Cruijsen *et. al.*, 1993) will be a good indication of the development of the acrotelm.
- It would be useful to extend the transmissivity measurements to entire Clara Bog East.
- An investigation of the vegetation development will give more information about the development of the acrotelm.

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APPENDICES

A. The Von Post humification scale
B. Transmissivity data set Raheenmore Bog 2002/03.
C. Transmissivity data set Raheenmore Bog 1991/92.
D. Wilcoxon test transmissivity ratios flow path area versus flow path length on Raheenmore Bog.
E. Wilcoxon test hummock versus hollow transmissivities Raheenmore Bog.
F. Wilcoxon test transmissivity ratios 1991/92 versus 2002/03 Raheenmore Bog.
G. Estimated discharge Clara Bog East.
H. Transmissivity data set Clara Bog East 1992/93 and 2003.
I. Wilcoxon test transmissivity ratios 1992/93 versus 2002 Clara Bog East.
J. Wilcoxon test hummock versus hollow transmissivities Clara Bog East.
K. Wilcoxon test acrotelm thickness 1991/92 – 2002/03 Raheenmore Bog.

APPENDIX A. THE VON POST HUMIFICATION SCALE

(Von Post, 1922)

H1 Completely unhumified plant remains, from which by only almost colourless water can be squeezed.

H2 Almost unhumified plant remains, the squeezed water is light brown and almost clear.

H3 Very poorly humified plant remains, the squeezed water is brown and a bit cloudy.

H4 Poorly humified plant remains, peaty substance does not escape from between the fingers by squeezing, and the water is brown and cloudy.

H5 Moderately humified plant remains, the structure however is still clearly visible, the squeezed water is dark brown and very cloudy and some peat escapes through the fingers.

H6 Fairly highly humified plant remains, the structure 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.

H7 Highly humified plant remains, about half of the material escapes when squeezed. The water, which may escape is dark brown in colour.

H8 Very highly humified plant remains, two third of the material escapes through the fingers. The remainder consists mainly of resistant bits of roots and wood.

H9 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 through the fingers without any water being squeezed out.

APPENDIX B. TRANSMISSIVITY DATA SET RAHEENMORE BOG 2002/03

Table B.1. Theoretical transmissivities of Raheenmore Bog using flow path length and slope in 2002/03.

	Calculating theoretical transmissivities on Raheenmore Bog using flowpath and slope																						
	Site	L-1	L0	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	J6	K6	M6	N6	O6	P6	Q6
Surface slope		0,0093	0,0072	0,0052	0,0014	0,0014	0,0008	0,0008	0,0023	0,0043	0,0031	0,0021	0,0031	0,0054	0,0067	0,0089	0,0045	0,0033	0,0016	0,001	0,0013	0,0016	0,002
flowpath length		310	200	144	133	244	267	378	456	544	656	800	944	1089	678	744	544	544	456	456	500	567	478
Theoretic m^2/d																							
Date	Spec discharge mm/d																						
04-dec-02	2,3								228,0	145,5	243,4		350,2	231,9	116,4	96,1							
05-dec-02	1,84	30,7	25,6	25,5	87,4	160,3	303,3	434,7				350,5					111,2	151,7					
06-dec-03	1,59																		226,6	362,5	305,8	281,7	190,0
20-jan-03	1,95	32,5	27,1	27,0	92,6	169,9			193,3	123,3	206,3	371,4	296,9	196,6	98,7	81,5							
21-jan-03	1,61						265,4	380,4									97,3	132,7	229,4	367,1	309,6	285,3	192,4
17-feb-03	0,32	5,3	4,4	4,4	15,2	27,9	52,7			20,2	33,9	61,0	48,7	32,3	16,2	13,4							
18-feb-03	0,33																			75,2	63,5	58,5	39,4
19-feb-03	0,32							75,6	31,7								19,3	26,4	45,6				
23-feb-03	0,32								31,7	20,2	33,9	61,0	48,7	32,3	16,2	13,4	19,3	26,4					
24-feb-03	0,27	4,5	3,8	3,7	12,8	23,5	44,5	63,8											38,5	61,6	51,9	47,8	32,3
12-mrt-03	0,95	15,8	13,2	13,2	45,1	82,8	156,6	224,4	94,2	60,1	100,5	181,0	144,6	95,8	48,1	39,7	57,4	78,3					
13-mrt-03	0,75																		106,9	171,0	144,2	132,9	89,6
Measured																							
04-dec-02	2,3								135,5	160,7	239,2		249,2	258,6	289,8	47,8							
05-dec-02	1,84	72,2	33,6	488,1	158,5	14,4	24,9	175,0				7155,2					131,4	6,3					
06-dec-02	1,59																		61,7	32,5	69,2	610,8	102,8
20-jan-03	1,95	36,6	25,2	313,3	132,9	15,6			156,9	119,7	110,4	3078,5	106,8	132,1	266,0	37,7							
21-jan-03	1,61						3,6	84,9									38,5	24,7	28,4	84,8	49,9	105,9	66,5
17-feb-03	0,32	24,4	11,8	226,6	93,9	6,1	3,4			33,0	62,2	430,3	40,2	162,1	176,5	46,5							
18-feb-03	0,33																			73,3	29,4	85,8	31,7
19-feb-03	0,32							82,9	172,1								35,7	19,0	21,0				
23-feb-03	0,32								45,4	13,8	26,7	535,4	16,6	12,6	37,8	12,6	13,0	11,4					
24-feb-03	0,27	9,3	7,1	225,2	69,7	2,6	1,4	25,6											11,4	46,8	15,2	63,6	12,2
12-mrt-03	0,95	22,2	34,0	383,1	74,3	5,6	2,6	80,0	113,9	36,1	66,5	3625,0	69,5	90,2	78,8	21,1	29,8	19,0					
13-mrt-03	0,75																		39,0	85,3	29,1	75,9	29,4
T calc/Tmeas		0,54	0,66	0,05	0,48	10,50	22,95	2,63	0,93	1,02	1,22	0,07	1,84	0,90	0,35	1,47	1,23	5,17	4,01	3,22	4,54	0,86	2,24

Table B.2. Theoretical transmissivities of Raheenmore Bog using flow path area and slope in 2002/03.

			Calculating theoretical transmissivities on Raheenmore Bog using flowpath area and slope																				
	Site	L-1	L0	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	J6	K6	M6	N6	O6	P6	Q6
Surface slope		0,0093	0,0072	0,0052	0,0014	0,0014	0,0008	0,0008	0,0023	0,0043	0,0031	0,0021	0,0031	0,0054	0,0067	0,0089	0,0045	0,0033	0,0016	0,001	0,0013	0,0016	0,002
Upstream area		2,5	2,3	1,3	0,7	0,8	1	1	2	3	4,5	6	6	6	7	6	2,5	2	2	2	1,5	2	3
Theoretic																							
Date	Spec discharge																						
04-dec-02	2,3								200,0	160,5	333,9		445,2	255,6	240,3	155,1							
05-dec-02	1,84	49,5	58,8	46,0	92,0	105,1	227,2	230,0				525,7					102,2	111,5					
06-dec-02	1,59																		198,8	318,0	183,5	198,8	238,5
20-jan-03	1,95	52,4	62,3	48,8	97,5	111,4			169,6	136,0	283,1	557,1	377,4	216,7	203,7	131,5							
21-jan-03	1,61						198,8	201,3									89,4	97,6	201,3	322,0	185,8	201,3	241,5
17-feb-03	0,32	8,6	10,2	8,0	16,0	18,3	39,5			22,3	46,5	91,4	61,9	35,6	33,4	21,6							
18-feb-03	0,33																			66,0	38,1	41,3	49,5
19-feb-03	0,32							40,0	27,8								17,8	19,4	40,0				
23-feb-03	0,32								27,8	22,3	46,5	91,4	61,9	35,6	33,4	21,6	17,8	19,4					
24-feb-03	0,27	7,3	8,6	6,8	13,5	15,4	33,3	33,8											33,8	54,0	31,2	33,8	40,5
12-mrt-03	0,95	25,5	30,3	23,8	47,5	54,3	117,3	118,8	82,6	66,3	137,9	271,4	183,9	105,6	99,3	64,0	52,8	57,6					
13-mrt-03	0,75																		93,8	150,0	86,5	93,8	112,5
Measured																							
04-dec-02	2,3								135,5	160,7	239,2		249,2	258,6	289,8	47,8							
05-dec-02	1,84	72,2	33,6	488,1	158,5	14,4	24,9	175,0				7155,2					131,43	6,3					
06-dec-02	1,59																		61,7	32,5	69,2	610,8	102,8
20-jan-03	1,95	36,6	25,2	313,3	132,9	15,6			156,9	119,7	110,4	3078,5	106,8	132,1	266,0	37,7							
21-jan-03	1,61						3,6	84,9									38,5	24,7	28,4	84,8	49,9	105,9	66,5
17-feb-03	0,32	24,4	11,8	226,6	93,9	6,1	3,4			33,0	62,2	430,3	40,2	162,1	176,5	46,5							
18-feb-03	0,33																			73,3	29,4	85,8	31,7
19-feb-03	0,32							82,9	172,1								35,7	19,0	21,0				
23-feb-03	0,32								45,4	13,8	26,7	535,4	16,6	12,6	37,8	12,6	13,0	11,4					
24-feb-03	0,27	9,3	7,1	225,2	69,7	2,6	1,4	25,6											11,4	46,8	15,2	63,6	12,2
12-mrt-03	0,95	22,2	34,0	383,1	74,3	5,6	2,6	80,0	113,9	36,1	66,5	3625,0	69,5	90,2	78,8	21,1	29,8	19,0					
13-mrt-03	0,75																		39,0	85,3	29,1	75,9	29,4
T calc/Tmeas		0,9	1,5	0,1	0,5	6,9	17,2	1,4	0,8	1,1	1,7	0,1	2,3	1,0	0,7	2,4	1,1	3,8	3,5	2,8	2,7	0,6	2,8

APPENDIX C. TRANSMISSIVITY DATA SET RAHEENMORE BOG 1991/92

Table C.1. Theoretical transmissivities of Raheenmore Bog using flow path length and slope in 1991/92.

	Calculating theoretical transmissivities on Raheenmore Bog using flowpath area and slope																						
	Site	L-1	L0	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	J6	K6	M6	N6	O6	P6	Q6
Surface slope		0,0093	0,0081	0,0058	0,0018	0,0031	0,0016	0,0012	0,0027	0,0043	0,0026	0,002	0,0032	0,0046	0,0067	0,0089	0,0043	0,0039	0,0019	0,0013	0,0008	0,0009	0,0025
Upstream area		2,5	2,3	1,3	0,7	0,8	1	1	2	3	4,5	6	6	6	7	6	2,5	2	2	2	1,5	2	3
Theoretic																							
Date	Spec discharge (mm/d)																						
16-apr-91	1,5	40,3	42,6	33,6	58,3	38,7	93,8	125,0	111,1	104,7	259,6	450,0	281,3	195,7	156,7	101,1	87,2	76,9	157,9	230,8	281,3	340,9	180,0
01-nov-91	2,7	72,6	76,7	60,5	105,0	69,7	168,8	225,0	200,0	188,4	467,3	810,0		352,2			157,0	138,5	284,2	415,4	506,3	613,6	324,0
19-nov-91	2,2	59,1	62,5	49,3	85,6	56,8	137,5	183,3	163,0	153,5	380,8	660,0		287,0	229,9	148,3	127,9	112,8	231,6	338,5	412,5	500,0	264,0
25-mrt-92	1,2						75,0	100,0	88,9	83,7	207,7	360,0		156,5	125,4								
Measured																							
16-apr-91	1,5	6,6	3,4	4,2	40,0	110,0	21,0	75,0	69,3	6,3	118,0	1350,0	59,0	140,0	76,1	79,2	11,1	34,8	130,0	42,0	62,0	44,1	78,0
01-nov-91	2,7	44,0	4,4	2,9	89,0	180,0	2,6	30,0	35,0	3,9	67,1	549,0		35,8			20	24,7	150,0	65,0	200,0	111,0	316,0
19-nov-91	2,2	13,2	2,2	6,1	97,0	110,0	4,1	936,0	28,9	5,4	67,1	922,0		142,0	66,8	76,6	5,9	14,2	120,0	70,0	130,0	64,5	120,0
25-mrt-92	1,2						2,5	67,0	26,4	5,2	116,0	1100,0		38,7	41,3								
T calc/Tmeas		2,7	18,2	10,9	1,1	0,4	15,7	0,6	3,5	25,5	3,6	0,6	4,8	2,8	2,8	1,6	10,1	4,5	1,7	5,5	3,1	6,6	1,5

Table C.2. Theoretical transmissivities of Raheenmore Bog using flow path area and slope in 1991/92.

	Calculating theoretical transmissivities on Raheenmore Bog using flowpath and slope																						
	Site	L-1	L0	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	J6	K6	M6	N6	O6	P6	Q6
Surface slope		0,0093	0,0081	0,0058	0,0018	0,0031	0,0016	0,0012	0,0027	0,0043	0,0026	0,002	0,0032	0,0046	0,0067	0,0089	0,0043	0,0039	0,0019	0,0013	0,0008	0,0009	0,0025
flow path length		310	200	144	133	244	267	378	456	544	656	800	944	1089	678	744	544	544	456	456	500	567	478
Theoretic m^2/d																							
Date	Spec discharge mm/d																						
16-apr-91	1,5	25,00	18,52	18,62	55,42	59,03	125,16	236,25	126,67	94,88	189,23	300,00	221,25	177,55	75,90	62,70	94,88	104,62	180,00	263,08	468,75	483,24	143,40
01-nov-91	2,7	45,00	33,33	33,52	99,75	106,26	225,28	425,25	228,00	170,79	340,62	540,00		319,60			170,79	188,31	324,00	473,54	843,75	869,83	258,12
19-nov-91	2,2	36,67	27,16	27,31	81,28	86,58	183,56	346,50	185,78	139,16	277,54	440,00		260,41	111,31	91,96	139,16	153,44	264,00	385,85	687,50	708,75	210,32
25-mrt-92	1,2						100,13	189,00	101,33	75,91	151,38	240,00		142,04	60,72								
Measured																							
16-apr-91	1,5	6,6	3,4	4,2	40,0	110,0	21,0	75,0	69,3	6,3	118,0	1350,0	59,0	140,0	76,1	79,2	11,1	34,8	130,0	42,0	62,0	44,1	78,0
01-nov-91	2,7	44,0	4,4	2,9	89,0	180,0	2,6	30,0	35,0	3,9	67,1	549,0		35,8			20	24,7	150,0	66,0	200,0	111,0	316,0
19-nov-91	2,2	13,2	2,2	6,1	97,0	110,0	4,1	935,0	28,9	5,4	67,1	922,0		142,0	66,8	76,6	5,9	14,2	120,0	70,0	130,0	64,5	120,0
25-mrt-92	1,2						2,5	67,0	26,4	5,2	116,0	1100,0		38,7	41,3								
T calc/Tmeas		1,67	7,90	6,02	1,05	0,63	19,28	0,97	4,06	25,95	3,20	0,45	3,75	2,38	1,31	0,99	10,94	6,06	1,92	6,31	5,10	9,39	1,19

APPENDIX D. WILCOXON TEST TRANSMISSIVITY RATIOS RAHEENMORE BOG

Non Parametric Wilcoxon Signed Ranks Test, Acrotelm transmissivity ratio's $T_{calculated}/T_{measured}$ 1991 & 2002 using flow path area method (fpa) and flow path length method (fpl) for Raheenmore Bog.

Results 1991

Ranks

		N	Mean Rank	Sum of Ranks
fpl 1991 – fpa 1991	Negative Ranks	11[a]	11,95	131,50
	Positive Ranks	11[b]	11,05	121,50
	Ties	0[c]		
	Total	22		

a fpl 1991 < fpa 1991

b fpl 1991 > fpa 1991

c fpa 1991 = fpl 1991

Test Statistics[b]

	fpl 1991 – fpa 1991
Z	-0,162[a]
Asymp. Sig. (2-tailed)	,871

a Based on positive ranks.

b Wilcoxon Signed Ranks Test

Small significance values (<0.05) indicate that the two variables differ in distribution.

Here the significance value > 0.05, thus the two methods flows path area and flow path length to calculate the discharge en thus the acrotelm transmissivity ratios in 1991 do **not** differ significantly.

Results 2002

Ranks

		N	Mean Rank	Sum of Ranks
fpl 2002 – fpa 2002	Negative Ranks	12[a]	9,00	108,00
	Positive Ranks	10[b]	14,50	145,00
	Ties	0[c]		
	Total	22		

a fpl 2002 < fpa 2002

b fpl 2002 > fpa 2002

c fpa 2002 = fpl 2002

Test Statistics[b]

	fpl 2002 – fpa 2002
Z	-0,601[a]
Asymp. Sig. (2-tailed)	0,548

a Based on positive ranks.

b Wilcoxon Signed Ranks Test

Small significance values (<0.05) indicate that the two variables differ in distribution.

Here the significance value > 0.05, thus the two methods flows path area and flow path length to calculate the discharge en thus the acrotelm transmissivity ratios in 2002 do **not** differ significantly.

As well the results of 1991 as of 2002 show that the two methods, flow path area and flow path length to calculate the transmissivity ratios, do **not** differ significantly. Therefore the results of both methods can be used as duplicates (pers. comm Torfs, 2003).

APPENDIX E. WILCOXON TEST HUMMOCK VERSUS HOLLOW TRANSMISSIVITIES RAHEENMORE BOG

Non Parametric Wilcoxon Signed Ranks Test, Hummock and hollow transmissivities Raheenmore Bog for four measuring clusters.

1) Results 4/5/6 December 2002

Ranks

		N	Mean Rank	Sum of Ranks
hollow - hummock	Negative Ranks	4[a]	7,75	31,00
	Positive Ranks	8[b]	5,88	47,00
	Ties	0[c]		
	Total	12		

a hollow < hummock

b hollow > hummock

c hummock = hollow

Test Statistics[b]

	hollow - hummock
Z	-,628[a]
Asymp. Sig. (2-tailed)	,530

a Based on negative ranks.

b Wilcoxon Signed Ranks Test.

Small significance values (<0.05) indicate that the two variables differ in distribution.

Here the significance value > 0.05, thus the transmissivity of hummock and hollows of Raheenmore Bog do not differ significantly.

2) Results 20/21 January 2003

Ranks

		N	Mean Rank	Sum of Ranks
hollow - hummock	Negative Ranks	10[a]	8,00	80,00
	Positive Ranks	9[b]	12,22	110,00
	Ties	0[c]		
	Total	19		

a hollow < hummock

b hollow > hummock

c hummock = hollow

Test Statistics[b]

	hollow - hummock
Z	-,604[a]
Asymp. Sig. (2-tailed)	,546

a Based on negative ranks.

b Wilcoxon Signed Ranks Test

Small significance values (<0.05) indicate that the two variables differ in distribution.

Here the significance value > 0.05, thus the transmissivity of hummock and hollows of Raheenmore Bog do not differ significantly.

3) Results 17/18/19 February 2003

Ranks

		N	Mean Rank	Sum of Ranks
hollow - hummock	Negative Ranks	8[a]	8,38	67,00
	Positive Ranks	11[b]	11,18	123,00
	Ties	0[c]		
	Total	19		

a hollow < hummock

b hollow > hummock

c hummock = hollow

Test Statistics[b]

	hollow - hummock
Z	-1,127[a]
Asymp. Sig. (2-tailed)	,260

a Based on negative ranks.

b Wilcoxon Signed Ranks Test

Small significance values (<0.05) indicate that the two variables differ in distribution.

Here the significance value > 0.05, thus the transmissivity of hummock and hollows of Raheenmore Bog do not differ significantly.

4) Results 23/24 February 2003

Ranks

		N	Mean Rank	Sum of Ranks
hollow - hummock	Negative Ranks	10[a]	10,80	108,00
	Positive Ranks	9[b]	9,11	82,00
	Ties	0[c]		

	Total	19		

a hollow < hummock

b hollow > hummock

c hummock = hollow

Test Statistics[b]

	hollow - hummock
Z	-1,408[a]
Asymp. Sig. (2-tailed)	,159

a Based on negative ranks.

b Wilcoxon Signed Ranks Test

Small significance values (<0.05) indicate that the two variables differ in distribution.

Here the significance value > 0.05, thus the transmissivity of hummock and hollows of Raheenmore Bog do not differ significantly.

From the results of all measuring clusters can be concluded that the transmissivity of hummock and hollows of Raheenmore Bog do not differ significantly.

APPENDIX F. WILCOXON TEST TRANSMISSIVITY RATIOS 1991/92 VERSUS 2002/03 RAHEENMORE BOG

Non Parametric Wilcoxon Signed Ranks Test, Acrotelm transmissivity ratio's $T_{calculated}/T_{measured}$ 1991/92 & 2002/03 for Raheenmore Bog.

Results

Ranks

		N	Mean Rank	Sum of Ranks
fpl 200203 – fpa 1991/92	Negative Ranks	32[a]	23,80	761,50
	Positive Ranks	12[b]	19,04	228,50
	Ties	0[c]		
	Total	44		

a 2002/03 < 1991/92

b 2002/03 > 1991/92

c 1991/92 = 2002/03

Test Statistics[b]

	2002/03 – 1991/92
Z	-3,110[a]
Asymp. Sig. (2-tailed)	0,002

a Based on positive ranks.

b Wilcoxon Signed Ranks Test

Small significance values (<0.05) indicate that the two variables differ in distribution.

Here the significance value < 0.05, thus the transmissivity ratio's in 1991/92 and 2002/03 for Raheenmore Bog differ significantly.

APPENDIX G. ESTIMATED DISCHARGE CLARA BOG EAST

Table G.1. Estimated discharge Clara Bog East using 2 approaches as described in chapter 5.

Estimated discharge Clara Bog East using 2 approaches (described in chapter 5)						
	Method 1	Method 2	Method 2			
Date	Plot A,B,C	Plot A	Plot B,C			
13-feb-03	0,48	0,16	0,78			
14-feb-03	0,21	0,13	0,68			
21-feb-03	0,34	-	0,14			
22-feb-03	0,34	-	0,20			
06-mrt-03	1,0	0,88	1,0			
22-mrt-03	0,2	-	-			

APPENDIX H. TRANSMISSIVITY DATA SET CLARA BOG EAST 1992/93 AND 2003

Table H.1. Transmissivity ratios $T_{calculated}/T_{measured}$ using flow path area and flow path length method in 1992/93.

	Flow path length						
	Site	Aa	Ab	Bb	Bc	Cb	Cc
	Surface slope	0,0018	0,0031	0,003	0,002	0,0055	0,0061
	flow path lengt	354	250	521	458	104	208
Theoretic							
Date	Spec discharge (mm/d)						
24-nov-92	3,30		266,1			31,2	56,3
25-nov-92	3,60	708,0		312,6	412,2		
09-dec-92	2,30	452,3	185,5	199,7	263,4	21,7	39,2
10-feb-93	0,58	114,1	46,8		66,4		
12-feb-93	0,53			46,0	60,7		
13-feb-93	0,50					4,7	
Measured							
Date	Spec discharge (mm/d)						
24-nov-92	3,30		51,0			5,6	11,1
25-nov-92	3,60	138,4		42,2	68,7		
09-dec-92	2,30	73,0	18,5	28,6	40,5	6,2	9,6
10-feb-93	0,58	33,2	9,0		7,2		
12-feb-93	0,53			14,1	6,3		
13-feb-93	0,50					1,0	
	Tcalc/Tmeas	**5,2**	**6,3**	**6,6**	**6,5**	**4,5**	**4,6**
	Flow path area						
	Site	Aa	Ab	Bb	Bc	Cb	Cc
	Surface slope	0,0018	0,0031	0,003	0,002	0,0055	0,0061
	flow path area	3,5	2,5	3	3,5	0,6	1,5
Theoretic							
Date	Spec discharge (mm/d)						
24-nov-92	3,30		266,13			36,00	81,15
25-nov-92	3,60	700,00		360,00	630,00		
09-dec-92	2,30	447,22	185,48	230,00	402,50	25,09	56,56
10-feb-93	0,58	112,78	46,77		101,50		
12-feb-93	0,53			53,00	92,75		
13-feb-93	0,50					5,45	
	Tcalc/Tmeas	**5,2**	**6,3**	**7,6**	**10,0**	**5,2**	**6,7**

Table H.2. Transmissivity ratios $T_{calculated}/T_{measured}$ using flow path area and flow path length method in 2003.

	Flow path length						
	Site	Aa	Ab	Bb	Bc	Cb	Cc
	Surface slope	0,0027	0,0025	0,0039	0,0033	0,0076	0,008
	flow path length	354	250	521	458	104	208
Theoretic							
Date	ec discharge (mm/d)						
13-feb-03	0,48	62,9	48,0				
14-feb-03	0,21			14,0	14,6	1,4	2,7
21-feb-03	0,34	44,6	34,0	22,7	23,6		
22-feb-03	0,34					2,3	4,4
06-mrt-03	1,01	132,4	101,0	67,5	70,1	6,9	13,1
22-mrt-03	0,20	26,2	20,0	13,4	13,9	1,4	2,6
Measured							
Date	Spec discharge						
13-feb-03	0,48	778,2	746,1				
14-feb-03	0,21			98,3	12,1	1,1	7,5
21-feb-03	0,34	82,7	79,6	60,9	35,7		
22-feb-03	0,34					0,9	1,2
06-mrt-03	1,01	624,1	630,8	129,3	147,1	4,6	21,0
22-mrt-03	0,20	72,5	69,9	94,9	75,0	1,0	2,7
Tcalc/Tmeas		**0,2**	**0,1**	**0,3**	**0,5**	**1,6**	**0,7**
	Flow path area						
	Site	Aa	Ab	Bb	Bc	Cb	Cc
	Surface slope	0,0027	0,0025	0,0039	0,0033	0,0076	0,008
	flow path area	3,5	2,5	3	3,5	0,6	1,5
Theoretic							
Date	ec discharge (mm/d)						
13-feb-03	0,48	62,22	48,00				
14-feb-03	0,21			16,15	22,27	1,66	3,94
21-feb-03	0,34	44,07	34,00	26,15	36,06		
22-feb-03	0,34					2,68	6,38
06-mrt-03	1,01	130,93	101,00	77,69	107,12	7,97	18,94
22-mrt-03	0,20	25,93	20,00	15,38	21,21	1,58	3,75
Tcalc/Tmeas		**0,2**	**0,1**	**0,4**	**0,7**	**1,9**	**1,0**

APPENDIX I. WILCOXON TEST ACROTELM TRANSMISSIVITY RATIOS 1992/93 VERSUS 2002 CLARA BOG EAST

Non Parametric Wilcoxon Signed Ranks Test, Acrotelm transmissivity ratio's $T_{calculated}/T_{measured}$ 1992/93 & 2002 using the flow path area method (fpa) and flow path length method (fpl) for Clara Bog East.

Results 1992/93

Ranks

		N	Mean Rank	Sum of Ranks
fpl 1992/93 – fpa 1992/93	Negative Ranks	4[a]	3,50	14,00
	Positive Ranks	1[b]	1,00	1,00
	Ties	1[c]		
	Total	6		

a fpl 1992/93 < fpa 1992/93

b fpl 1992/93 > fpa 1992/93

c fpa 1992/93 = fpl 1992/93

Test Statistics[b]

	fpl 1992/93 – fpa 1992/93
Z	-1,753[a]
Asymp. Sig. (2-tailed)	0,080

a Based on positive ranks.

b Wilcoxon Signed Ranks Test

Small significance values (<0.05) indicate that the two variables differ in distribution.

Here the significance value > 0.05, thus the two methods flows path area and flow path length to calculate the discharge en thus the acrotelm transmissivity ratios in 1992/93 for Clara Bog East do not differ significantly.

Results 2003

Ranks

		N	Mean Rank	Sum of Ranks
fpl 2003 – fpa 2003	Negative Ranks	4[a]	2,50	10,00
	Positive Ranks	0[b]	0,00	0,00
	Ties	2[c]		
	Total	6		

a fpl 2003 < fpa 2003

b fpl 2003 > fpa 2003

c fpa 2003 = fpl 2003

Test Statistics[b]

	fpl 2003 – fpa 2003
Z	-1,826[a]
Asymp. Sig. (2-tailed)	0,068

a Based on positive ranks.

b Wilcoxon Signed Ranks Test

Small significance values (<0.05) indicate that the two variables differ in distribution.

Here the significance value > 0.05, thus the two methods flows path area and flow path length to calculate the discharge en thus the acrotelm transmissivity ratios in 2003 for Clara Bog East do not differ significantly.

As well the results of 1992/93 as for 2003 show that the two methods, flow path area and flow path length, to calculate the acrotelm transmissivity ratios do not differ significantly. Therefore the results of both methods can be used as duplicates (pers. comm Torfs, 2003) to compare the transmissivity ratios of 1992/93 and 2003. This is done below using a non parametric Wilcoxon signed ranks test.

Results 1992/93 versus 2003

Ranks

		N	Mean Rank	Sum of Ranks
2003 – 1992/93	Negative Ranks	12[a]	6,50	78,00
	Positive Ranks	0[b]	0,00	0,00
	Ties	0[c]		
	Total	12		

a 2003 < 1992/93

b 2003 > 1992/93

c 1992/93 = 2003

Test Statistics[b]

	2003 – 1992/93
Z	-3,061[a]
Asymp. Sig. (2-tailed)	0,002

a Based on positive ranks.

b Wilcoxon Signed Ranks Test

Small significance values (<0.05) indicate that the two variables differ in distribution.

Here the significance value < 0.05, thus the transmissivity ratio's in 1992/93 and 2003 differ significantly for Clara Bog East.

APPENDIX J. WILCOXON TEST HUMMOCK VERSUS HOLLOW TRANSMISSIVITIES CLARA BOG EAST

Non Parametric Wilcoxon Signed Ranks Test, Hummock and hollow transmissivities Clara Bog East for four measuring clusters.

<u>1) Results 13/14 February 2003</u>

Ranks

		N	Mean Rank	Sum of Ranks
hummock – hollow	Negative Ranks	3[a]	6,67	20,00
	Positive Ranks	9[b]	6,44	58,00
	Ties	0[c]		
	Total	12		

a hollow < hummock

b hollow > hummock

c hummock = hollow

Test Statistics[b]

	hollow - hummock
Z	-1,490[a]
Asymp. Sig. (2-tailed)	,136

a Based on negative ranks.

b Wilcoxon Signed Ranks Test

Small significance values (<0.05) indicate that the two variables differ in distribution.

Here the significance value > 0.05, thus the transmissivity of hummocks and hollows of Clara Bog East do not differ significantly.

<u>2) Results 21/22 February 2003</u>

Ranks

		N	Mean Rank	Sum of Ranks
Hollow - hummock	Negative Ranks	5[a]	6,40	32,00
	Positive Ranks	10[b]	8,80	88,00
	Ties	0[c]		
	Total	15		

a hollow < hummock

b hollow > hummock

c hummock = hollow

Test Statistics[b]

	hollow - hummock

Z	-1,590[a]
Asymp. Sig. (2-tailed)	,112

a Based on negative ranks.

b Wilcoxon Signed Ranks Test

Small significance values (<0.05) indicate that the two variables differ in distribution.

Here the significance value > 0.05, thus the transmissivity of hummocks and hollows of Clara Bog East do not differ significantly.

3) Results 6 March 2003

Ranks

		N	Mean Rank	Sum of Ranks
hollow - hummock	Negative Ranks	6[a]	7,33	44,00
	Positive Ranks	11[b]	9,91	109,00
	Ties	0[c]		
	Total	17		

a hollow < hummock

b hollow > hummock

c hummock = hollow

Test Statistics[b]

	hollow - hummock
Z	-1,538[a]
Asymp. Sig. (2-tailed)	,124

a Based on negative ranks.

b Wilcoxon Signed Ranks Test

Small significance values (<0.05) indicate that the two variables differ in distribution.

Here the significance value > 0.05, thus the transmissivity of hummocks and hollows of Clara Bog East do not differ significantly.

4) Results 22 March 2003

Ranks

		N	Mean Rank	Sum of Ranks
holow - hummock	Negative Ranks	6[a]	5,83	35,00
	Positive Ranks	9[b]	9,44	85,00
	Ties	0[c]		
	Total	15		

a hollow < hummock

b hollow > hummock

c hummock = hollow

Test Statistics[b]

	Hollow -hummock
Z	-1,420[a]
Asymp. Sig. (2-tailed)	,156

a Based on negative ranks.

b Wilcoxon Signed Ranks Test

Small significance values (<0.05) indicate that the two variables differ in distribution.

Here the significance value > 0.05, thus the transmissivity of hummock sand hollows of Clara Bog East do not differ significantly.

From the results of all measuring clusters can be concluded that the transmissivity of hummocks and hollows of Clara Bog East do not differ significantly.

APPENDIX K. WILCOXON ACROTELM THICKNESS 1991/92 – 2002/03 RAHEENMORE BOG

Non Parametric Wilcoxon Signed Ranks, Acrotelm thickness 1991/92 – 2002/03 2003 Raheenmore Bog

Results

Ranks

		N	Mean Rank	Sum of Ranks
1991/92 – 2002/03	Negative Ranks	83[a]	57,10	4739,50
	Positive Ranks	28[b]	52,73	1476,50
	Ties	16[c]		
	Total	127		

a 1991/92 < 2002/03

b 1991/92 > 2002/03

c 1991/92 = 2002/03

Test Statistics[b]

	1992 – 2003
Z	-4,820[a]
Asymp. Sig. (2-tailed)	,000

a Based on positive ranks.

b Wilcoxon Signed Ranks Test

Small significance values (<0.05) indicate that the two variables differ in distribution.

Here the significance value < 0.05, thus the two variables acrotelm thickness 1991 and acrotelm thickness 2003 differ significantly.