Promotor: dr. ir. R.A. Feddes

Hoogleraar in de bodemnatuurkunde, agrohydrologie en het grondwaterbeheer

Analysis of the hydrology of raised bogs in the Irish Midlands

A case study of Raheenmore Bog and Clara Bog

STELLINGEN

1. Acrotelm en catotelm in hoogvenen zijn geen horizonten, maar concepten die bijdragen tot een beter begrip van de waterhuishouding van hoogvenen.
   Dit proefschrift.

2. De in hoogveenliteratuur nogal eens aangehaalde *Groundwater Mound Theory* van Ingram kan niet dienen als verklaring voor de vorm van dwarsdoorsneden van hoogvenen.
   Ingram, H.A.P., 1982. Size and shape in raised mire ecosystems: a geophysical model. *Nature* 297:300-303.
   Dit proefschrift.

3. In hydrologische zin is de gebruikelijke onderverdeling van mosveen in *Fresh Sphagnum Peat* en *Strongly Humified Sphagnum Peat* dan wel *Younger* en *Older Sphagnum Peat* in Ierse hoogvenen niet functioneel.
   Dit proefschrift.

4. Het uitdrukken van veengroei als stijging van het veenoppervlak geeft, ook bij een bekend volume-aandeel organische stof in een nieuw gevormde toplaag, geen informatie omtrent de toename van de hoeveelheid veen.
   Dit proefschrift.

5. Het model van Van der Molen (1981) dat bedoeld is als berekeningsmethode voor de breedte van bufferzones langs hoogveenresten is zeer geschikt om de relatieve onbeduidendheid van zijdelingse afvoer uit de catotelm aan te tonen, maar juist daarom ongeschikt voor zijn oorspronkelijke doel.
   Van der Molen, W.H., 1981. Über die Breite hydrologischer Schutzzonen um Naturschutzgebiete in Mooren. *Telma* 11:213-220.
   Dit proefschrift.

6. "Peat producers" don't produce peat.

7. Het verdient aanbeveling om op grondwaterkaarten de grootte van grondwaterwinningen aan te duiden met de omvang van hun intrekgebied in plaats van het per tijd onttrokken volume water.

8. Natuurgebieden worden niet veiliggesteld door verwerving alleen, maar pas als in ruime mate wordt geïnvesteerd in kennis van processen die zich afspelen in de betreffende ecosystemen.

9. Het onderscheid tussen de geologische tijdperken Tertiair en Kwartair komt voornamelijk voort uit zelfoverschatting van het mensdom.

10. Het slechts tegen betaling toegankelijk maken van gegevensbestanden door onderzoeksinstellingen leidt tot een verzwakking van de positie van de individuele burger tegenover overheid en bedrijven. Dit betekent een aantasting van de rechtsstaat.

11. Teksten in fraai klinkende volzinnen met geringe informatiedichtheid, voorzien van kleurige illustraties in al even kleurige omslagen vervullen tegenwoordig bij beleidsmakers nagenoeg dezelfde rol als in vroeger tijden kraaltjes en spiegeltjes bij zogenaamde wilden.

12. Hoeveelheden beschikbare tijd plegen geringer te zijn naarmate meer tijd wordt bespaard.

13. De echte Nederlandse provinciaal woont in Amsterdam.

Stellingen behorend bij het proefschrift *Analysis of the hydrology of raised bogs in the Irish Midlands. A case study of Raheenmore Bog and Clara Bog* van S. van der Schaaf, 14 juni 1999.

Sake van der Schaaf

Analysis of the hydrology of raised bogs in the Irish Midlands

A case study of Raheenmore Bog and Clara Bog

Proefschrift

ter verkrijging van de graad van doctor

op gezag van de rector magnificus

van de Landbouwuniversiteit Wageningen.

dr. C.M. Karssen,

in het openbaar te verdedigen

op maandag 14 juni 1999

des namiddags te half twee in de Aula

The facilities needed for the fieldwork in 1989-1993 were jointly funded by the Irish National Parks and Wildlife Service of the Office of Public Works, Dublin and the Dutch National Forest Service (Staatsbosbeheer), Driebergen.

Nederlandse vertaling van de titel:

Analyse van de hydrologie van hoogvenen in de Ierse Midlands.
Een onderzoek aan Raheenmore Bog en Clara Bog

Cover: sketch of Clara Bog by Catherine OBrien, Clara, Co. Offaly

Printed by Grafisch bedrijf Van Essen B.V., Molenaarsgraaf, The Netherlands

ISBN 90-5808-062-5

ABSTRACT

Schaaf, S. van der, 1999. Analysis of the hydrology of raised bogs in the Irish Midlands - A case study of Raheenmore Bog and Clara Bog. Doctoral thesis, Wageningen Agricultural University. 375 pp, 178 figs, 54 tables, 4 app, 209 ref.

In the framework of the Irish-Dutch Raised Bog Project the hydrology of two raised bogs in the Irish Midlands, Raheenmore Bog and Clara Bog, was studied.
The work focuses on relationships in the bog system and how they are affected by drain age and turf cutting along margins. The concept of diplotelmy, a differentiation of the bog body into a shallow highly permeable top layer called acrotelm and a subjacent deep poorly permeable peat layer called catotelm, is followed. Some measuring methods yielded wrong results in bogs, so were modified to produce acceptable results. A novel field method to measure the transmissivity of the acrotelm was developed.

The acrotelm behaves as an aquifer with a constant hydraulic gradient -the surface slope- and a transmissivity that is controlled by the phreatic level. The transmissivity increases by an order of magnitude when the phreatic level rises less than 10 cm and decreases as the level falls. Discharge varies accordingly. This mechanism and the large storage coefficient of the acrotelm ensure small seasonal fluctuations of the phreatic level (20 cm or less). Thus the acrotelm has a regulating effect on the hydrological conditions in a raised bog. Acrotelm transmissivity and-depth depend on surface slope. Well-developed acrotelms occur almost exclusively at surface slopes below 1%.

The catotelm acts as an aquitard. Downward seepage from Clara bog amounts to 5-10 mm a^{-1}. The seepage from Raheenmore Bog is 10-15 mma^{-1}, in spite of differences of up to 3 m between phreatic levels in the acrotelm and piezometric levels in the mineral subsoil. Water loss by horizontal flow in the catotelm is 1 mm a^{-1} or less in both bogs. Thus the hydrological system of the bogs depends little on its surroundings.

Turf cutting and drainage of bog margins directly cause surface subsidence over distances of only a few metres from the margin. This results in a local increase of the surface slope. A steeper surface slope causes a reduction of the regulating properties of the acrotelm and thus a spreading of subsidence into the bogs. Because of the difference in composition of the peat in the centre and along natural margins, subsidence in the centre caused by internal drainage may be larger than along margins, causing watershed positions to shift to the margin. A prominent example is the convergent flow on Clara Bog towards the soak system of Shanley's Lough. Both are the result of subsidence caused by the road that bisects Clara Bog.

Drainage on the bog destroys the acrotelm within a few years. Natural recovery of the bog ecosystem from such damage may take more than a century. Evapotranspiration from both bogs was 0.9 to 1.2 times Penman open water evaporation, depending on precipitation in spring and summer.

Additional index words: ecohydrology, mire, peatland, soaks, subsidence, acrotelm, catotelm.

VOORWOORD

Mijn eerste kennismaking met de venen Raheenmore Bog en Clara Bog was op een zondag in september 1989. Ik zou op een symposium over "Agricultural Engineering" in Dublin een voordracht houden over een totaal ander onderwerp, de wijze van berekening van een bijzonder soort drainage van een terrein bij Lunteren. Het Iers-Nederlandse veenproject zou de volgende maand van start gaan. Mijn collega Jos Schouwenaars zou het hydrologische onderzoek aan de venen gaan leiden. Omdat ik toch naar Ierland zou gaan, hadden we afgesproken dat ik alvast zou gaan kijken en Jos mijn bevindingen zou meedelen. Ik nam dus de trein van Dublin naar Clara en werd daar opgewacht door Pat Warner van Wildlife Service die me een rondleiding gaf en met wie ik namens Jos voorlopige afspraken maakte.

Ik had toen geen enkel vermoeden dat ik ruim een jaar later volop bij datzelfde project zou zijn betrokken doordat Jos aan het eind van de zomer van 1990 onze vakgroep zou verlaten. Omdat ik Ierland enigszins kende en me ook wel eens had beziggehouden met de hydrologie van natuurgebieden, werd mij op een bespreking in de zomer van 1990 gevraagd of ik de taken van Jos in Ierland zou willen overnemen. Aldus geschiedde. Er volgden gesprekken met Jos en met Jan Streefkerk van Staatsbosbeheer, die vooral de Nederlandse kant van het project coördineerde. Beiden praatten me zo goed mogelijk bij over de ins en outs van het project. Met Roel Dijksma die in 1989 de installatie van stuwen en andere meetapparatuur had verzorgd en zich in Ierland met zijn doortastende werkwijze de koosnaam 'The Crazy Dutchman'had verworven en Jan Streefkerk toog ik op 9 oktober 1990 naar Clara. Daar bleek dat er in weinig tijd veel geregeld moest worden. Sommige apparaten, waaronder onze niveaurecorders, functioneerden niet of niet naar behoren en het verschil in werkcultuur tussen Ieren en Nederlanders bleek de nodige strubbelingen te hebben veroorzaakt.

Het probleem van de niveaurecorders was inmiddels opgelost door Donal Daly van de Geological Survey of Ireland, die een vijftal apparaten van de dienst had 'geregeld'. Een ander technisch probleem was de afvoermeting van Clara Bog. Onze watermeter was niet bestand tegen zweef'vuil'in het veenwater. Het probleem werd pas opgelost toen Harry Shine van The Office of Public Works een tweede stuw in plaats van de meter had laten installeren en kunststof schermen waren geplaatst om de afvoer van Clara Bog langs de meetstuwen te leiden. Het was wederom Donal die met het materiaal voor de schermen op de proppen kwam.

De diplomatieke gaven van Matthijs Schouten waren in die turbulente periode van groot nut. Als hij zich met een kwestie bemoeide leidde dat vrijwel altijd tot een werkbare en door iedereen aanvaarde oplossing.

CONTENTS

1. INTRODUCTION 1
- 1.1. Scope 1
- 1.2. Terminology: peatlands, mires, fens and bogs 1
- 1.3. Mire protection: what becomes rare, becomes precious 4
- 1.4. The role of hydrology in mire protection. 8

2. HYDROLOGICAL PROPERTIES OF RAISED BOG SYSTEMS 11
- 2.1. Introduction 11
- 2.2. Seasonal oscillation of the surface level 12
- 2.3. Fluctuation of the phreatic level 13
- 2.4. Reduction of evapotranspiration at low phreatic levels 15
- 2.5. The storage coefficient 16
- 2.6. Discharge behaviour 19
- 2.7. Subsidence 21
- 2.8. Diplotelmic bogs. 23
- 2.9. Ingram's groundwater mound theory 27
  - 2.9.1. The theory and its underlying assumptions 27
  - 2.9.2. Cross-sectional shape and acrotelm hydrology 33
- 2.10. Towards a conceptual hydrological model of (damaged) raised bogs. 34

3. THE BOGS AND THE MEASURING METHODS 36
- 3.1. Introduction 36
- 3.2. The bogs: Clara Bog and Raheenmore Bog. 36
  - 3.2.1. Geological and meteorological setting 36
  - 3.2.2. Raheenmore Bog 38
  - 3.2.3. Clara Bog 39
- 3.3. Phreatic and piezometric levels. 42
  - 3.3.1. Points concerning both Raheenmore and Clara Bog 42
  - 3.3.2. Raheenmore Bog 43
  - 3.3.3. Clara Bog East 43
  - 3.3.4. Clara Bog West 44
- 3.4. Level recorders 46
- 3.5. Reference levels of dip wells 48
- 3.6. Vertical movement of the bog surface. 48
- 3.7. Precipitation 49
- 3.8. Surface slope 50
- 3.9. Hydraulic conductivity of the catotelm and peat thickness 51
  - 3.9.1. Introduction 51
  - 3.9.2. Horizontal and vertical hydraulic conductivity in peat 52
  - 3.9.3. The piezometer method 53
  - 3.9.4. Non-Darcyan flow in hydraulic conductivity tests in peat 55
  - 3.9.5. Testing and modifying the piezometer method 58
- 3.10. Volume fraction of organic matter, degree of humification 60
  - 3.10.1. Introduction 60
  - 3.10.2. The measuring technique and the measuring sites 62

3.10.3. Comparing profiles 64
3.11. Evapotranspiration 66
3.12. Storage coefficients 68
3.13. Acrotelm depth 69
3.14. Acrotelm transmissivity 69
3.14.1. Introduction 69
3.14.2. The semi-steady state method. 70
3.14.3. The pit bailing method 73
3.15. Discharge 75
4. HYDROLOGICAL PROPERTIES OF THE CATOTELM 78
4.1. Introduction 78
4.2. Spatial patterns of some peat properties 78
4.2.1. Introduction 78
4.2.2. Spatial patterns of humification 81
4.2.3. Spatial patterns of the volume fraction of organic matter 90
4.2.4. Hydraulic conductivity 93
4.2.5. Discussion and conclusions on spatial patterns 98
4.3. Hydrophysical relationships 99
4.3.1. Introduction 99
4.3.2. Volume fraction of organic matter and humification 99
4.3.3. Hydraulic conductivity and volume fraction of organic matter 102
4.3.4. Humification and hydraulic conductivity 105
4.3.5. Discussion and conclusions on hydrophysical relationships 108
5. FLOW IN THE CATOTELM 110
5.1. Introduction 110
5.2. Concepts 110
5.3. Estimating T_c and C_c from K 114
5.3.1. Introduction 114
5.3.2. Estimating k from ϕ_o; method of reduced major axis 114
5.3.3. Frequency distributions of measured and estimated k 117
5.3.4. Comparing k_h and k_v, obtained from measured and/or estimated k 118
5.3.5. Discussion and conclusions 127
5.4. Lateral discharge from the catotelm 128
5.4.1. Introduction 128
5.4.2. Raheenmore Bog 129
5.4.3. Clara Bog 139
5.5. Exfiltration 145
5.5.1. Introduction 145
5.5.2. The estimating method 146
5.5.3. Results 146
5.5.4. Discussion 149
5.5.5. Conclusions 151
6. ACROTELM HYDROLOGY 153
6.1. Introduction 153
6.2. The storage coefficient 154
6.2.1. Introduction 154
6.2.2. Storage coefficients from lysimeters 154

6.2.3. Storage coefficients from rain gauge and phreatic level recordings 159
6.2.4. Conclusions 162
6.3. Acrotelm transmissivity 163
6.3.1. Introduction 163
6.3.2. Comparing methods. 163
6.3.3. Acrotelm transmissivity and phreatic level 170
6.3.4. Acrotelm transmissivity and discharge 176
6.3.5. Spatial patterns of acrotelm transmissivity 181
6.3.6. Acrotelm transmissivity as a function of slope and flow pattern 184
6.3.7. Testing the theory of self-regulating acrotelm transmissivity 187
6.4. Acrotelm depth 196
6.4.1. Introduction 196
6.4.2. The spatial pattern 197
6.4.3. Acrotelm depth and -transmissivity 200
6.4.4. Acrotelm depth as a function of surface slope and flow path length 202
6.4.5. Conclusions on acrotelm depth 205
6.5. A model of acrotelm growth based on hydrological conditions 205
6.6. Conclusions on acrotelm hydrology 209
6.6.1. The storage coefficient 209
6.6.2. Transmissivity 210
6.6.3. Acrotelm depth 211
7. VOLUME FRACTION OF ORGANIC MATTER AND SUBSIDENCE 212
7.1. Introduction 212
7.2. Some remarks on the process of subsidence along disturbed margins 213
7.3. Raheenmore Bog 214
7.3.1. Introduction 214
7.3.2. Volume of solid matter per peat type: spatial patterns 214
7.3.3. Reconstructing former bog surface levels 218
7.4. Clara Bog West 223
7.4.1. Introduction 223
7.4.2. Volume of solid matter per peat type: spatial patterns and comparison with Raheenmore Bog 224
7.4.3. Reconstructing former bog surface levels 230
7.5. Subsidence in recent years 236
7.5.1. Introduction 236
7.5.2. Raheenmore Bog 236
7.5.3. Clara Bog 241
7.6. Conclusions 244
8. PHREATIC LEVELS AND THEIR FLUCTUATION 248
8.1. Introduction 248
8.2. Conversions of phreatic level data 248
8.2.1. Representing fluctuations of the phreatic level as a single quantity 248
8.2.2. Effects of *Mooratmung* on measured phreatic levels 250
8.2.3. Effect of observation period length on mean and standard deviation of phreatic levels 251
8.3. Fluctuation patterns of phreatic levels 252
8.4. Statistical relationships 256
8.4.1. Introduction 256

8.4.2. Surface slope and mean depth of the phreatic level 256
8.4.3. Surface slope and fluctuation of the phreatic level 257
8.4.4. Mean and fluctuation of the phreatic level 258
8.4.5. Acrotelm depth and mean phreatic level 258
8.4.6. Acrotelm depth and fluctuation of the phreatic level 259
8.4.7. Drain levels and mean and fluctuation of the phreatic level on Clara Bog East 260
8.5. The transects 262
8.5.1. Raheenmore Bog 262
8.5.2. Clara Bog West 266
8.6. Discussion and conclusions 271
9. THE WATER BALANCES 274
9.1. Introduction 274
9.2. Catchment sizes 274
9.3. Precipitation 276
9.3.1. Raheenmore Bog 276
9.3.2. Clara Bog 277
9.3.3. Comparing precipitation sums of the bogs with the nearest meteorological stations and 30 year normals 278
9.4. Evapotranspiration 280
9.4.1. Raheenmore Bog 280
9.4.2. Clara Bog 286
9.4.3. Discussion 290
9.5. Release of water from storage 292
9.6. Water balances 293
9.6.1. Balances based on lysimeter evapotranspiration 293
9.6.2. Water balances over the entire observation period 295
9.6.3. Conclusions 297
9.7. Conclusions 298
10. SUMMARY AND CONCLUSIONS 300
10.1. The project and the bogs 300
10.2. Research questions 300
10.3. Measuring methods 301
10.4. General points on raised bog hydrology 302
10.4.1. Bogs as groundwater mounds 302
10.4.2. Vertical seepage 303
10.4.3. Effects of external drainage on bog hydrology 304
10.4.4. Internal drainage and subsidence 304
10.4.5. Surface shape and acrotelm transmissivity 305
10.4.6. Acrotelm properties and phreatic level fluctuations 306
10.4.7. The acrotelm as a regulator of bog discharge 306
10.4.8. The acrotelm as a self-regulating and self-healing system 307
10.4.9. Evapotranspiration 307
10.5. Specific points on the hydrology of Clara Bog and Raheenmore Bog 308
10.5.1. Hydrological effects of the old drains on Raheenmore Bog 308
10.5.2. Effects of external drainage on the hydrological conditions on the bogs 308
10.5.3. The Clara-Rahan road 309

10.5.4. The drainage system on Clara East 309
10.5.5. The water balance of the two bogs 310

11. SAMENVATTING EN CONCLUSIES 311
11.1. Het project en de venen 311
11.2. Onderzoeksvragen 311
11.3. Meetmethoden 312
11.4. Algemene vraagstukken met betrekking tot de hydrologie van hoogvenen ... 314
11.4.1. Hoogvenen als grondwaterheuvels 314
11.4.2. Wegzijging 315
11.4.3. Uitwerking van externe ontwatering op de hydrologie van hoogvenen 316
11.4.4. Interne ontwatering en zetting. 316
11.4.5. De vorm van het veenoppervlak en het doorlaatvermogen van de acrotelm 317
11.4.6. Acrotelmeigenschappen en grondwaterstandsschommelingen 318
11.4.7. De acrotelm als regulator van de afvoer van hoogvenen 318
11.4.8. De acrotelm als zelfregulerend en zelfherstellend systeem 319
11.4.9. Evapotranspiratie 320
11.5. Specifieke punten met betrekking tot de hydrologie van Clara Bog en Raheenmore Bog. 320
11.5.1. Hydrologische effecten van de greppels op Raheenmore Bog 320
11.5.2. De invloed van externe ontwatering op de hydrologische omstandigheden in de venen 321
11.5.3. De weg van Clara naar Rahan 321
11.5.4. Het ontwateringsstelsel van Clara Oost. 322
11.5.5. De waterbalans van beide venen 322

REFERENCES 323

APPENDICES 338
A. Humification and volume fraction of solid matter transects 339
A.1. Transect positions 339
A.2. Cross sections along the transects 339
A.3. Humification profiles 343
A.4. Profiles of volume fraction of solid matter 348
A.5. Average ϕ_b and correlation of ϕ_b and H with depth at individual sites 353
B. Hydraulic conductivity transects 356
B.1. Transect positions 356
B.2. k-profiles 357
B.3. Geometric mean of k and correlation of k with depth at individual sites ... 359
C. Vertical resistance and vertical flow in the catotelm 361
C.1. Site positions 361
C.2. Results 362
D. Fitted Parameters of acrotelm transmissivity models 367
D.1. Site positions 367
D.2. Results 368

SYMBOLS AND ABBREVIATIONS 370

ABOUT THE AUTHOR 375

1. INTRODUCTION

1.1. Scope

This thesis is based on fieldwork carried out in the framework of Irish-Dutch Raised Bog Study. The project was a result of an agreement between the Irish and the Dutch governments, signed in 1989. An important reason for the agreement was the acquirement by the Irish government of several bogs for protection. The project was meant to combine knowledge on bog restoration techniques and hydrological management of bog remnants as developed in the Netherlands and knowledge on the much less damaged Irish bogs, available at the Irish Wildlife Service. Conservation, restoration and regeneration of raised bogs require an in-depth knowledge of the role of the biotic and abiotic components of a bog ecosystem and their role in bog development. It was expected that the Dutch experience could be useful in bog conservation in Ireland and that nature conservation in the Netherlands could benefit from available knowledge on living bogs in Ireland. In addition, a field research project on Irish bogs was envisaged.

The field project consisted of case studies on two bogs, Clara Bog and Raheenmore Bog. Their geographical positions are shown in Fig. 1.1. Both bogs were believed to be only slightly damaged. Fieldwork started in the autumn of 1989 with Irish and Dutch organisations participating. The fieldwork on Clara Bog and Raheenmore Bog ended in the summer of 1993. It comprised the geology, geophysics, hydrology and ecology of the bogs and their surroundings. Although the hydrological system of the bogs is embedded in a regional system, this thesis is confined to the hydrological system of the bogs only.

1.2. Terminology: peatlands, mires, fens and bogs

The word *mire* usually refers to a peat-forming ecosystem that has developed a peat layer of such a depth that the soil may be classified as a peat soil. A fundamental subdivision of mires is into *fen* and *bog* (Gore, 1983). The words *fen* and *bog* are roughly equivalent to the German *Niedermoor* and *Hochmoor*, respectively. Fen systems obtain at least part of their water from other sources than the atmosphere, for example groundwater from surrounding mineral soils or water from river flooding, whilst bogs depend solely on atmospheric water.

When the continuing accumulation of organic debris causes fens to grow above the (ground)water level of their surroundings, they may develop into bogs if climatic conditions are sufficiently humid and cool to permit such a development (e.g. Succow and Jeschke, 1990). Sometimes bogs or parts of bogs have also developed directly on mineral soils. Bogs can be classified in different ways. Several reviews on this subject are available in mire literature, such as the one by Gore (1983).

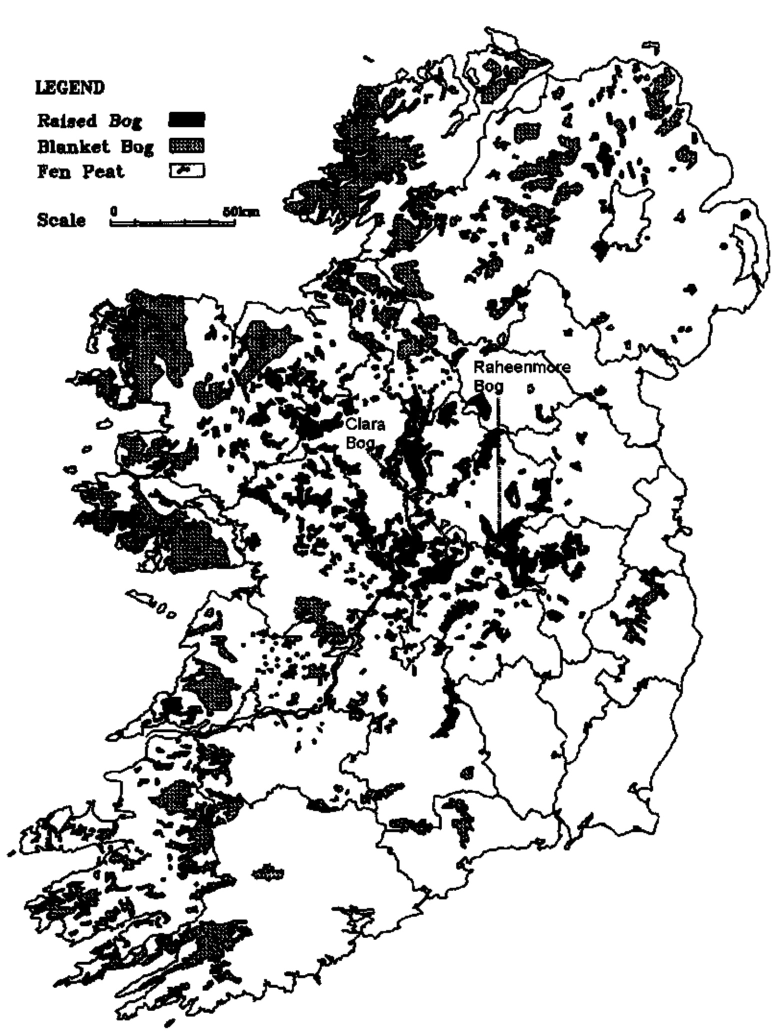

Fig. 1.1. Raised bogs, blanket bogs and fens in Ireland (O'Donnell, 1996). The grey lines point to *Clara Bog* and *Raheenmore Bog*, which are positioned in the heart of the grey circles at their end.

In Ireland, two principal types of bog occur: blanket bogs and raised bogs. Blanket bogs follow the topography of the underlying mineral substratum. They occur where the average annual precipitation exceeds 1250 mm and the average number of rain days is 225 or more (Hammond, 1981). In Ireland these are the lowlands and uplands of the extreme west and north-west and most uplands in other parts of the country (Fig. 1.1). In Europe, blanket bogs also occur in Scotland and Norway (Fig. 1.2, Fig. 1.3).

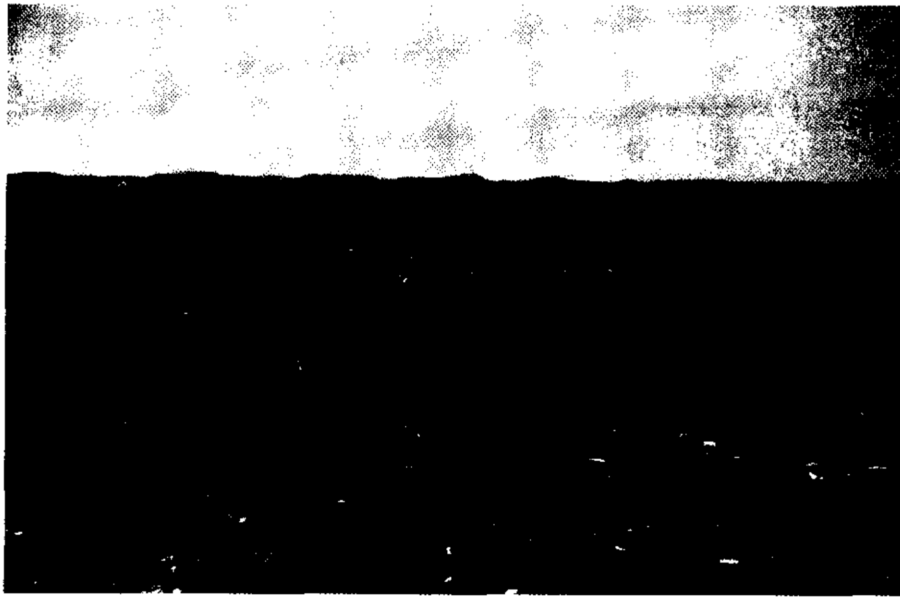

Fig. 1.2. Lowland blanket bog (Toppmyrane, Smøla, Norway, July 1994).

Fig. 1.3. Mountain blanket bog (Skuløy, Norway, 1994). Background: reclaimed blanket bog with spruce forest.

Raised bogs (Fig. 1.5 and Fig. 1.6) have developed in the less extreme climatic conditions of the Irish Midlands where the average annual precipitation generally amounts to 800 to 1000 mm. The average annual excess precipitation, based on potential grassland evapotranspiration as calculated from Penman open water evaporation by the Irish Meteorological Service (Met Éireann), is around 350-500 mm. Where the average annual excess precipitation in Ireland is less than 250 mm, no bogs occur (Hammond, 1984).

Most raised bogs have grown on top of fen peat that had first filled in waterlogged depressions in the morainic landscape (Fig. 1.4), left behind by the land-ice cover of the Midlandian[1] ice age (Mitchell, 1976). Contrary to blanket bogs, raised bogs have a distinct recognisable boundary along most if not all of their perimeter (Gore, 1983). In Ireland, raised bogs once covered about 310 000 ha. As a result of cutting of peat for fuel and industrial peat extraction, in 1989 only 22 000 ha or 7% remained that were believed to be reasonably intact (Cross, 1989). Later surveys by the Irish Wildlife Service showed that this figure is overestimated, but exact information has not been published yet.

In this thesis, the term *mire* is used where it includes both *bog* and *fen* ecosystems. The term *peatland* includes both mires and land with peat soils that are no substratum of (potential) peat forming ecosystems, such as cutover areas or areas of peat soils that are in use as agricultural land.

1.3. Mire protection: what becomes rare, becomes precious

In the 18th century mires were a common feature in the landscape of western and north-western Europe. However, already in the late Middle ages peat was cut at a large scale for fuel in Flanders. Hardly any trace of those peatlands is left today (Borger, 1990). In the 17th century, large-scale peat extraction occurred in the Netherlands and turf was even shipped to harbours in north-west Germany in spite of the proximity of bogs to these cities. The main reason was the accessibility over canals of the bogs in the Netherlands, resulting in the possibility of cheap transport (De Zeeuw, 1976). The cleared subsoil was reclaimed for agriculture. Obviously, the turf was considered more precious than the bogs that were looked upon as wastelands.

Linnaeus (1751) was very descriptive as to the way bogs were looked upon in the middle of the 18th century. He depicted them as less than useless areas for farmers, because cattle often got stuck and died in the deep mud. In his view, the bog could best be used to improve agricultural yields on condition that proper measures would be taken. Such measures included cutting a deep drain right across the bog to the side where discharge would be easiest. After drainage, the entire vegetation should be rooted up, put into piles to rot and be burnt. In Linnaeus' view, this would yield a perfect fertiliser to improve the farmland, so that those living near a bog and having poor land with weeds should blame themselves rather than nature for this. He advised to install a dense system of drains in the bog after this treatment and to mix the topsoil with mineral subsoil ma-

---

[1] On the European continent this ice age is generally referred to as Weichselian.

terial in case it had been brought up from the drains, thus converting the bog to agricultural land. Linnaeus even specified the grass species that were likely to grow best.

In 1765 Friedrich II, King of Prussia, declared all mires without owner state property with the intention to reclaim them. The royal peatland commissioner J.C. Findorff (1720-1792) developed a large-scale reclamation plan. The colonists in the Findorff settlements usually obtained part of their small income from cutting and selling turf and part from cultivating buckwheat. The crop was grown on peatland that had been burnt subsequent to shallow drainage, in order to make some nutrients available to the crop. When the German *Hochmoorkultur*, developed at the *Moorversuchsstation* (peatland research station) in Bremen, founded in 1877, replaced the buckwheat culture (Eshuis and Kruitbosch, 1948), even more bogland was reclaimed, not in the least because in those days the nutrient problem could be solved by the application of artificial fertiliser. When the physical properties of the older reclaimed peatlands became increasingly problematic for agriculture, the German *Sandmischkultur* (sand mix cultivation), developed at the Bremen Institute in the late 1930's was applied. This caused the conversion of many previously reclaimed peat soils of 1 to 1.60 m deep into mixed organic/mineral soils (Kuntze, 1972).

As a result of these and similar developments in other countries, mires disappeared from the landscape of north-western Europe with increasing speed. In north-western Germany and the Netherlands the last important areas of bog were reclaimed or mined in the 1950's and 1960's.

In Ireland, where roughly 17% of the country was covered by peat, the development of bog utilisation differed strongly from what happened in Germany and the Netherlands. Turf cutting occurred mostly at a relatively small scale for the production of household fuel until the late 1930's, when the large bog areas were still reasonably intact. Only after World War II, rapid changes occurred. Large-scale industrial mining schemes were started, mostly by the state-owned company Bord na Móna, aiming at reducing Ireland's dependence on imported fuels, its economic dependence on Britain and fighting the poverty in the Irish Midlands. The production included household fuel (turf and peat briquettes), generation of electricity and garden peat. In the Irish Midlands, several peat-fuelled power stations are still in operation (Fig. 1.7).

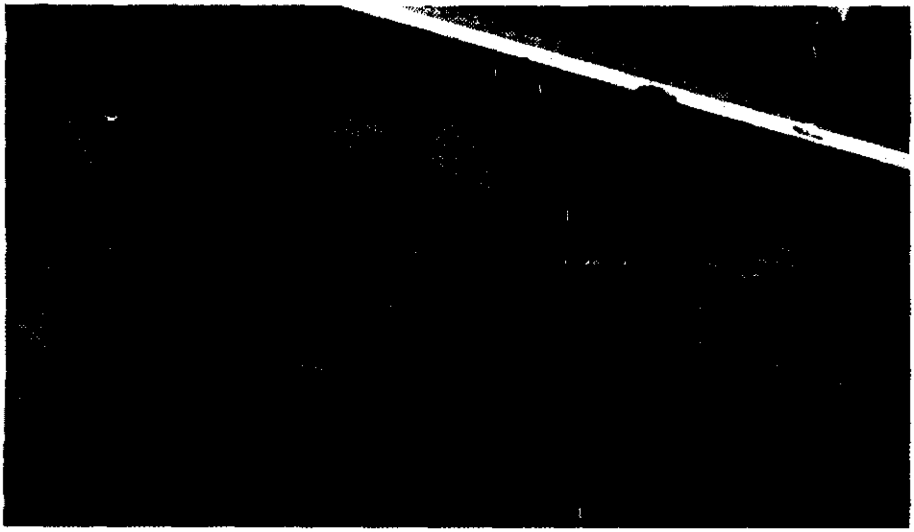

Fig. 1.4. Infilling lake south of Lower Red Lake, North Minnesota (July 1998, from a height of 250 m). Probably similar to an early stage of development of Raheenmore Bog and Clara Bog.

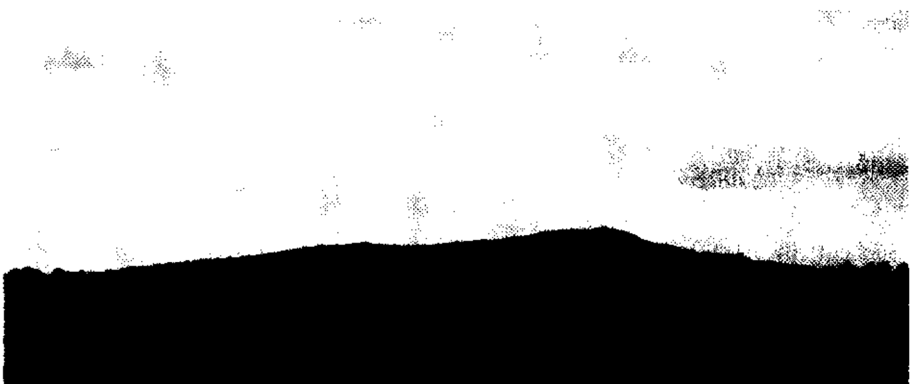

Fig. 1.5. Raheenmore Bog (October 1990), one of the two raised bogs studied. The vegetation is dominated visually by *Eriophorum vaginatum*. In the background Croghan, an outcrop of volcanic rock.

The growing awareness that undisturbed mires were becoming rare and thus precious remnants of once common elements of the landscape of north-western Europe, caused the general attitude towards mires and bogs to swing gradually towards protection instead of utilisation of mires.

In the concluding chapter of his book on the bog of Augstumal (then part of the kingdom of Prussia, now in Lithuania), Weber (1902) showed a different view on bogs and their conservation, even though he still favoured reclamation for agriculture. He described that the bog he had known until 1898 as a hardly accessible wetland had been turned into an easily accessible area with newly built homes and worked fields in 1900. Weber recalled the beauty of the wilderness, but at the same time mentioned the sound of playing children and the view of a thriving agriculture that had replaced the silence and remoteness of the bog. Although Weber showed little doubt as to which of both should be preferred, he called the disappearance of the beauty of nature a painful experience. The year before, the same author (Weber, 1901) had advocated the conservation of a number of mires in Northwest Germany, foreseeing their extinction in a not too distant future as a result of reclamation and peat extraction. Weber's pledge was in vain. He appeared to be too far ahead of the generally accepted ideas of his days. The areas Weber had in mind for conservation were too attractive for peat extraction and reclamation for agriculture (Grosse-Brauckmann, 1996) and short-term economic considerations prevailed over those of nature protection.

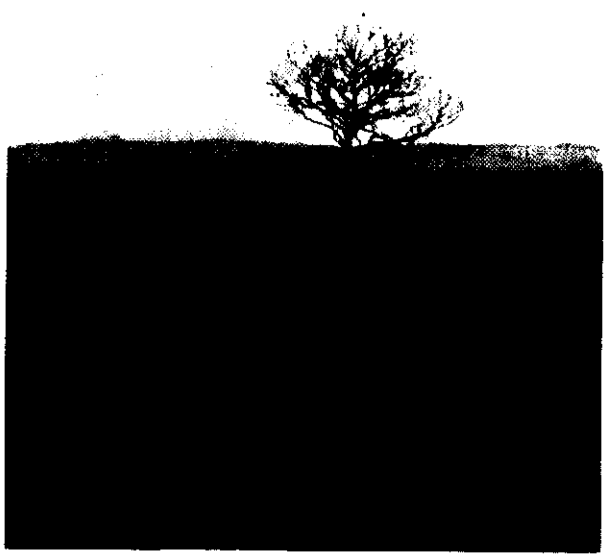

Fig. 1.6. Clara Bog seen from the soak area of Shanley's Lough (December 1990). Clara Bog is one of the two raised bogs studied. The solitary birch tree (*Betula pubescens*) is an "outpost" of the birch grove near the lake. Foreground: bog pool with *Menyanthes trifoliata*, a species that occurs in some pools around Shanley's Lough. The vegetation is visually dominated by *Eriophorum vaginatum* and *Calluna vulgaris* (on the hummocks). In the background the esker between Clara town and the bog.

It was not until the 1970's that in most European countries government policy towards mires began to change. In Germany for example, a federal law on nature conservation and landscape management came into effect in 1976 (Grosse-Brauckmann, 1996). In Switzerland, the Rothenthurm Initiative enforced the conservation of mires and mire landscapes by referendum in 1987 (Grünig, 1994). In the Netherlands, law enforced an end to peat extraction in the 1990's.

The text to the Peatland Map of Ireland (Hammond, 1981), even in the paragraph on future developments, still focused on the usage of Irish peatlands for agriculture and forestry. The agreement of 1989 that marked the beginning of the Irish-Dutch co-operation demonstrated the rapid change in attitude towards bogs in Ireland. In 1990 the Irish government expressed its wish to eventually acquire 10 000 ha of raised bogs and 40 000 ha of blanket bogs for protection (Treacy, 1990).

Today, many of the usually small remnants of the peatlands of Western Europe are protected and often large sums are spent on their conservation and restoration. In the Netherlands alone, an amount in the order of magnitude of 100 million guilders has been spent since about 1970 on measures for protection, restoration and regeneration.

1.4. The role of hydrology in mire protection.

Mire systems can only develop and sustain in the presence of sufficient water that prevents decay of plant remains by cutting them off from atmospheric oxygen. Hence, the main component of a mire soil is water and hydrology is an essential part of comprehensive mire studies. However, until the 1970's, most hydrological knowledge on mires was gathered for the purpose of industrial peat extraction and reclamation for agriculture or forestry. In Western Europe, most of the purely scientific attention for mire ecosystems came from botanists and geologists.

In the former Soviet Union, this situation changed immediately after World War II. Even though many mires were mined or reclaimed for agriculture, mire hydrology became an object of study. The main reason was that the usage of aerial photographs for geobotanical mapping by Jekaterina Galkina, a Russian geographer, had shown its value for military purposes during the Leningrad blockade (Masing, 1998). This led to the founding of several field stations where observations on hydrology and botany were done by specialised staff and on a regular basis, such as those at Lammin Suo (Russia) and Tooma (Estonia). The work resulted in a large number of publications, mostly in Russian. Only a small part has been translated into English, such as the books by Ivanov (1981) and Romanov (1968a, 1968b) and several articles in Soviet Hydrology.

In the 1970's, the need of hydrological knowledge in mire conservation and restoration began to become clear in Western Europe. Until then, measures were often taken on an empirical basis, such as the construction of the first embankments for rewetting and protecting Meerstalblok, a tiny remnant of the huge Bourtangermoor that once stretched along both sides of the border between Germany and the Netherlands. The number of publications on mire hydrology that focused on the systems themselves and restoration rather than drainage and its effects gradually increased in the 1980's and 1990's. Symposia and other meetings on mire conservation and restoration often had a good number of papers on mire hydrology in their proceedings. Examples are Bragg *et al.* (1992) and Wheeler *et al.* (1995). More than ever, mires are now looked upon as ecosystems in which the role of water is crucial. The mechanisms that determine relationships of hydrological conditions and bog growth should be known in depth and preferably be quantifiable. This kind of knowledge is needed to ensure the survival of mires in a world in which man has conquered the means to adjust his environment to his requirements.

During the last years it is becoming increasingly clear that hydrological management of bogs and bog remnants, although essential in bog restoration projects, may not provide the one and only key to success. This seems particularly true in bog remnants that have been strongly damaged and in regeneration projects in areas where most of the peat has been extracted. In many parts of such areas in the Netherlands for example, *Sphagnum* growth does not even start or does not get beyond a stage with predominant *Sphagnum cuspidatum* and/or *Sphagnum recurvum*, whilst in other parts with apparently the same hydrological conditions, peat forming *Sphagna* such as *S. magellanicum* thrive. The role of the deposition from the atmosphere of nitrogen and other compounds and the calcium- and carbon dioxide balances in mires are still unclear. A review of available knowledge and desirable research is given by Schouwenaars *et al.* (1997). These aspects, although probably highly important in bog restoration projects, are beyond the scope of this thesis, but are mentioned here to show the context in which quantitative mire hydrology is to be placed.

An element of increasing importance in the discussion on the ecological role of mire systems is their function as a carbon sink. Sound hydrological management of mires is essential in maintaining this function and in preventing mires from becoming sources of atmospheric carbon. For a (very) rough impression of the global importance of mires in the discussion on greenhouse gases, a few data are given below.

About 3% of the Earth's land surface is covered by mires (Lappalainen, 1996). Assuming an average peat depth of 1.50 m and an average volume fraction of organic matter of 0.09, Lappalainen estimated the total amount of carbon accumulated in peat in the world in the order of $250*10^{12}$ kg. Clymo's estimate (Clymo, 1998) is $600*10^{12}$ kg. This is roughly 40-100% of the mass of carbon dioxide that is currently contained by the atmosphere. Reclamation and mining will eventually cause most of this carbon to enter the atmosphere in the form of carbon dioxide, thus adding to the greenhouse effect.

Fig. 1.7. Industrial peat mining area with electric power station and rail transport of milled peat (Boora, March 1993).

Measured accumulation rates of carbon in Finland in regrowth surfaces after peat extraction were approximately 750 kg ha^{-1} a^{-1} (Vasander and Roderfeld, 1996). If decay is taken into account, the net accumulation in older mires may be estimated at approximately 250 kg ha^{-1}, the approximate average of data from different countries compiled by Franzén (1992). Reclamation of peatlands has a net effect on the carbon balance of carbon release the atmosphere that (considerably) exceeds the value found by Vasander and Roderfeld.

2. HYDROLOGICAL PROPERTIES OF RAISED BOG SYSTEMS

2.1. Introduction

This chapter starts with a review of literature on hydrological properties of raised bogs. The concept of diplotelmy as formulated by Ingram (1982) and Ingram and Bragg (1984) is discussed as to its possibilities to serve as a basis for a comprehensive concept of the hydrology of raised bog systems. After a short general description of both Clara Bog and Raheenmore Bog, the research questions that should lead to a conceptual approach to the hydrology of raised bog systems in general and Clara and Raheenmore Bog in particular, are formulated.

Mire systems differ hydrologically from mineral soil areas in a number of ways. These differences are caused by genesis and soil material. A distinguishing property of peat soils in a living mire is that their material is produced in situ and undergoes diagenesis - or partial decay- under the influence of alternating drying and wetting and exposure to atmospheric oxygen, until eventually the material becomes permanently waterlogged. Then the speed of decay becomes extremely slow. Although mire soils are generally termed "organic soils", their main component is water. According to Ivanov (1981), the volume of water in undisturbed and saturated peat may be between 88 and 97%.

Moore and Bellamy (1974) distinguished three hydrological stages of a mire: primary, secondary and tertiary mires. Primary mires are formed in waterlogged basins or depressions. Secondary mires do not depend on basins, but still are influenced by groundwater. Tertiary mires are those that develop "above the physical limits of the ground water", so they are in fact bogs. The authors also state that the water in tertiary mires is held by forces of capillarity, but as Ingram (1982) argues and as can simply be checked in the field with a few piezometers, this is not true. Their three stages coincide approximately with the respective rheotrophic, transitional and ombrotrophic stages as distinguished and described by Hobbs (1986).

Raised bogs are tertiary mires as defined by Moore and Bellamy (1974) and ombrotrophic mires in the terminology as adopted by Hobbs (1986). They solely depend on precipitation for their supply of water. Although their surface level lies above the phreatic level in the neighbouring area, the water table remains close to the surface. Bogs can only develop in a climate that causes the surface layer to remain wet enough to limit the decay of newly formed organic matter to a rate below that at which new material is produced by the vegetation cover. In Europe, raised bogs generally occur north of a latitude of about 51-52° N. They also occur in mountainous regions at more southern latitudes, e.g. in the Alps and the Jura. Schneider and Schneider (1990) presented a zonation map, based on Kac (1971) and area totals of mires for different countries.

A raised bog surface can reach a height of several metres above its surroundings. A reconstruction by Eggelsmann (1967) of 64 raised bog surfaces in Lower Saxony, based on topographic maps of around 1900 showed an average height of 5 m at an average diameter of 6 km. Granlund (1932) found a relationship between annual precipitation and bog size and the height of bog domes for some parts of Southern Sweden. Granlunds results for Småland showed an average height of the peat dome of 3 to 5 m at cross sections of 1 km and at an average annual precipitation sum of 500-600 mm to 900-1000 mm, respectively.

The view that raised bogs are solely precipitation fed is more than 175 years old. Dau (1821, cit. Overbeck, 1975) already showed to be aware of this in his book on bogs of Schleswig and Holstein. Besides this observation that raised bogs depend on precipitation, an interesting aspect of Dau's view was that he looked upon bogs as systems or even organisms.

Undisturbed raised bogs are normally surrounded by a lagg. "Lagg" is Swedish for a zone where the runoff from the bog and mostly (subsurface) runoff from the surrounding mineral area is collected and from which the water is further discharged. A lagg normally is extremely wet. Contrary to the vegetation on the bog, the lagg vegetation usually indicates minerotrophic conditions (the influence of dissolved mineral components in groundwater) because of the hydraulic contact with mineral strata.

The most important characteristics that are typical for raised bogs and that distinguish them in a hydrological sense from areas with mineral soils are

- the vertical oscillation of the surface resulting from wetting and drying
- the small temporal fluctuation of the phreatic level
- reduction of evapotranspiration that already occurs at shallow phreatic levels
- large storage coefficients
- a discharge behaviour that is characterised by large discharge peaks during and shortly after periods of precipitation and a quick recession to a fraction of the peak discharge, usually within one or two days
- large surface subsidence occurring after drainage

A discussion of these points, based on available literature, is given in the next sections.

2.2. Seasonal oscillation of the surface level

The surface level of bogs moves up and down with the seasons. In north-western Europe, the lowest levels normally occur at the end of the summer, the highest at the end of the winter or in early spring. A graph presented by Nilsson (1982) clearly shows the relationship of water level fluctuations and movement of the surface level in the bog Komosse in Småland, southern Sweden. Uhden (1956) called the phenomenon *Atmen* *der Hochmoore*, which probably was shortened later to *Mooratmung*, bog breathing. For an undisturbed raised bog Uhden reported a difference between highest and lowest levels of up to 0.07 m and mentioned a measured all time maximum in Niedersachsen of 0.11 m.

Baden and Eggelsmann (1964) discussed data measured in 1956 and 1957 from both uncultivated and cultivated parts of Königsmoor near Tostedt between Hamburg and Bremen. The difference between the highest and the lowest surface level in the uncultivated peatland was 0.015 and 0.030 m in the two years, respectively. 50% of the movement in the uncultivated bog occurred in the upper 0.35 m. The differences in a drained part of Königsmoor were 50-100% larger.

Uhden (1967) presented data over 1955-1962 of the undisturbed part of another bog, the Esterweger Dose. However, probably as a result of drainage in adjacent parts of the bog, his fluctuation line of the bog surface level, even after correction for problems in the measuring equipment, contained a component of surface subsidence. After removal of this effect over 1955-1958, a fluctuation of some 4-5 cm can be derived with the highest surface levels around March and the lowest ones around August. Uhden's data of 1959 and later seem unreliable because of the combined influence of the dry summer of 1959 and the decreased size of the trial area.

The available data from Uhden show that in years with wet summers the fluctuations tend to be smaller than in years with dry summers. This is easily understood as the bog surface reaches the same level in almost any winter, whilst the reversible subsidence in the summer depends on the precipitation deficit of that season. Under the climatic conditions of north-western Germany the fluctuations in undisturbed bogs do not normally exceed 10 cm. Nilsson's data for Komosse suggest slightly larger extremes for southern Sweden. In Irish Midland conditions such fluctuations may generally be smaller because of the difference in climatic conditions. Because the dry matter volume in the peat does not change, the volume involved in the fluctuation is the volume of water. Consequently a fluctuation of the surface level by a few cm means an equal change in water storage. This may not be a negligible amount in water balance studies.

2.3. Fluctuation of the phreatic level

In average years, raised bogs receive considerably more water from precipitation than they lose by evapotranspiration. At the same time, they have a precipitation deficit during at least a part of most summers. Nonetheless, the groundwater level in raised bogs fluctuates little compared to the level in mineral soils under similar climatic conditions.

Sphagna, which usually are the most important producers of organic matter in raised bogs, only grow in situations with a mean phreatic level near or at the surface and small seasonal fluctuations. Ivanov (1981, p.13) mentions some values. *Sphagnum magellani-*

cum has a mean depth of the water table below the moss surface of 5-25 cm; only *S. fuscum* has larger values. The values for all other *Sphagna* in Ivanov's table are smaller.

Balyasova (1974) analysed about 20 years of daily observations on eight raised bogs in the European part of the former USSR. For ridge-pool complexes with *Sphagnum-Eriophorum* vegetations with some low pine and "subshrub" she derived probability levels of annual mean, maximum and minimum water levels and presented them in a graphical form. Table 2.1 shows values, derived from her graphs.

Table 2.1. Probabilities of larger values of annual mean, maximum and minimum water levels in ridge-pool complexes in raised bogs in the European part of the former USSR, derived from Balyasova (1974). Values in m above average surface level.

Probability	0.05	0.20	0.50	0.80	0.95
Annual mean level	-0.04	-0.07	-0.11	-0.16	-0.23
Maximum level	0.21	0.12	0.05	-0.01	-0.08
Minimum level	-0.10	-0.17	-0.25	-0.30	-0.35

Although annual mean, maximum and minimum levels with equal probability of exceedance do not necessarily occur in the same year, Table 2.1 suggests that on average the highest and lowest levels in a year differ by some 30 cm. This is much less than what usually would occur in a mineral soil with a groundwater table close to the surface.

Baden and Eggelsmann (1964) presented data on phreatic levels, derived from daily measurements over 1951-58 in an uncultivated but superficially drained part of Königsmoor. According to Eggelsmann (1963) the vegetation included *Calluna vulgaris, Erica tetralix, Sphagnum recurvum, "Sphagnum rubra"* (probably *S. rubellum* was meant), *S. imbricatum, S. fuscum, S. acutifolium* and *Eriophorum vaginatum*, which indicates that the bog had not been disturbed to an extent that would have made the results of the test incomparable to results from other undisturbed bogs. Again the difference between mean annual highest and lowest level in the highest (least disturbed) part of the bog was about 30 cm, the mean highest level being just above the surface. The authors are not quite clear as to their definition of "surface level", but probably the bog surface around the observation wells was relatively flat. Most likely, the drains have caused an increase of the fluctuation of the groundwater levels, compared to a fully undisturbed situation.

Mott (1973, cit. Ingram, 1983) calculated residence times vs. depth of the phreatic level, based on data recorded at 6 hour intervals over 1970-72 at Dun Moss near Blairgowrie in Scotland. Here the levels fluctuated between 4 cm above and 26 cm below the "surface level", which in this case was the bottom level of the hollows. Again this means a difference of about 0.30 m, but now for observations over three years. Approximately

50% of the time the level in the centre of the bog was between 4 cm above and 3 cm below the surface.

In a diagram of a peat profile in a small raised bog in Minnesota, Verry (1984) presented some data based on 22 years (1961-1982) of continuous measurements with a groundwater level recorder. The difference between mean annual maximum and mean annual minimum water level in this diagram is about 25 cm.

These data from literature show that in raised bogs the annual fluctuations of the water level are small: about 0.30 m or a little less between the mean highest and lowest levels relative to the surface. Seasonal oscillation of the surface level contributes to some extent to this small fluctuation. However, this component is relatively small and as a result of delayed effects of fluctuations of the groundwater level the lowest surface levels do not necessarily coincide with the lowest water levels. In Europe it seems that the fluctuations have a tendency to decrease somewhat from east to west, possibly as a result of a more even distribution of precipitation over the seasons in Atlantic than in more continental climates. The absence of trees on Atlantic raised bogs might contribute to this decrease. The results quoted have all been measured on the flatter parts of bogs. Along bog margins the fluctuations may be larger, resulting from drainage towards the lagg.

2.4. Reduction of evapotranspiration at low phreatic levels

Many authors claim that the small fluctuations of the water table in raised bogs are in part caused by the properties of *Sphagna*. If the groundwater level becomes too deep to ensure sufficient capillary rise, the evapotranspiration of *Sphagna* may reduce considerably.

In a test with *Sphagnum* covered peat monoliths, however, Nichols and Brown (1980) found an increase of the evapotranspiration by more than 20% when the water table was lowered from the surface to 5 cm below it. The authors reported to have found no reduced evapotranspiration when the phreatic level was lowered to 0.15 m. However, having given the monoliths 48 h to equilibrate they measured over periods of only 8 hours in a growth chamber. It is therefore possible that the *Sphagnum* layer still contained sufficient water to reach potential evapotranspiration. The authors admit they probably would have found a reduction, had they lowered the phreatic level further than 0.15 m.

In a lysimeter test in the Engbertsdijksvenen in the Netherlands, Schouwenaars (1990) found that *Sphagnum papillosum* reduced its evapotranspiration by 20 to 40% when the phreatic level was lowered to more than 15 cm below the moss surface.

For the raised bog Lammin Suo on the Karelian Isthmus, Romanov (1968b) concluded that the evapotranspiration in July and August mainly depends on precipitation. This indicates a reduction of evapotranspiration that can only have resulted from a lowered phreatic level. Romanov also mentioned that in the same bog in average years the phreatic level does not fall below 24-30 cm under the surface, but that it may reach a depth of 55 cm or more in August of a dry year. Reportedly, bog fires could occur easily under such conditions, which indicates that potential evapotranspiration considerably exceeded the upward capillary flux.

Romanov presented a graph of the evapotranspiration of hummocks of *Sphagnum fuscum*, a species that usually forms compact hummocks and is known for its ability to grow in situations with deeper groundwater levels than other *Sphagna*. It showed an abrupt decrease in evapotranspiration of about 25% when the water table dropped from 46 to 50 cm below the moss surface.

Boelter (1964) concluded that upward flow of water in undecomposed *Sphagnum* virtually stops at a phreatic level of 20-30 cm below the surface. *Sphagna* lack stomata, a cuticle and an effective internal mechanism for water transport.

The literature quoted above indicates that evapotranspiration of *Sphagna* is reduced at relatively shallow phreatic levels of up to 45 cm below the surface, depending on the species.

Joosten (1993) described another mechanism that possibly leads to reduction of the evapotranspiration of a *Sphagnum* surface at "deep" phreatic levels. Because *Sphagna* hardly are able to regulate their water loss, the capitula dry out when capillary rise between the moss plants does not bring up sufficient water to compensate for transpiration losses. The surface colour of the *Sphagnum* vegetation turns almost white, because the hyaline cells fill with air, a phenomenon that has also been described by Schouwenaars (1990) and Van der Molen (1992). According to both authors, this causes an increased albedo, resulting in an increased reflection of solar radiation and thus less available latent heat for evapotranspiration. In this way, the upper parts of the *Sphagnum* protect the lower parts from drying out. After rewetting, new shoots develop quickly below the dried layer and form a new green cover in 1-2 weeks (Schouwenaars, 1990).

2.5. The storage coefficient

Another mechanism that limits the fluctuation of the water table in a raised bog is the relatively large storage coefficient. The storage coefficient is defined by

$$\mu = \frac{\mathrm{d}s_w}{\mathrm{d}h} \tag{2.1}$$

where

μ = storage coefficient [-]

s_w = specific storage [L], which is the volume of water stored per unit of area above a certain reference level

h = hydraulic head [L] (if a change in specific storage is directly related to a change in phreatic level, h is the phreatic level)

The volume fraction taken up by water in slightly decomposed peat may be well above 0.95, but only part of it can be removed by free drainage.

Boelter (1964) measured water contents of some peat types at different suctions. Fig. 2.1 was derived from his tabulated values. It shows moisture retention curves in the form of pF-curves of "undecomposed", "partially decomposed" and "decomposed" moss peat. From his description, Von Post humification values of roughly 1-2, 5-6 and 8-9 (Von Post, 1922) respectively can be estimated.

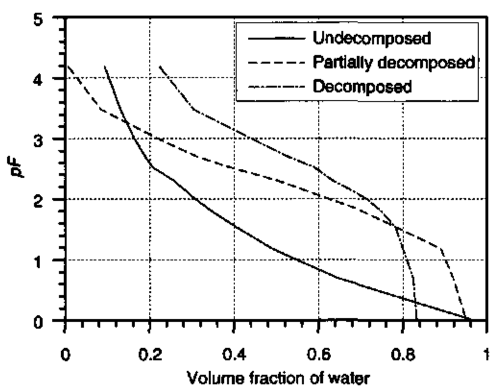

Fig. 2.1. Water retention curves of peats in different states of decomposition (data from Boelter, 1964).

The curve of "undecomposed" moss peat shows a loss of about half the water content at a suction of 10 cm (pF=1). The more decomposed peats hardly lost water at these low suctions. If a gradual increase of the water content with depth is taken into account, this indicates a value of μ in the range of 0.2 to 0.4.

Hayward and Clymo (1982) presented profiles of the water content of columns of *Sphagnum capillifolium* and *S. papillosum*. In *S. capillifolium* the volumetric water content at the surface reduced from near 1 to 0.15 when the water table was lowered from 0 to 9 cm below the surface and in *S. papillosum* to 0.25-0.30 when the water table was lowered from 0 to 8.5 cm. This indicates a storage coefficient μ in the order of 0.35-0.45 in the upper 10 cm of *Sphagnum*. It also shows that differences in species could play a certain role. *S. papillosum* is a species that tends to form carpets rather than hummocks. *S. capillifolium* mostly occurs in hummocks with a more compact consistency. The data of Hayward and Clymo also show an increasing dry bulk density (g cm^{-3} of dry matter) with depth, indicating that the storage properties may change with depth in the sense that at equal suctions the lower material will retain more water than the upper.

In a lysimeter test with *Sphagnum papillosum* in the bog remnant Engbertsdijksvenen in the Netherlands, Schouwenaars and Vink (1992) recorded water levels, which allowed them to calculate μ. They found μ-values ranging from 0.17 to 0.34, depending on depth. The highest values were recorded in the upper 15 cm where the lowest degree of humification occurred. In bogs with a hummock and hollow pattern, the areal storage coefficient[1] must be even higher as long as the hollows are filled with water. In a bog area with 30% of surface water, which is by no means exceptional, the results of Schouwenaars and Vink would yield areal μ-values around 0.50-0.60.

Ivanov (1981) presented graphs of depth versus storage coefficient for different bog microlandscapes[2]. All graphs show a strong decrease of μ with increasing depth. The μ-values are very high (up to 0.8), which is at least in part caused by the definition of "surface level" Ivanov uses. It is an average surface level over the microlandscape. In a model study on the bog Turbenriet in the Swiss canton St. Gallen, Schneebeli (1991) applied values for μ ranging from 0.10 in strongly humified peat to 0.70 in slightly humified peat, similar to those mentioned by Ivanov.

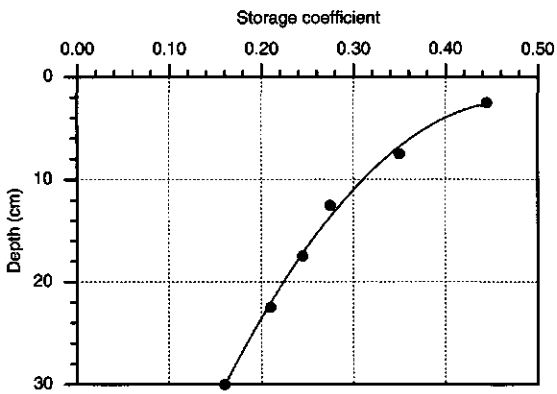

Fig. 2.2. Storage coefficients μ as a function of depth in Lamminsuo with fitted 2nd degree polynomial. (after Vorobiev, 1963).

Vorobiev (1963) presented storage coefficients of the bog Lamminsuo, calculated from rainfall data of a recording rain gauge and groundwater level recorder data over 1953-54 and 1960 and corrected for interception of rainfall by the vegetation. A graph of his results is reproduced in Fig. 2.2. The curvature at small depths probably indicates the presence of surface water.

From the data in this section it can be concluded that in an intact raised bog μ is in the range of 0.30 or higher. The areal μ in a raised bog decreases with a falling phreatic level as a result of the increase of the degree of decomposition (humification) with depth and the decrease of the area of surface water with a falling groundwater table.

The shape of Mott's residence curves of Dun Moss, presented by Ingram (1983) and discussed before in this chapter can probably be explained by these mechanisms.

[1] The storage coefficient of a (mire) area of about a hectare or more

[2] A microlandscape, according to Ingram's translation of Ivanov (1981), is a distinguishable portion of the earth's surface and plant cover of about 1 hectare to 1 km^2, in an area with uniform environmental conditions and vegetation structure.

2.6. Discharge behaviour

Being systems with excess precipitation, raised bogs discharge water. The discharge includes both surface and subsurface runoff. Bogs also store water for a long time. This combination must have led to the common belief that raised bogs act as reservoirs that during dry periods gradually release the water that has been stored during wet times. This view has been controversial during a long time. According to Uhden (1951), it goes back to statements by Von Humboldt, that were repeated later by the geologist Hochstetter (1855, cited by Uhden, 1951). Lüttig (1989) presented a review of the discussion.

Kautz (1906, cit. Uhden, 1967) observed that raised bogs in the Harz release excess water almost instantaneously and that streams that were fed by bogs were filled with water during and immediately after a period of rain, but dried up within a few days after the rain had ceased. Uhden also described a trial, conducted in 1950-1962 in the bog Esterweger Dose near Papenburg in NW Germany. Daily discharges from a drained and cultivated bog and from a virgin bog area were recorded simultaneously during 1955-1961. The size of the drained area was 65 ha. The size of the virgin part decreased from 70 ha in the beginning to 22 ha at the end of the trial. The virgin bog showed a faster recession of the discharge than the drained bog. However, winter peak discharges in the cultivated part were generally higher than in the virgin bog. This is not in agreement with the hypothesis Uhden tried to prove. Summer peaks, however, often showed the opposite with the largest values usually occurring in the virgin part. This difference is probably caused by the conditions in the trial area:

- The saturated hydraulic conductivity k of the top peat layer in the cultivated area was an order of magnitude smaller than in the virgin part ($\bar{k}$ about 0.2 versus 1.9 m d^{-1}).
- At 0.60-0.70 m and deeper below the surface the hydraulic conductivity in the drained area was less than 0.005 m d^{-1}, so substantial groundwater flow was practically confined to the upper 50 cm.
- The phreatic levels in the cultivated part were shallow and varied from 0.16 to 0.44 m below the surface.
- Drain distances in the cultivated part were about 13 m.

Applying a drain spacing equation like Hooghoudt's to the above situation would yield the specific discharge that occurs when the phreatic level touches the surface. When this situation is reached, surface runoff starts (assuming a sufficient infiltration capacity of the soil to prevent surface runoff before the event), which may cause sharp and high discharge peaks.

Hooghoudt's (steady state) drain spacing equation reads as follows:

$$v = \frac{8k_1 D_e (h_m - h_d) + 4k_2 (h_m - h_d)^2}{L^2} \quad (2.2)$$

where

v	=	specific discharge [LT^{-1}]
k_1	=	saturated hydraulic conductivity below the drain level [LT^{-1}]
k_2	=	saturated hydraulic conductivity above the drain level [LT^{-1}]
D_e	=	Hooghoudt's "equivalent layer thickness" [L] (*cf.* e.g. Van der Molen and Wesseling, 1989)
h_m	=	the phreatic level halfway between the drains [L]
h_d	=	the water level in the drains [L]
L	=	the distance between the (parallel) drains [L]

When drain levels of 50 cm below the surface are assumed in the situation as described above, Eq. (2.2) yields groundwater levels at the surface at a specific discharge of only 1-2 mm d^{-1}.

In the climate of NW Germany, where the long term mean precipitation excess is already half this value, such specific discharges must occur several times in almost any winter. This means that surface runoff must have occurred frequently in the situation described. The almost unimpeded outflow *via* the open drains explains the large peak discharges from the drained area in the winter. In the summer the unsaturated top layer forms a reservoir that has a reverse effect on the discharge behaviour.

Nicholson *et al.* (1989) found similar effects in Blacklaw Moss, a raised bog of 28 ha, about 45 km Southwest of Edinburgh. They compared the hydrological behaviour of a part of the bog during a few years before and after drainage was installed in 1962. Baseflow depletion curves for both situations showed a considerably faster recession in the undrained than in the drained situation. The authors also mention that before drainage the outlet channel dried out for 16% of the time, but that outflow remained uninterrupted after drainage.

From an analysis of discharges of a number of catchments in Minnesota that contained raised bogs, Bay (1969) concluded that the bogs in his study had no regulating effect at all on discharge.

Verry and Boelter (1975) concluded from data that were also used in Bay's study that undisturbed raised bogs cause a certain flattening of stormflow peaks, which, however, is due to the flat topography and size of the bog rather than to storage in the bog. This seems in agreement with Uhden's data of 1967. Their general conclusion is that "contrary to popular belief" neither groundwater fed mires nor raised bogs have a regulating effect on discharges.

Verry *et al.* (1988) concluded from 27 years of discharge data that streamflow from a small raised bog (3.24 ha) in Minnesota responded to large storms in almost the same way as streamflow from an unregulated reservoir. Verry (1984) observed in the same bog that outflow stopped completely when the water table in its centre was about 4 cm below the 22-year mean.

Burt *et al.* (1990) gave some discharge data of a small stream fed from a bog in the headwaters of the Shiny Brook near Huddersfield (UK). Comparing its discharge peaks to those of rural catchments, they concluded that the discharge from a bog fed catchment is much more sudden than from a rural one.

Apparently, a natural raised bog releases its water easily when the phreatic level is high, although not as easily as a drained bog. In undisturbed raised bogs the lateral outflow process stops when the water table still is relatively high. This is a remarkable property, because even a relatively low phreatic level in a raised bog normally lies above the level in the surrounding area. In 2.8 the underlying mechanism of this phenomenon will be discussed.

2.7. Subsidence

On both Raheenmore and Clara Bog, man-induced subsidence has occurred. This may be concluded from the slope of the bog surface at both sides of the Clara-Rahan road and the surface slopes towards face banks, particularly the older ones.

The average volume fraction of water in the peat profiles of Clara and Raheenmore Bog lies around 0.96 (*cf.* Chapter 4); often a little more at the surface and usually less at the bottom of the peat. If such a bog is drained in whatever way, water is extracted from the peat. This causes a reduction in pore pressure. The flexible peat matrix responds by collapsing to some extent, thus causing surface subsidence. Subsidence induced by drainage can be considerable and may be a fast process in the beginning. According to Van der Molen (1975) drainage may cause an initial subsidence of 0.5 to 1 m in 10 years in thick peat layers.

Uhden (1960) calculated subsidence values of the Grosse Moor at Ostenholz, at the Southern margin of the Lüneburger Heide in Germany from levelling data of 1842, 1913, 1932 and 1942. In 1842 the bog was still pristine. In 1868 the first drainage activities took place. Human activities like burning for buckwheat cultivation had occurred since. Reclamations at a large scale with deeper and denser drainage systems were undertaken in 1915-1922. Fig. 2.3 shows averaged subsidences calculated for 1914, 1932 and 1942 versus original peat thickness in 1868.

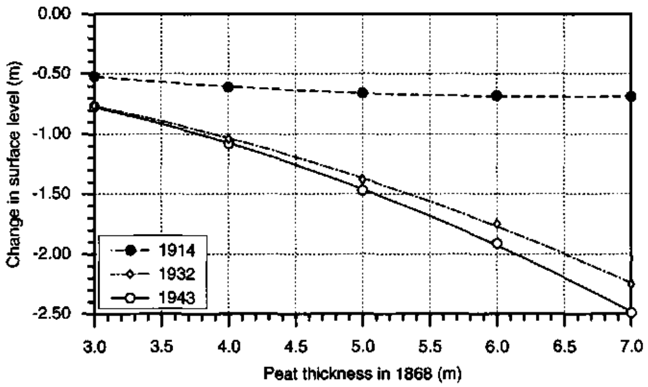

Fig. 2.3. Reconstructed subsidence values of 1914, 1932 and 1943 in the Grosse Moor near Ostenholz versus original peat thickness (data from Uhden, 1960).

From Fig. 2.3 the conclusion can be drawn that subsidence caused by the first superficial drainage was relatively small and depended on the thickness of the peat. The reclamation in 1915-1922 caused a more substantial subsidence, again depending on peat thickness, slowing down in time. Uhden also found a larger shrinkage in the upper bog layers than in the deeper ones.

Baden and Eggelsmann (1964) obtained similar results for Königsmoor. They concluded that between 1911 and 1960 drainage for the German *Hochmoorkultur* had caused a subsidence by $^1/_3$ to $^1/_4$ of the original peat thickness. As in the Grosse Moor, the smallest relative subsidences, expressed as fractions of the original peat thickness, occurred at the largest peat thickness. However, a deepening of the open drains in 1958/59 had caused a considerable additional subsidence of some 0.30 m in 1960, in which effect the dry summer of 1959 might have played a role. The authors mentioned that most subsidence occurred in the upper part of the profile.

Eggelsmann (1990b) presented a number of subsidence data of different drained bogs in Germany. Generally the subsidence values are in the order of 20-35% of the original peat thickness.

Schothorst (1982) found subsidence values of up to 1.40 m in 10 years in cultivated peatlands in the Netherlands, after the drainage level had been lowered from 0.20-0.40 m to 0.70-1.00 m. He found that most shrinkage occurred in the upper 0.40 m. This is in agreement with the results presented by Uhden (1960) and Baden and Eggelsmann (1964).

Other processes that contribute to subsidence in raised bogs are slow oxidation and burning. Oxidation has its largest effect when the phreatic level is (almost) permanently below the surface. Under Northwest European conditions it causes a slow shrinkage under agricultural use. Schothorst (1982) found subsidence values due to oxidation of 2 to 5 mm a^{-1} at drainage depths of 20 to 50-100 cm respectively, in fen peats under pasture in the Netherlands. Schothorst's values were based on a dry bulk density of 0.2 g cm^{-3}, which is approximately equivalent to a volume fraction of organic matter of 0.14.

This is more than found in any sample taken on Clara or Raheenmore Bog. Near a surface of young *Sphagnum* peat, the fraction of the volume taken up by organic matter is about one fifth of this value. At the same rate of oxidation expressed in terms of mass, this would mean a subsidence of at least five times the values found by Schothorst. However, in ombrotrophic peat the rates of oxidation are considerably smaller than in fen peat. Eggelsmann (1990b) reported oxidation rates for cultivated bog peat that were three to four times as small as for cultivated fen peat. Absence of cultivation -implying no addition of nutrients- almost certainly reduces the rate of oxidation. *Therefore a contribution by oxidation of 2 mm* a^{-1} *to subsidence in an uncultivated drained raised bog (or part of a raised bog) seems a safe maximum value,* especially where the phreatic level has remained close to the surface. The humid Irish climate might also have contributed to a relatively low rate of oxidation.

Burning, which has occurred on a more or less regular basis on both Clara and Raheenmore Bog, might have caused relatively large losses of peat in the past. Eggelsmann (1990b) mentioned *a lowering of the surface level by 2-4 cm for each time German and Dutch bogs were burnt in spring* for the cultivation of buckwheat. His values agree well with the average of 3 cm a^{-1} (of a range of "at least" 0.5-5 cm a^{-1}) reported by Hallakorpi (1936) for annual burning in southern Finland.

It can be concluded that the subsidence of bogs as a result of drainage can be a relatively fast process. It may amount to a relatively large proportion of the original peat thickness. Subsidence may therefore considerably change the cross section of the bog surface in one or two decades. This in itself must have an influence on the hydrology of the bog system, because of the changes of the hydraulic gradient and of the surface slope that result from it. Natural oxidation of dried out parts and burning may be additional causes of subsidence because of loss of peat material, but generally with much smaller effects than subsidence by compaction.

2.8. Diplotelmic bogs.

At the surface of a growing raised bog, fresh biomass is produced that dies and is covered by younger material each year. The original material is mostly loose and fibrous, but as it gets buried slowly, it partly decays. *The process of decay is often called humification.* During humification the fibres lose part of their strength. This and the overburden of younger material cause a certain degree of collapse. As a result of this collapse hydrophysical properties change from the surface downwards. It seems therefore reasonable to distinguish different layers in a growing bog. Clymo (1992) distinguished four different layers in the top half-metre. For most hydrological purposes however, a concept of two different layers over the entire vertical bog profile seems to be sufficient, as is argued in this section.

Lopatin (1949) as cited by Verry (1984 and Ingram and Bragg (1984) was probably the first to distinguish an "active layer" in raised bogs. This "active layer" is the relatively thin top layer (usually 10-40 cm deep), including the living peat moss. Ivanov (1953, cited by Ingram, 1978) described it as follows: "...contains the oscillating water table, possesses a high hydraulic conductivity, shows a variable water content, is subject to periodic air entry on de-watering; is rich in peat forming aerobic bacteria and other micro-organisms and has a live matrix of growing plant material".

Romanov (1968a) described the lower boundary of the "active layer" as "...the level above which the water conditions and the degree of decomposition vary rapidly, while below this level they either remain constant or vary slightly." Romanov extensively discussed the structure and hydrophysical properties of the active layer in different elements of bog microrelief[1]. The main properties he mentioned are a low mass of organic matter per unit of volume (density) and a big share of large pores. As a result of humification, density increases and the volume with large pores decreases downwards. This results in a decrease of the hydraulic conductivity with increasing depth.

To distinguish it from the similarly termed layer in permafrost soils, Ingram (1978) *proposed the neologism "acrotelm" as a name for the active layer.* He described it as "the surface layer of a mire soil, differing from the subjacent layer in the nature, greater range or more abrupt variation of its physical properties and biological attributes and in function the principal site of matter and energy exchange in the mire ecosystem". *For the subjacent layer, the actual body of the bog, he proposed the term "catotelm" in the same publication.* In his proposal, a bog in which both acrotelm and catotelm are present, is termed "diplotelmic" and a bog where only a catotelm remains, "haplotelmic". The terms "acrotelm" and "catotelm" have become generally accepted since. With its depth of up to some dm, the acrotelm usually represents only a tiny fraction of the entire peat profile (Fig. 2.4).

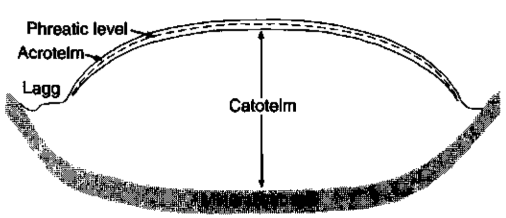

Fig. 2.4. Schematic section through a raised bog with acrotelm and catotelm (redrawn after Ingram

Ivanov's, Romanov's and Ingram's descriptions of the acrotelm are no definitions in the strict sense. They lack reproducibility. Consequently, these descriptions do not define the exact position of the boundary between both layers. Verry (1984) suggested some refinements to the above descriptions and proposed some additions. Not all Verry's additions, however, mean improvements in reproducibility, but his proposal includes one

[1]microrelief: the relief of a microtope

important point: to include in Ingram's definition "dead plant material undergoing diagenesis by humification, but not yielding peat substance between the fingers when squeezed". This means a degree of humification of 4 or less on the scale of Von Post (Von Post, 1922; Von Post and Granlund, 1926). The addition allows a more precise identification of the boundary between acrotelm and catotelm. However, the addition might still contradict other elements of the definition. To this author's opinion, it would be more convenient, at least for hydrological purposes, to simply define the acrotelm as the top layer of a (raised) bog from the surface to the depth where the degree of humification has increased to 4 (or perhaps 3) on the Von Post scale. It is the type of definition that was applied during the fieldwork on Raheenmore Bog and Clara Bog.

Apart from a large hydraulic conductivity -several thousand m d^{-1} in the top few cm is no exception- the acrotelm has a large storage coefficient. The decrease in storage coefficient with depth as described in 2.5 is directly related to the process of gradual humification that occurs in the acrotelm. The process of humification also causes a decrease in hydraulic conductivity as a result of compaction by loss of fibre strength and an increasing overburden. From a large number of measurements, Baden and Eggelsmann (1963a) derived a sharp decrease of the hydraulic conductivity of Sphagnum peat with increasing humification until a level of 3-4 on the Von Post scale. Above this level, the decrease became rather small. This result would be another good reason to define the acrotelm as suggested in the previous paragraph. Baden and Eggelsmann (1963b) also found a strong decrease of the hydraulic conductivity with increasing compaction: about an order of magnitude for an increase of the organic matter content from 3% to 5% by volume. Their result seems to agree well with a graph presented by Ivanov (1981). Although Ivanov expressed the degree of humification in % of humified material instead of class number of the Von Post classification, an approximate conversion of his results is possible using the comparison between different methods for determining humification as described by Stanek and Silc (1977). Apparently unaware of their results, Hänninen (1987) found similar relationships. Balyasova (1979) described the decrease of hydraulic conductivity with depth in the acrotelm by some orders of magnitude over depth intervals of about 10 to 30 cm for several raised bogs in the former Soviet Union.

The referenced literature shows that the saturated hydraulic conductivity in the acrotelm decreases strongly with depth. Ivanov (1957, cited by Romanov, 1968a) developed the following empirical equation for the dependence of the hydraulic conductivity on depth in the acrotelm:

$$k(z) = \frac{a_1}{(1-z)^{m_1}} \tag{2.3}$$

where

k = saturated hydraulic conductivity of the acrotelm in cm s^{-1}

z = vertical position with respect to surface level; positive above and negative below it (cm)

a_I = empirical quantity (dimension depending on the value of m; its numerical value is the saturated hydraulic conductivity at the surface in cm s^{-1})

m_I = empirical quantity [1] describing the rate of decrease of the hydraulic conductivity with depth.

Romanov (1968a) reproduced some values of a_I and m_I from Ivanov for different microlandscapes. For four different situations in Sphagnum bogs the value of a_I was in the range of 270-3670 cm s^{-1} and m_I in the range of 1.8-3.8.

Bragg (1982, cited by Ingram and Bragg, 1984) found values of 2000 and 5000 cm s^{-1} for a_I and 3.5 and 3.6 for m_I on monoliths of Sphagnum dominated acrotelm taken from Dun Moss, but her results did not fit to the curve so well as suggested by Ivanov's data.

The flow rate in the acrotelm is determined by its transmissivity T_a, not by the hydraulic conductivity k. T_a depends on k by:

$$T_a = \int_{z_{ac}}^{h} k(z)\mathrm{d}z \qquad (2.4)$$

where

h = phreatic level [L]

k = saturated hydraulic conductivity [L T^{-1}]

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

z_{ac} = level of the transition between acrotelm and catotelm [L]

Equation (2.4) would thus yield an expression for T_a based on Ivanov's concept. To produce a result, however, the bottom level of the acrotelm must be known. In reality, the flow is not confined to the acrotelm, but as will be shown later, the outflow through the catotelm in raised bogs is usually a negligible fraction of the total lateral outflow. Substituting $k(z)$ in Eq. (2.4) using Eq. (2.3) and integrating yields:

$$T_a = \frac{8.64 a_I \{(1-h)^{1-m_I} - (1-z_{ac})^{1-m_I}\}}{m_I - 1} \quad \text{for} \quad m_I > 1 \qquad (2.5)$$

where T_a is expressed in m^2 d^{-1} (the constant 8.64 converts cm^2 s^{-1} to m^2 d^{-1}) and h and z_{ac} are expressed in cm relative to the bog surface.

The value of z_{ac} is usually not exactly known. However, if the value of m_I is sufficiently large, e.g. 2.5 or more, and the acrotelm sufficiently thick, e.g. more than 10 cm, the right hand term in Eq. (2.5) becomes negligibly small. Neglecting the right hand term implies $z_{ac}=-\infty$. Eq. (2.5) then reduces to

$$T_a \approx \frac{8.64 a_I (1-h)^{1-m_I}}{m_I - 1} \quad \text{for} \quad m_I > 1 \qquad (2.6)$$

Because in most cases it is impossible to obtain an exact value of z_{ac}, Eq. (2.6) will be used to derive values of a_I and m_I from measured data. Neither Eq. (2.5) nor (2.6) takes microtopography into account. The differences in surface level may vary considerably, particularly in well-developed hummock and hollow complexes. In such complexes, the "surface level" is not easily defined and at high water levels surface flow may occur. Some parts of a raised bog may therefore have areas with surface water during shorter or longer times. Such areas may become temporarily interconnected at events of large discharge. According to Eggelsmann (1967), channelling is usually limited to areas close to the margin zone.

The mechanism approximated by Ivanov's empirical equation and worked out further in equations (2.5) and (2.6) is the main agent that causes high outflows from raised bogs during wet times and virtually stops outflow when the water table has lowered to a certain extent.

2.9. Ingram's groundwater mound theory

2.9.1. The theory and its underlying assumptions

A concept that was meant to explain the cross-sectional shape of raised bogs by regarding them as a groundwater mound was developed by Ingram (1982). Its is based on the concept of a catotelm body that loses water by lateral outflow in which the outflow is compensated for by infiltration from the overlying acrotelm. Because of lateral outflow of (part of) the infiltrated water, the water level in the catotelm and hence the catotelm surface must be highest at or near the centre of the bog, unless the bog lies in a sloping position and thus is eccentric. In the groundwater mound concept a bog is a groundwater mound and its shape a function of the hydraulic conductivity in the catotelm and the infiltration rate from the acrotelm into the catotelm. The assumptions adopted in Ingram's groundwater mound theory and related models are:

(a) The validity of the Dupuit-Forchheimer assumption

(b) The presence of a flat, horizontal, impervious base directly under the catotelm

(c) The hydraulic conductivity is constant, regardless of the spatial position.

(d) The infiltration rate of water from the bog surface into the catotelm is constant in space.

(e) The infiltration rate into the catotelm is constant in time.

The following points with regard to these assumptions are made:

Substituting Q_{hc} in Eq. (2.7) using (2.8), integration and solving the integration constant for the boundary condition $r=R \Rightarrow h=0$ yields:

$$\frac{U_c}{k_{hc}} = \frac{2h^2}{R^2 - r^2} \quad \text{for} \quad r < R \tag{2.9}$$

where

R = radius of the bog [L]

For the centre of the bog where $h=h_m$ and $r=0$, Eq. (2.9) reduces to

$$\frac{U_c}{k_{hc}} = \frac{2h_m^2}{R^2} \tag{2.10}$$

which describes the relation between the ratio U_c/k_{hc}, the radius of the bog R and the height of its dome h_m.

In a raised bog of infinite length and parallel margins the equivalent of equation (2.9) is:

$$\frac{U_c}{k_{hc}} = \frac{4h^2}{L^2 - 4x^2} \quad \text{for} \quad x < \frac{L}{2} \tag{2.11}$$

where

L = distance between the parallel margins [L]

x = distance from the centre [L]

Both Eq. (2.9) and (2.11) describe ellipses. This implies that for bogs of more natural irregular horizontal shapes, the shape of vertical cross sections should not deviate too much from elliptic. The equivalent of (2.10) for a longitudinal bog is

$$\frac{U_c}{k_{hc}} = \frac{4h_m^2}{L^2} \tag{2.12}$$

For $L=2R$, the resulting height in the centre of the longitudinal bog is twice as large as in the case of the circular bog. The difference with the circular bog is related to the difference in flow pattern: parallel in the parallel bog and diverging towards the margin in the circular case.

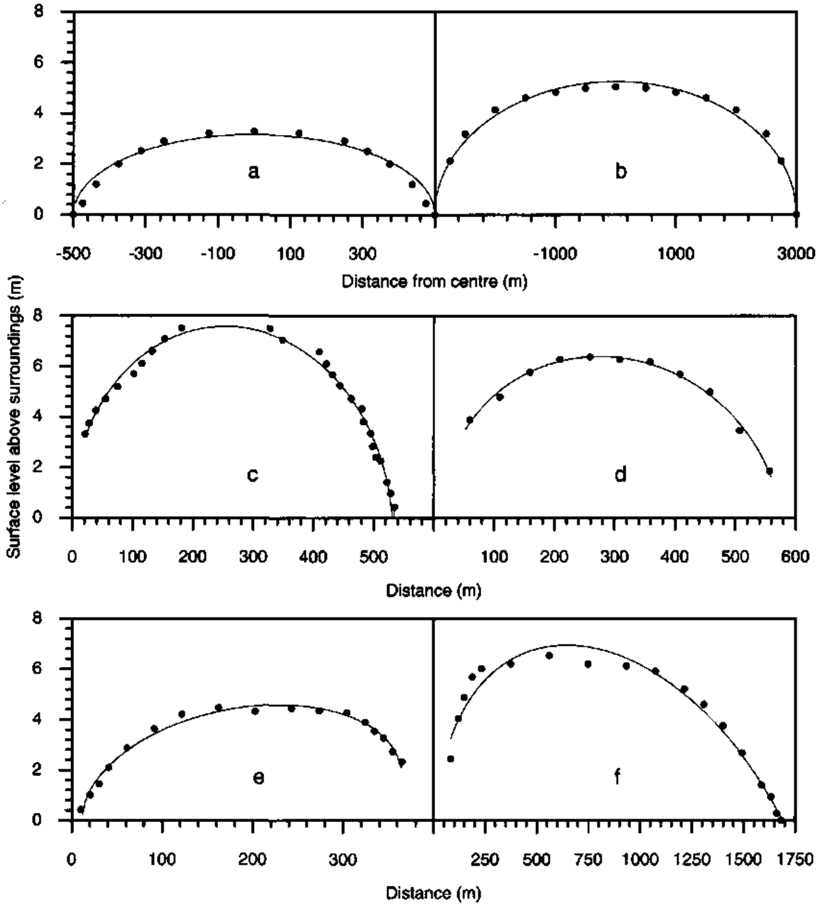

Fig. 2.6. Cross sections through different raised bogs with fitted ellipses. Points in the diagrams were measured from originals; curves were fitted through the points shown. a. Reconstructed average of 64 raised bogs in Lower Saxony (after Eggelsmann, 1967); b. Average of 28 raised bogs in Bavaria (after Eggelsmann, 1990a); c. Dun Moss (after Ingram, 1982); d. Ellergower Moss (after Ingram, 1987); e. Fastebo Mosse (after Granlund, 1932); f. Blängsmossen (after Granlund, 1932).

The cross-sectional shapes of both Dun Moss and Ellergower Moss as shown by Ingram in 1982 and 1987, respectively, indeed resemble ellipses. The average cross section of 64 raised bogs in Niedersachsen calculated by Eggelsmann (1967) also resembles a rather flat ellipse. Probably after a similar comparison by Weber (1900) he called the shape *Uhrglasförmig*: having the shape of the glass of a watch. Using data from Weber (1902), Eggelsmann found a similar elliptic shape of the bog of Augstumal (size 33 km^2) in the delta of the river Nemunas in present Lithuania. The average cross section of 28 raised bogs in Bavaria (Eggelsmann, 1990a) also resembles an ellipse.

Eggelsmann's and Ingram's cross sections are shown in Fig. 2.6. Two other cross sections, taken from Granlund (1932) have been added. They represent Fastebo Mosse near Valdemarsvik, south-east of Norrköping and Blängsmossen near Skövde, between the lakes Vänern and Vättern. The plotted points in Eggelsmann's and Granlund's profiles are measurements from their respective diagrams. Those in Ingram's profiles are the same as shown in the original publication. The points of Dun Moss are the intersections with surface contours with an interval of 0.50 m.

Most cross sections in Fig. 2.6 show deviations from the elliptic shape. Eggelsmann's averaged data (a and b) show a bog expanse that is slightly flatter near the centre than the fitted ellipse. Ingram's and Granlund's data fit reasonably well to tilted ellipses, but neither of Ingram's or Granlund's cross sections represents a complete half of an ellipse. They comprise the part with the smaller curvature. A seemingly good fit of an ellipse is attained more easily if no data points have to be fitted at the largest curvature, as was necessary in Eggelsmann's data. In other words: the sensitivity to deviations from the elliptic shape decreases if the fit is limited to the less curved part.

A tilted elliptic shape of a groundwater table cannot result from radial outflow superimposed on a straight slope. Because in the mound the catotelm transmissivity T_c is supposed to depend on h, superposition of the sloping and the elliptic water table is not applicable (Edelman, 1972).

A bog cross section flatter than an ellipse may indicate a decrease of k_{hc} or an increase of U_c from centre to margin, or a concave base of the bog (e.g. a kettle bog, assuming k_{hc} of the deeper peat contributes substantially to T_c). This matter will be discussed further in Chapter 5.

Although the groundwater mound theory in its original form is based on some unproven and sometimes rather doubtful assumptions, it seems to give a fairly adequate description of cross-sectional shapes of raised bogs for a number of cases. It should be borne in mind, however, that cross-sectional shapes of bogs that apparently support the theory could also result from situations in which assumptions are not valid. For example, an approximately elliptic cross-section may also occur where U_c and k_{hc} are not constant in space. If the margins of the bog are not taken into account, an ellipse can often be fitted easily through a set of points taken from a cross section. Where k_{hc} varies strongly in the vertical direction, applying the concept of transmissivity T in flow equations is more practical than k. Analogous to Eq. (2.4), the relationship is

$$T_c = \int_{z_b}^{z_{wc}} k(z)\,\mathrm{d}z \qquad (2.13)$$

where

z_b = bottom level [L] of the catotelm

2.9.2. Cross-sectional shape and acrotelm hydrology

Although the groundwater mound concept basically deals with catotelm flow, is also relevant to the hydrology of the acrotelm. Such consequences were merely touched by Ingram and Bragg (1984) and Van der Molen *et al.* (1992), but not worked out.

The hydraulic gradient in the acrotelm is almost entirely determined by the shape of the catotelm (*cf.* Fig. 2.4) and hence approximately constant in time. This implies that at a certain discharge from a bog, its acrotelm must have the transmissivity that will transport exactly that discharge at the given hydraulic gradient. Thus, contrary to common aquifers in which the flux and the hydraulic gradient are proportional quantities, the catotelm is an aquifer where transmissivity and flux are proportional. As was shown in 2.8, the transmissivity of the acrotelm depends on the phreatic level in it. Consequently, the water table in the acrotelm will assume the level that yields the required transmissivity T_a. T_a thus depends directly on flux and surface slope. The flux across a certain width of acrotelm depends on the area of the upstream flow path and its specific discharge. These important points are developed further in Chapter 6.

Because at any point on a bog the flow paths through catotelm and acrotelm have the same size and length, a relationship of specific discharge and transmissivity of acrotelm and catotelm exists:

$$\frac{T_a}{v_a} = \frac{T_c}{v_{hc}} \qquad (2.14)$$

where

v_a = specific discharge [LT^{-1}] *via* the acrotelm

v_{hc} = horizontal component of the specific discharge [LT^{-1}] *via* the catotelm (or average flux density from acrotelm into catotelm)

Equation (2.14) does not require all the original assumptions of the groundwater mound theory to be valid. The unnecessary assumptions are:

- the flat, and horizontal base, because the equation contains T_c instead of k_{hc}
- the uniform hydraulic conductivity in the catotelm for the same reason as above
- the impervious base (it is actually not even needed in Ingram's original models, because they solely deal with and are fully determined by the horizontal component of the catotelm flow)

According to Eqs. (2.10) and (2.12) the height of a peat dome is proportional to its diameter at equal U_c. The results of both Granlund (1932) and Eggelsmann (1990a) show that dome heights of raised bogs are by no means proportional to the diameter (*cf.* Fig. 2.6). If differences in T_c are assumed to be negligible, U_{hc} must be smaller in large raised bogs than in small ones. The disproportionality of heights and diameters shown in Fig. 2.6 also means that T_a at equal specific discharges must be considerably larger in the larger bogs than in the smaller ones.

2.10. Towards a conceptual hydrological model of (damaged) raised bogs.

To effectively preserve and restore raised bogs, an understanding of the interrelationships of the different processes that occur in them is indispensable. Because water is crucial in bogs, the basis must be provided for by hydrology. This implies the development of a conceptual model of the hydrology of raised bogs.

The diplotelmic approach of Lopatin, Ivanov and Romanov, developed further by Ingram, seems to provide a sensible basis. The elementary questions should concern:

As to the catotelm:

- The extent to which the cross-sectional shape of a raised bog be explained by the horizontal flow component in the catotelm;
- The losses of water to underlying strata; dependence on groundwater levels in the surroundings;
- The influence of drainage and subsidence on the above process.

As to the acrotelm:

- The storage properties of the acrotelm;
- The transmissivity properties of the acrotelm;
- The influence of acrotelm and catotelm properties on the amplitude of fluctuation of the water table;
- Effects of drainage and subsidence on storage and transmissivity of the acrotelm;
- Effects of the acrotelm as a non-linear aquifer on bog discharge;
- Effects of conditions like surface slope and drainage on acrotelm properties;
- The extent to which the acrotelm, being a product of the subtle balance of production and decay of organic matter, is self regulating as to the above processes.

As to acrotelm and catotelm

- The applicability of the groundwater mound theory and the extensions given to it in section 2.9 and possible modifications;
- The influence of subsidence on the cross-sectional shape and thus on the surface slope of a bog.

As to the hydrology of the bogs Raheenmore Bog and Clara Bog:

- The effect of the old drains on Raheenmore Bog on the hydrology of the bog;

- The effects of the superficial drainage on Clara East, the actual effectiveness of the blocking of these drains and the necessary effectiveness;
- The effects of the marginal drains around the bogs;
- The effects of peat cutting along bog margins;
- Effects of vegetation and weather conditions on evapotranspiration;
- The water balance of Clara Bog and Raheenmore Bog.

3. THE BOGS AND THE MEASURING METHODS

3.1. Introduction

This chapter starts with a short description of Clara Bog and Raheenmore Bog, including some information on the geological and meteorological setting. The description is followed by a discussion on the measurements needed to answer the research questions formulated in 2.10.

Because of the number of aspects that had to be covered, of distances between measuring sites, often adverse conditions on the bogs and limited available manpower, different aspects had to be concentrated on during different periods. Methods for measuring acrotelm transmissivity and hydraulic conductivity of the catotelm had to be developed, modified and tested. Newly developed and modified methods are described.

The reference for surface levels is Ordnance Datum (OD), approximately equal to sea level.

3.2. The bogs: Clara Bog and Raheenmore Bog.

3.2.1. Geological and meteorological setting

Both Clara and Raheenmore Bog have developed in glacial basins that are related to the land ice sheet that covered a large part of Ireland during the Midlandian. The lithology of the Clara Bog basin was described by Bloetjes and Van der Meer (1992), Flynn (1993) and Daly and Johnston (1994). In Clara Bog, the peat is often underlain by shell marl on glaciolacustrine clay with a clear varve structure. The latter was confirmed in a drilling of the Geological Survey of Ireland in the centre of the bog in 1991. Under the clay, glacial till of varying granular composition occurs. It overlies the limestone of the Lower Carboniferous, which is the common bedrock in almost the entire Irish Midland plain.

The scarce data of Raheenmore Bog indicate mostly underlying gritty clay on glacial till.

The stratigraphy of the overlying peat in both bogs generally shows a succession from bottom to top of a peat containing recognisable remains of *Phragmites*, with *Alnus* and *Betula* via *Phragmites* and *Carex* peat ("fen peat") to a peat which is dominated by remains of *Eriophorum* and *Sphagnum* sp. ("bog peat").

The succession shows the transition from a rheotrophic stage in which a mire develops under the influence of both the level of and the dissolved components in surface water via a transitional stage to an ombrotrophic stage. In the ombrotrophic stage the mire surface has grown so far above the groundwater level in its surroundings that it depends

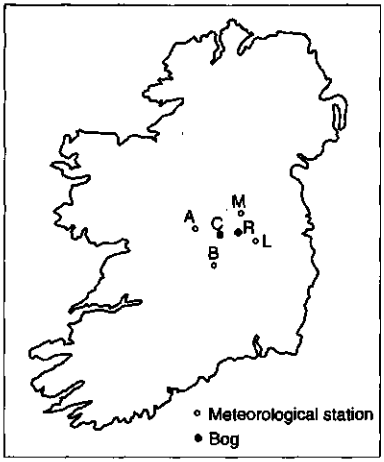

Fig. 3.1. Positions of Clara Bog (C), Raheenmore Bog (R) and the meteorological stations Athlone (A), Birr (B), Lullymore (L) and Mullingar (M).

entirely on precipitation for its supply of water (Hobbs, 1986). According to Daly and Johnston (1994), this is the most common succession in Irish raised bogs. It is rather similar to descriptions by Overbeck (1975) and other authors of dome shaped raised bogs in North-west Germany.

Four meteorological stations of the Irish Meteorological Service, Met Éireann, are positioned around the area of Clara Bog and Raheenmore Bog. They are Birr, Athlone, Mullingar and Lullymore (positions shown in Fig. 3.1).

The mean annual temperature of Birr over 1951-1980 is 9.3 °C and the July and January means are 14.8 °C and 4.4°C, respectively. The values for Mullingar are 8.7 °C, 14.4 °C and 3.6 °C. The Irish Midlands have a mean annual precipitation of 800-1000 mm.

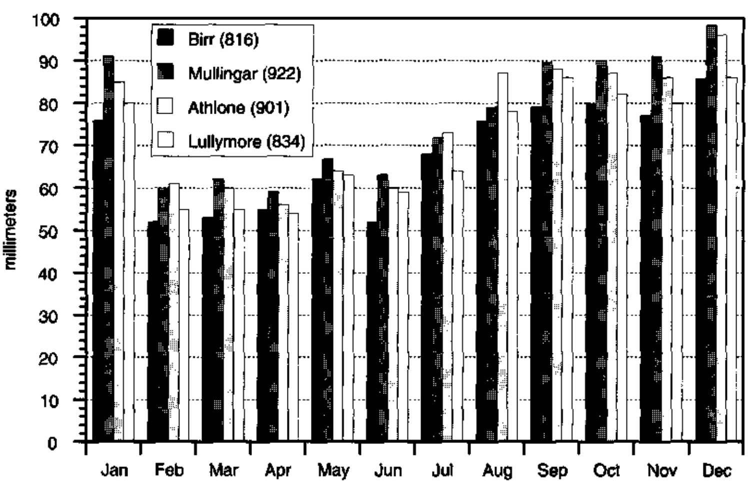

Fig. 3.2. Mean monthly precipitation sums (mm) over 1951-1980 of Birr, Mullingar, Athlone and Lullymore. Mean annual sums in parentheses. Data of Met Éireann, Dublin.

Fig. 3.2 shows mean monthly precipitation data over 1951-1980 of the stations Birr, Mullingar, Athlone and Lullymore.

The diagram indicates a rather even distribution of the precipitation over the year at all four stations and a high correlation between them. The mean annual potential evapotranspiration from grassland, based on the Penman open water equation lies around 450 mm. Details are given in 9.4 (Eq. 9.3. and 9.5).

Fig. 3.3 shows mean annual excess precipitation sums of the stations Birr and Mullingar. The evapotranspiration data are based on 1958-1982. They are Penman open water evaporation values, calculated by Met Éireann and multiplied by the crop factor for grassland.

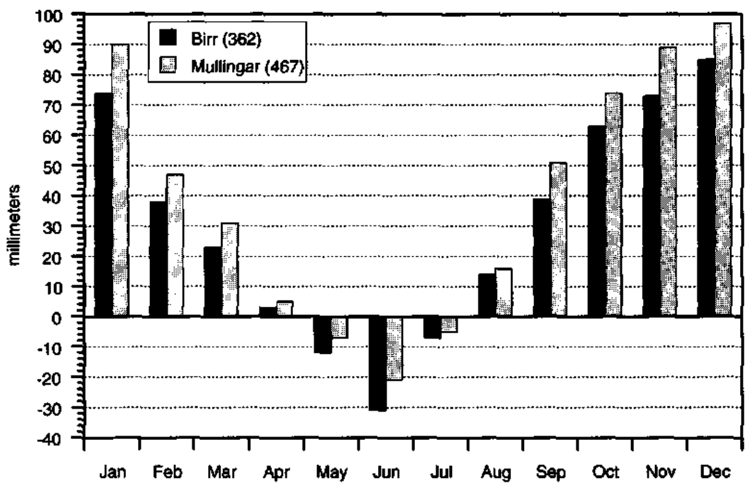

Fig. 3.3. Mean monthly excess precipitation sums (mm), based on 1951-1980 (precipitation) *and* 1958-1982 (evapotranspiration of grassland, based on Penman open water evaporation) of Birr and Mullingar. Mean annual sums in parentheses. Data from Met Éireann, Dublin.

3.2.2. Raheenmore Bog

Raheenmore Bog is a typically dome shaped and slightly asymmetric bog. The highest surface level on Raheenmore Bog lies between 3 and 7 m above the surrounding land surface. A surface contour map is shown in Fig. 3.4. From peat bottom contours measured by Bord na Móna in 1948, a maximum peat depth of 14-15 m can be derived. According to Cross (1989) the size of the nature reserve is 162 ha, including some cutaways. The actual bog comprises approximately 130 ha. The size has been reduced by turf cutting along the margin, but the reduction has not been considerable. In the Eastern part a system of old ingrown drains occurs. It has influenced the hydrological conditions on that part of the bog. Details will be discussed later.

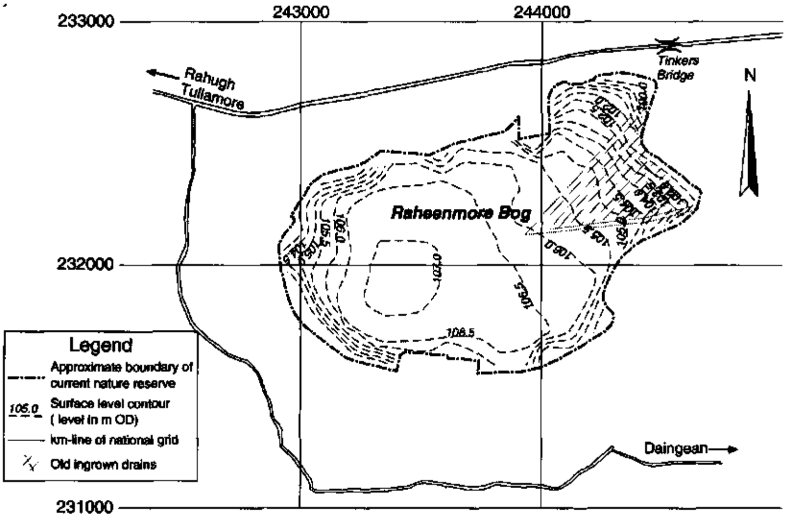

Fig. 3.4. Surface level contour map of *Raheenmore Bog* with position of old ingrown drain system.

A field inspection in 1993 showed that the topsoil south of the present southern margin turned from black peat into brown silty clay at some 30-60 m from the margin, indicating that no peat was ever formed there. Along the northern margin this distance often was even less than 30 m. These distances must include the former lagg, which now is completely destroyed by drainage. The last remaining part of it was drained during the fieldwork period of the Irish-Dutch Raised Bog Study in 1991. In the NE more peat may have been cut away than elsewhere. Air photographs taken in 1973 suggest a former connection to a larger and now heavily damaged bog complex in the N and NE through the valley at Tinkers Bridge. Such a connection is also shown on the Peatland Map of Ireland (Hammond, 1981).

A deep drain of 1-1.5 m wide and 2-4 m deep surrounds the bog. According to Lensen (1991), it was cut in 1984 to improve the drainage of the surrounding agricultural land.

3.2.3. Clara Bog

Clara Bog is situated in a former glacial basin South of the esker complex to the South of the town of Clara in Co. Offaly, Ireland. It is a more complex bog than Raheenmore Bog. It is divided into two parts of almost equal size by the road from Clara to Rahan. These parts now are often referred to as Clara (Bog) East and Clara (Bog) West. According to Van der Molen *et al.* (1992) the road was built in 1838. According to Bell (1991) and Samuels (1992) it has subsided by several metres since it was built.

The total area size of the state-owned Clara Bog nature reserve is 460 ha (Cross, 1989). It is the last remaining raised bog in Ireland that contains so-called soak systems, wet areas with complexes of pools or small lakes with a vegetation that indicates minerotrophic influences. The Eastern part of Clara Bog was drained in 1983 by Bord na Móna. The drainage consists of parallel open drains, 18-20 m apart and about 60 cm deep (Fig. 3.9). In 1989 a first attempt was made to block these drains.

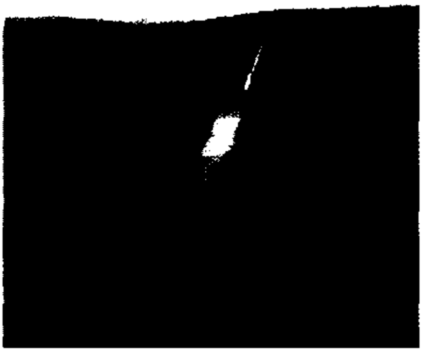

Fig. 3.5. Drain on *Clara Bog East* (October 1990). Foreground: properly blocked section with *Sphagnum cuspidatum* growth. Background: inadequately blocked section with lower water table.

The actual bog is larger than the nature reserve. Bellamy (1986) mentioned a size of 520 ha. Turf extraction continues along the southern and western margins where margin zones are private property. The resulting recession of the bog margin is locally several metres per year. This process has continued for some centuries. Van der Molen (1992) showed a series of four maps that demonstrate the recession of the bog margin since the early 19th century. The area of disappeared bog in the south has at least the size of present Clara Bog West. The original bog area can also be traced back on air photographs of 1973. Little cutting has taken place along the northern margin of the bog, except in the NW where a connection to a bog complex N of the esker complex of Clara has disappeared. The peat thickness in Clara Bog is up to 10.50 m (Bloetjes and Van der Meer, 1992). Fig. 3.6 shows a surface contour map of Clara Bog with positions of drains, road, etc.

The surface topography of the bog expanse is far more complex than on Raheenmore Bog. Along the Clara-Rahan road, the bog surface slopes towards the road. The eastern part of Clara Bog is slightly convex, but the western part is slightly concave, and slopes with the highest surface levels close to the northern, western and south-western margins. The result is a discharge that converges to a narrow outlet of a mere 100 m wide near the largest soak system in the South. It contains a small lake called Shanley's Lough. From an analysis of surface contours, Lensen (1991) estimated the size of the catchment that discharges via the area of Shanley's Lough at 100 ha. Leene and Tiebosch (1993) found a size of 93 ha. Most water in the outlet flows through two old drains that diverge from a point about 100 m S of Shanley's Lough.

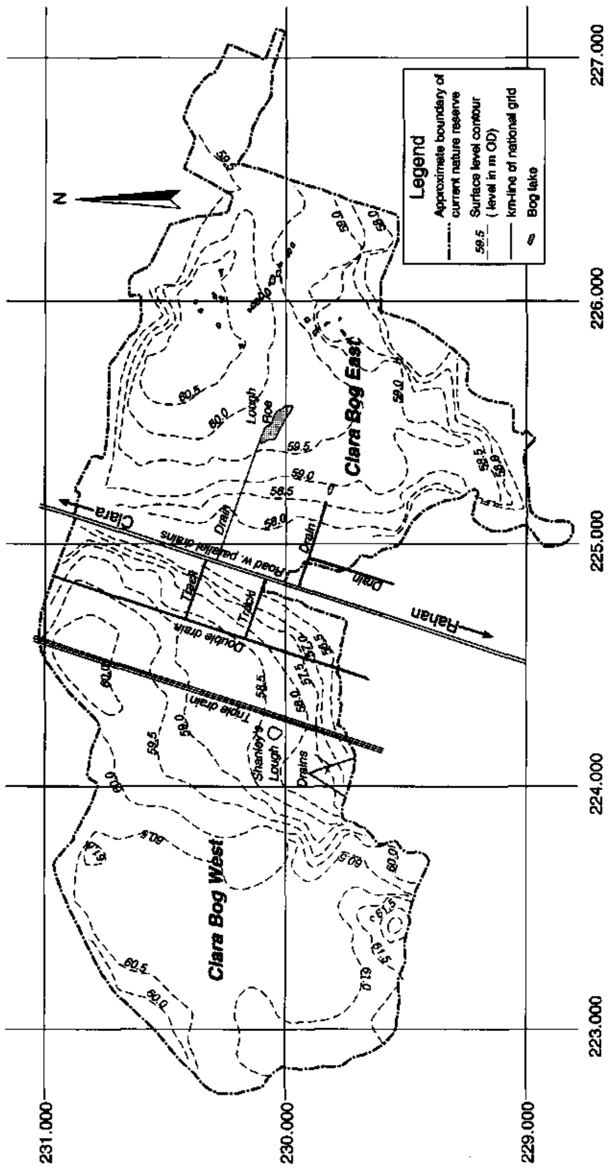

Fig. 3.6. Surface contour map of *Clara Bog* with positions of road and main drains.

About 400 m west of Shanley's Lough, the surface slopes upwards towards the W by about 2-2.50 m over a distance of 200 m. It is the eastern slope of a ridge of about 100 m long. At the Western side of the ridge the surface slopes only little downwards again. On top of the ridge lies a shallow layer of strongly humified peat that lies directly on till.

The lagg of Clara Bog has been destroyed in the south, east and west. It is heavily damaged or destroyed along the northern margin, where its position can still be traced in the field. Where lagg remnants exist, their hydrological conditions have been changed by deep artificial drainage and little is left of their original vegetation.

3.3. Phreatic and piezometric levels.

3.3.1. Points concerning both Raheenmore and Clara Bog

The purpose of the measurements was to assess fluctuations of the phreatic level in relation to factors as position on the bog, surface slope, acrotelm conditions and effects of drainage and to allow calculation of vertical fluxes

Both phreatic and piezometric levels were measured using dip wells of plastic tubing of 1" outer and 0.9" inner diameter. The phreatic wells were 1 m long and perforated over the entire subsurface length of 0.75 m.

The piezometers had a perforation over a length of 0.15 m. Standard depths of the piezometers were initially 1.5, 3.0, 4.5 m below the surface. Soon the difference in behaviour between the phreatic wells and the piezometers of 1.5 m deep appeared to be so small that the latter hardly provided information in addition to the phreatic tubes. Therefore and to obtain more information on piezometric levels deeper in the catotelm, in July 1990 most of the 1.5 m piezometers were provided with extension tubes and pressed down to a depth of 6.0 m. In October and November 1990 additional piezometers were installed at the bottom of the peat where it was deeper than 6 m. Thus a standard dip well site contained four piezometers and one phreatic. The monitoring frequency was once per two weeks.

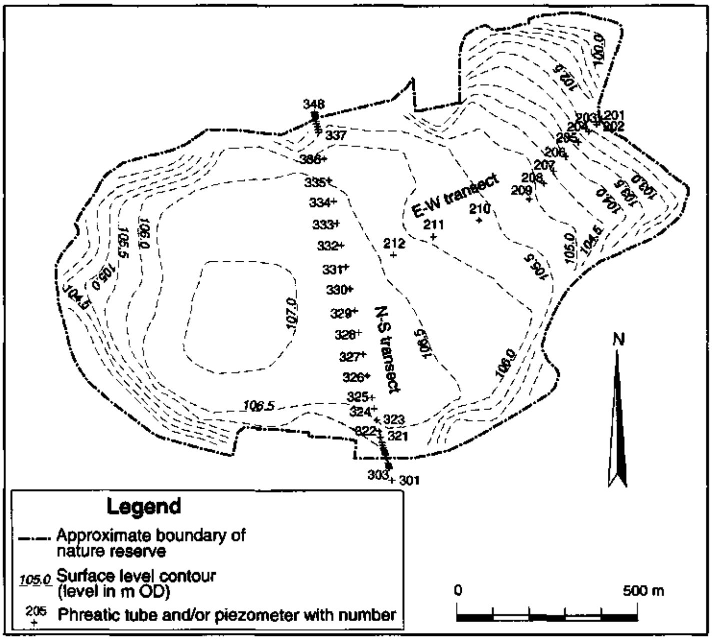

Fig. 3.7. Piezometer positions on *Raheenmore Bog.*

3.3.2. Raheenmore Bog

Two transects of dip wells were installed on Raheenmore Bog, named E-W and N-S. Their positions are shown in Fig. 3.7.

The N-S transect was available at the start of the project in October 1989; the E-W transect was installed in the autumn of 1989. Monitoring started on 26th October 1989 (N-S transect) and 16th November 1989 (E-W transect) and continued until 24th January 1992 when time was needed for an additional transect on Clara Bog.

In addition to the standard dip wells, the N-S transect had phreatic tubes of 2" perforated drain tubing of 0.50 m long. At some places 1" phreatic tubes were installed later. The differences in level between the 2" and 1" tubes at the same site were always within 1 cm.

3.3.3. Clara Bog East

The main question as to Clara Bog East was to assess the effect of the drains and their blocking on the phreatic level and its fluctuation. For this purpose phreatic dip wells had been installed on three sites, named Plot A, plot B and Plot C (Fig. 3.8). Plot A was installed in a flat and wet part of the bog, C in a dried out part and B in an area with apparently intermediate conditions.

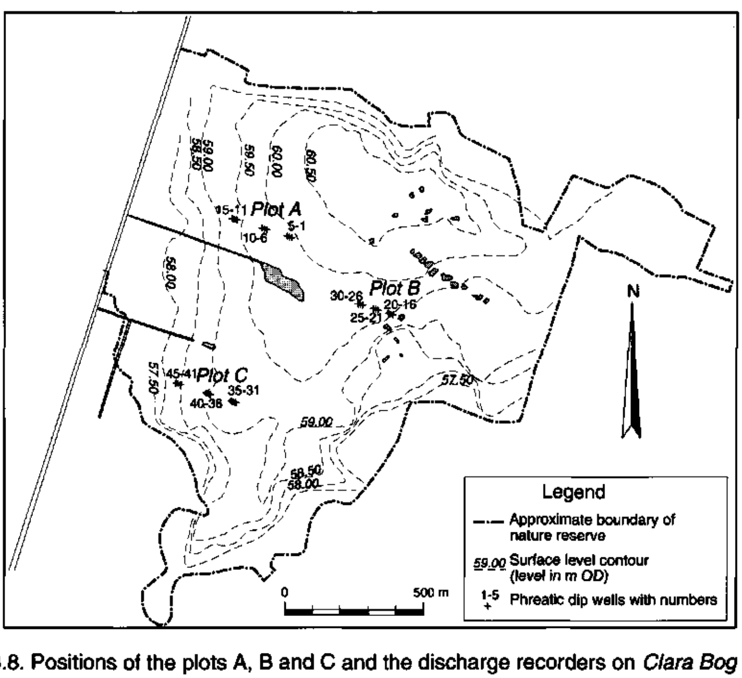

Fig. 3.8. Positions of the plots A, B and C and the discharge recorders on *Clara Bog East*.

Each site contained 15 wells, arranged in three mini-transects of five from one drain to the adjacent one. Of each five wells, two were placed in the drains, two at approximately 2 m from the drains and one halfway between them (Fig. 3.9).

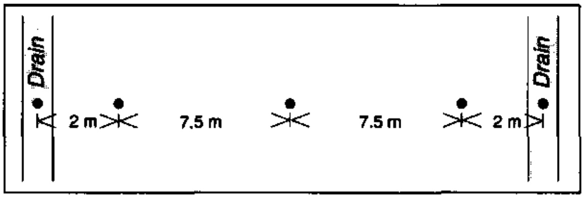

Fig. 3.9. Positioning of phreatic tubes in the mini-transects between adjacent drains (not to scale).

Monitoring started on 23rd November 1989 and ended on 18th October 1991.

3.3.4. Clara Bog West

Initially the sites with phreatic tubes and piezometers were concentrated around the soak system of Shanley's Lough in the south of the bog. The main reasons were the limited available time and the ecological value of the soak system. The area is indicated by the shaded polygon with the name "soak group" in Fig. 3.10 The sites of the soak group initially contained only a phreatic dip well. To find out whether the minerotrophic conditions in this area as indicated by the vegetation had anything to do with a possible upward seepage from the underlying mineral strata, a piezometer with filter screen at the bottom of the peat was added at most sites in October and November 1990.

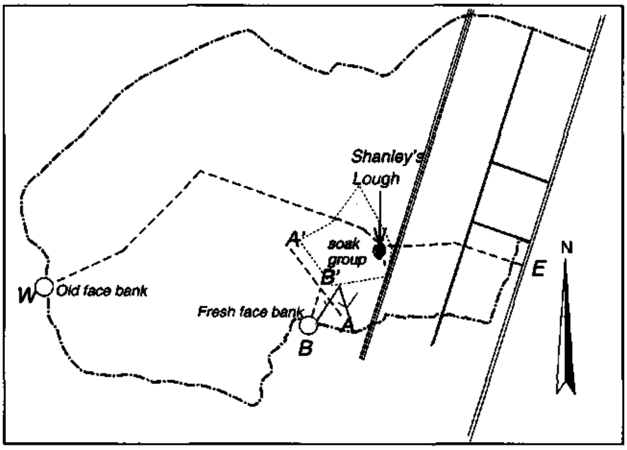

Fig. 3.10. Positions of dip well transects and the group of dip wells around Shanley's Lough ("soak group").

Two small transects, A-A' and B-B' were laid out to the southern margin of the bog where a fresh face bank existed. In the autumn of 1990 a small additional transect was installed at an older face bank at the south-western margin.

In the winter of 1992 a new transect marked E-W in Fig. 3.10, was laid out from the Clara-Rahan road to the old face bank in the south-west.

Each contained a set of piezometers consisting of a phreatic dip well and piezometers at a depth of 4.5 m and at the bottom of the peat. In the summer of 1992 the soak group was extended with three piezometer sites, 901-903 (Fig. 3.11). The first date of monitoring differed per transect. The first monitoring dates were:

- Transects A-A', B-B' and soak group: 7th December 1989.
- Fresh face bank: 13th June 1991.
- Old face bank: 11th September 1990
- E-W transect: 6th February 1992.
- Sites 901-903: 28th May 1992.

The monitoring continued until 22nd July 1993.

Positions of individual dip well sites are shown in Fig. 3.11. Fig. 3.12 is an enlarged map of Shanley's Lough and surroundings.

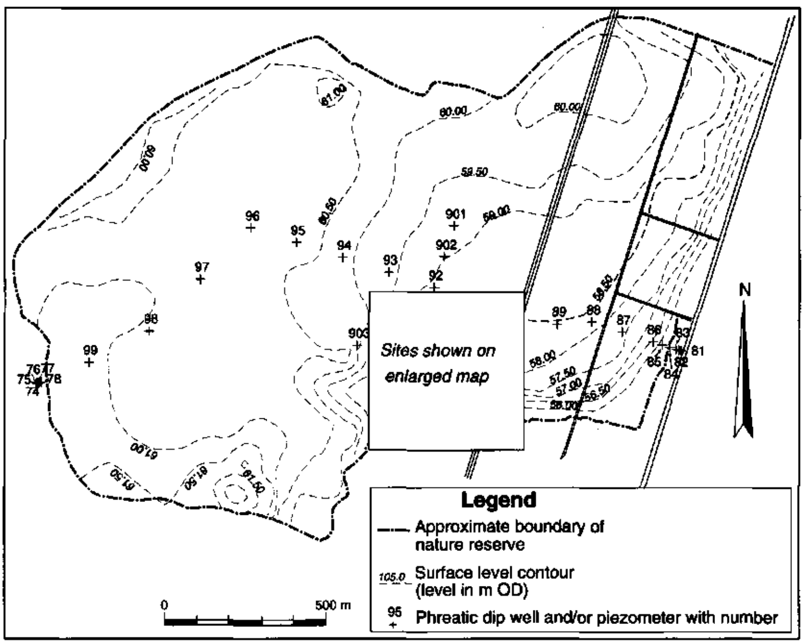

Fig. 3.11. Positions of dip well sites on Clara Bog West. Enlarged map of surroundings of Shanley's Lough in Fig. 3.12.

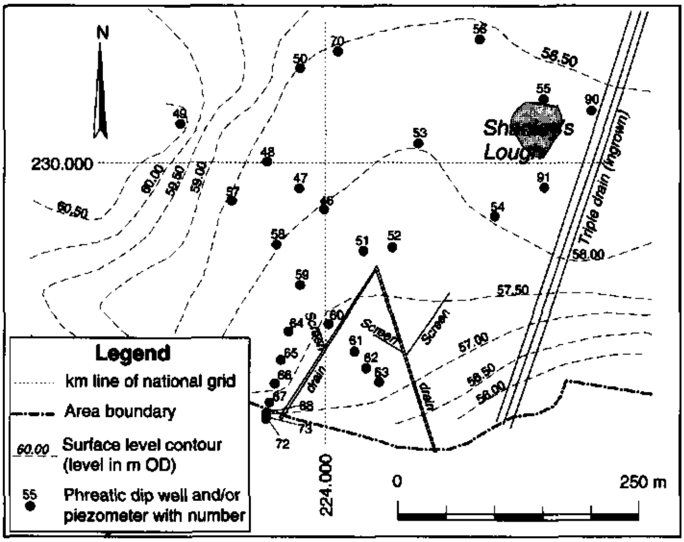

Fig. 3.12. Positions of dip well sites around Shanley's Lough (enlarged section of Fig. 3.11).

3.4. Level recorders

Groundwater level recorders were installed to obtain information on storage coefficients μ from a comparison of precipitation data and fluctuations of the phreatic level.

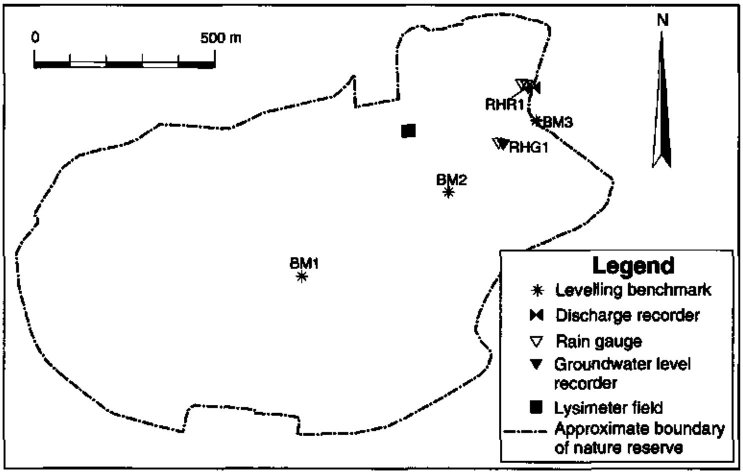

Fig. 3.13. Positions of benchmarks and measuring instruments on Raheenmore Bog.

On both bogs one recorder, owned by the Geological Survey of Ireland was installed on a platform that was anchored by concrete filled PVC tubes down to the mineral subsoil. The recorders were analogue types with a float and counterweight system. Float tubes had a diameter of 10 cm. Checks, including manual measurement of the levels, were made weekly. With a few exceptions that lasted no longer than two or three weeks the hysteresis value has not been larger than 4 mm. It was usually 2-3 mm, so in general the inaccuracy has been well within 1 cm. The charts covered one month. They were digitised at the Office of Public Works in Dublin to series with a time interval of 1 hour. The real timing inaccuracy may be estimated at 1-2 hours.

The position of the recorder on Raheenmore is shown in Fig. 3.13. With a few minor interruptions, due to instrument failure, levels were recorded from 18th September 1990 until 19th July 1993.

The recorder on Clara Bog was installed in the area near Shanley's Lough. It produced a continuous record from 11 September 1990 until 28 July 1993. Its position is shown in Fig. 3.14 (site marked "CWG1").

From 23rd May 1992 until 28th July 1993 two additional recorders were operated on Clara Bog West. They were installed because the area at Shanley's Lough did not properly represent hydrological conditions on other parts of Clara Bog West. The recorders were digital types with a float and counterweight system. They produced data at quartz crystal controlled one hour intervals. The sites are marked "CWG2" and "CWG3" in Fig. 3.14.

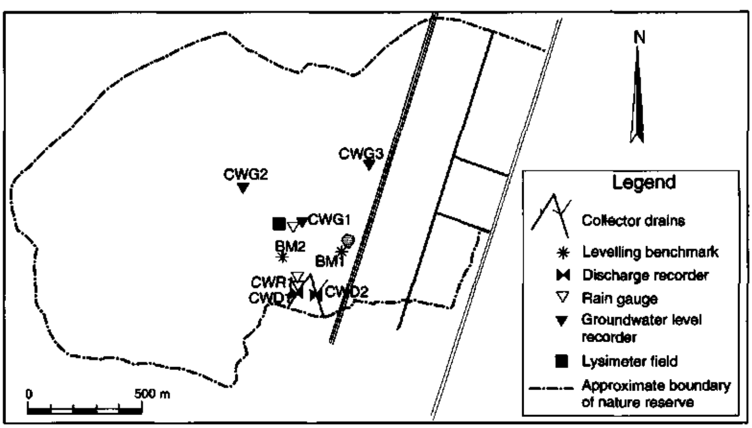

Fig. 3.14. Positions of benchmarks and measuring instruments on Clara Bog West

The recorder platforms were not anchored but provided with a deep piezometer, pressed down to the bottom of the catotelm that could serve as a benchmark for possible vertical movements (Fig. 3.15).

3.5. Reference levels of dip wells

Fig. 3.15. Checking level recorder CWG2 on Clara Bog (May 1992). To the left of the recorder: the deep piezometer tube used for measuring piezometric levels at the bottom of the catotelm and vertical movement of the recorder table. The pulley system is visible on the front of the recorder box, electronic readout module lying on the left.

In tube wells, groundwater levels are measured relative to the top of the tube. Conversion to a common reference such as Ordnance Datum requires the top level of the tube to be known relative to the reference level. Because dip wells in a bog, shallow ones in particular move up and down with the bog surface, relatively frequent levelling was necessary.

To account for vertical movement of the surface levels, dip wells were levelled about four times a year. Initially no good benchmarks were available and the available levelling instruments showed considerable deviations. This situation improved early 1991 when benchmarks were installed on the bogs by the Office of Public Works (OPW) and semi-automatic optical levelling gear became available from the same source. The benchmarks were made of 1¾" steel tubes, hammered into the underlying mineral layer. With the new equipment reliable levelling data were obtained in 1991-1993. The sites on Clara Bog were levelled with laser equipment in the summer of 1992 by OPW. The piezometers in the deepest part of the catotelm had an almost constant level and were later used as local benchmarks.

3.6. Vertical movement of the bog surface.

Vertical movement of the bog surface (*Mooratmung*) is a mechanism of storage and release of water and hence was measured. However, it could only be measured reliably after levelling benchmarks had been installed. On top of the tube a small steel table of about 25x25 cm was mounted (Fig. 3.16). A steel plate of a approximately the same size was placed on the bog surface at the bottom of the tube so that it could move up and down with the surface.

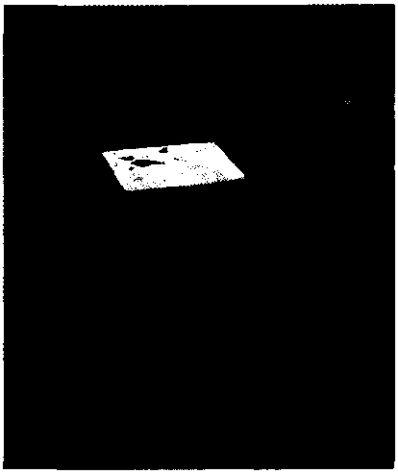

Fig. 3.16. Benchmark with table (BM3 on Raheenmore Bog, January 1996). The tube around the bottom of the pole is connected to the movable steel plate on the bog surface.

The average vertical distance from the corners of the upper plate to the lower plate was taken as the surface position of below benchmark level. Measurements were made about once per month during monitoring of the dip wells. After the regular monitoring of dip wells on Clara Bog East and Raheenmore bog had ended, surface level measurements at the corresponding sites were made only occasionally.

3.7. Precipitation

Precipitation is the only source of water in a raised bog and thus the only input term in its long term water balance. Precipitation was recorded to

- obtain the input term of the water balance;
- make assessments as to storage coefficients μ in combination with phreatic level data recorded at similar intervals as precipitation.

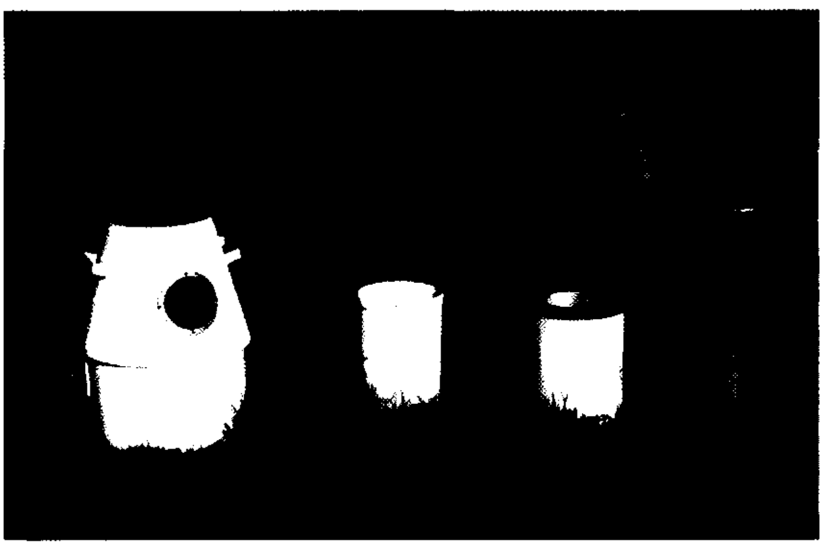

Fig. 3.17. Rain gauge models used in the project. From left to right: the approximate shape of the 8" siphon gauge used on Raheenmore Bog (not the original gauge), the 8" tipping bucket gauge used on Raheenmore Bog, the 400 cm^2 tipping bucket gauge of Clara Bog and one of the 5" hand gauges. Picture not taken on the sites.

Precipitation was recorded on both bogs. On Raheenmore Bog a 324 cm^2 (8" diameter) analogue recording siphon gauge and two 127 cm^2 hand gauges were installed. On Clara Bog West, a 400 cm^2 tipping bucket gauge with a resolution of 0.2 mm and two 127 cm^2 (5" diameter) hand gauges were installed (Fig. 3.17). The siphon gauge on Raheenmore Bog was about 0.6 m high, the other gauges 0.35-0.40 m. The orifice levels were roughly 20 cm above the surrounding vegetation. Recordings are available from November 1989 to 23 July 1993. The recording gauge on Clara Bog West worked with only a few minor problems during the entire fieldwork period of the project. The recording gauge on Raheenmore Bog developed failures on an almost regular basis. In May 1992 it was replaced by a 40 cm high 324 cm^2 tipping bucket type that worked reliably.

The recording gauges had an analogue recording unit with 1 week charts. The charts were digitised manually to 1-hour interval series using a computer programme that was written for the purpose. The hand gauges were normally read once a week.

The position of the recording rain gauge on Raheenmore Bog is marked "RHR1" in Fig. 3.13. The recording gauge on Clara West is marked "CWR1" in Fig. 3.14. The hand gauge positions are only marked with the sign for a rain gauge. The accuracy of the different gauges is discussed in 9.3.

3.8. Surface slope

The value of the surface slope was needed to assess effects of the slope on depth and fluctuations of the phreatic level and on acrotelm conditions. Most surface slope values were derived from the 100m x100 m surface level grid that was installed and levelled by the Office of Public Works during the autumn of 1990 and the winter of 1991.

To estimate the slope value at a grid point, the surface gradient into the X- and Y-direction was calculated from the difference in level between the pairs of neighbouring points in both directions and their distance. The slope was estimated from the vector sum of both. This method inevitably yields a rather rough average at the grid points.

Surface slopes at piezometer sites in transects, where the transect was perpendicular to the surface contours and the distance between neighbouring piezometers was less than 100 m, were calculated directly from the surface at the site and its neighbouring points. At other piezometer sites the surface slope was estimated from the surface level at the site and those at the four nearest grid points by fitting a plane through the five points. The equation of a plane in an (x,y,z) co-ordinate system is

$$z = a + bx + cy \tag{3.1}$$

and the surface slope, expressed as the tangent of the angle α of the plane described by (3.1)with a plane *z=constant*, is then found by

$$\tan\alpha = \tan\arccos\left(-\sqrt{\frac{1}{(b^2+c^2+1}}\right) \quad (3.2)$$

In parts of transects that are approximately perpendicular to the surface contours, the surface slope was estimated from surface levels at the piezometer sites. This is a more accurate method than the previous one if the distance between adjacent sites is about 50 m or less. It was applied at the ends of transects near a bog margin.

3.9. Hydraulic conductivity of the catotelm and peat thickness

3.9.1. Introduction

Measurements of the saturated hydraulic conductivity *k* were needed to calculate vertical fluxes from vertical hydraulic gradients, calculate horizontal catotelm outflow and to test the assumption of a spatially constant *k* in Ingram's groundwater mound theory.

No facilities were available to apply laboratory methods. Thus field methods were the only available option. Different field methods to determine saturated hydraulic conductivity are available. However, they cannot be applied in a living raised bog without modifications. Some are not even applicable at all.

An example of the latter is Hooghoudt's *auger hole method* (Van Beers, 1963). The reason is that the auger hole has a permeable perimeter over its entire depth and thus always has a hydraulic contact with the acrotelm. Van Gerven (1990) noted that it was impossible to measure *k* where a well-developed acrotelm existed, because the hole filled at such a speed that an accurate measurement of the rising speed of the water level with hand equipment was impossible. In bog parts with a destroyed acrotelm the auger hole method still is inconvenient because it gives an average hydraulic conductivity over its entire wetted length without a good possibility to distinguish between layers or depth intervals, as Aue (1992) also noted.

This is a reason to mistrust reports on hydraulic conductivities of raised bogs measured with the auger hole method, such as the extensive comparison by Baden and Eggelsmann (1963a) between results of the auger hole and piezometer methods, unless they are based entirely on data from haplotelmic bogs.

The *piezometer method* has been applied extensively in research on mire hydrology (Baden and Eggelsmann, 1963a, Dai and Sparling, 1973; Ingram *et al.*, 1974, Ingram *et al.*, 1985). It does not require the use of heavy or complicated equipment and thus is an attractive option in fieldwork on mires. It can be used to measure hydraulic conductivity at almost any depth. However, it only yields values of horizontal *k*.

Theoretically the *tube method*, a version of the piezometer method that employs a tube with only a flat bottom, can yield approximately vertical hydraulic conductivity values at arbitrary depths (Amoozegar and Warrick, 1986). At larger depths than 1- 2 m, however, it can only be applied at the expense of much time and effort. The largest peat depth found on Raheenmore Bog during the instalment of piezometers was 13 m and a few dm. Bloetjes and Van der Meer (1992) reported a largest depth of 10.50 m on Clara Bog. The smallest *k*, that have the largest effect on the vertical resistance, generally occur in the lower parts of the peat. Hence applying the tube method would have yielded the most useful results at large depths where application is almost impossible. The largest horizontal *k*-values in the catotelm usually occur in the upper part. These are the most important values for calculating catotelm transmissivity.

Thus the easily applicable piezometer method should preferably have been used in the upper and the much more demanding tube method in the lower strata of the catotelm. In view of the available time and facilities this was no viable option and sufficient reason to apply the piezometer test as the one and only method. Nonetheless it would be relevant to have at least a rough idea on the extent to which errors may be expected from applying horizontal hydraulic conductivities to vertical flow in raised bogs. Therefore literature was searched on information on the subject, which is discussed below.

3.9.2. Horizontal and vertical hydraulic conductivity in peat

Malmström (1925, 1939) presented laboratory data from the mire complex Degerö Stormyr in Västerbotten in Sweden. He found that vertical hydraulic conductivities k_v were generally larger than horizontal hydraulic conductivities k_h. His sampling technique consisted of sawing out blocks of peat, sized 35 cm x 32 cm x 5 cm. The size had to be very accurate because of the sealing technique used in the test, which suggests that the samples were not taken at larger depths than 1 m.

Data of Sarasto from Finnish bogs (1961, cited by Rycroft *et al.*, 1975a) did not indicate significant differences between horizontal and vertical conductivities.

Boelter (1965) reported no differences between k_h and k_v in peat types ranging from young undecomposed moss peat to well-decomposed peat of different kinds. Boelter applied both the piezometer and the tube method. However, he did not refer to any problems with non-linearity in his tests, although such problems had been reported by a number of other authors (to be discussed later).

Chason and Siegel (1986) examined a data set consisting of laboratory measurement results of k_h and k_v of a raised bog, a spring fen and an "external fen" (lagg). They found that k_h exceeded k_v at a 95% confidence level. Of their ten deepest measurement pairs in the raised bog between 2 and 3 m depth, however, five showed a larger k_v whereas the other five had a larger k_v. Over this depth range the average k_h was about twice the average k_v. The k of the raised bog profile were rather high (about 1 m d^{-1}) and did not decrease downwards. Because the investigated raised bog is not deeper than 3 m as can be seen from three cross sections by Siegel (1992), this is a somewhat surprising result. It suggests that the degree of humification may be rather low down to the bottom of the bog. This may be a relevant feature as will become clear from the next paragraph.

Hobbs (1986) stated that laboratory tests generally show peat to be anisotropic, with k_h usually exceeding k_v. He explained the phenomenon by fibres in peat, other than roots, tending to be prostrate. However, he added that tussock forming plants, which are common in raised bogs, will give mainly vertical structures, and that peat formed in spaces between them may be more prostrate in structure. The latter may be an indication of considerable variability in anisotropy in peat over short distances of 1 to 2 m. Continuing humification destroys the fibrous structure. Hence the fibre content is the basis of most classification systems for the humification of peat. The meaning as to the question of anisotropy is that anisotropy becomes less important as peat decays, which implies that in a bog anisotropy may be expected to decrease downwards as decay in the lower parts tends to be (considerably) larger than in the upper strata of a catotelm.

From the references quoted above it could not be concluded with reasonable certainty that peat of raised bogs is either (approximately) isotropic or anisotropic in its hydraulic conductivity. Differences found by different authors could be related to the methods applied. In estimating the vertical resistance of the catotelm, the deeper peat layers with the lowest hydraulic conductivity would largely determine the result. It seemed unlikely that the usage of k_h would be a main source of errors in the calculation of vertical catotelm flux from vertical resistance values and differences in hydraulic head between different depths, as long as the deepest peat would be involved in the calculation. The results in Chapter 5 will confirm this.

3.9.3. The piezometer method

The piezometer method was developed and described by Kirkham (1945) and Luthin and Kirkham (1949). It employs a piezometer with 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 either been removed from (rising head variant) or added to it (falling head variant). The equation (see also Fig. 3.18) is

$$k = \frac{\pi r_p^2}{A_p(t_{i+1} - t_i)} \ln \frac{y_i}{y_{i+1}} \qquad (3.3)$$

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 time t_i after the beginning of the test [L]

y_{i+1} = difference between the level in the tube at equilibrium and at 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]

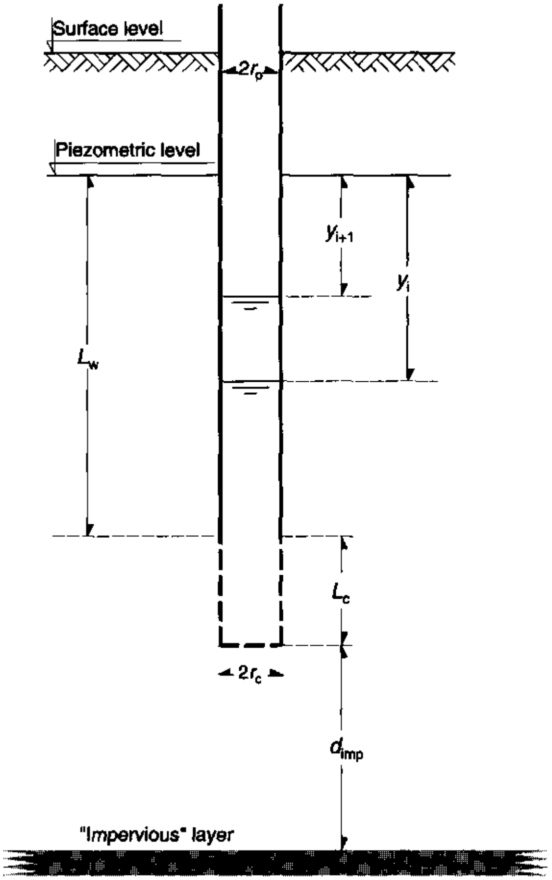

Fig. 3.18. Piezometer method with symbols (explained in the text).

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. Values for A derived from analogue experiments were presented in a graphical form by Luthin and Kirkham (1949) and Smiles and Youngs (1965) and have been tabulated by Youngs (1968).

Eq. (3.3) 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. This is the situation if Darcyan behaviour of the flow is assumed and there is no influence of a depression cone or compressibility of the medium on the flow during the test. If any such condition is not met Eq. (3.3) should be written as

$$k(t) = \frac{\pi r_p^2}{A_p} \frac{d}{dt}\left(\ln \frac{y_0}{y(t)} \right) \tag{3.4}$$

where

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

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

For peat soils Eq. (3.4) should be applied, as will be shown in the next section.

3.9.4. Non-Darcyan flow in hydraulic conductivity tests in peat

At a pumping test in blanket peat in Glenamoy in Mayo, Ireland, Galvin and Hanrahan (1967) found that neither the drawdown in observation wells nor well discharge showed a linear relationship with the drawdown in the pumping well. At large drawdowns between 3 and 7 m the discharge even decreased with increasing drawdown in the pumping well. Calculated k-values ranged from 0.98 cm d^{-1} at a drawdown in the pumping well of 0.97 m to 0.29 cm d^{-1} at a drawdown of 7.03 m. They explained their results by assuming blocking of pores by entrapped air. In a laboratory test the authors found a similar decrease of the hydraulic conductivity with decreasing pore pressure over a range of +84 to -28 kPa in all their samples.

Dai and Sparling (1973) reported on a number of tests, based on the method devised by Luthin and Kirkham. They applied different heads in both raised bog and poor fen sites in Kennedy Bog in NE Ontario. The bog peat consisted mainly of *Sphagnum* peat, the fen peat was sedge peat, both of an unspecified degree of humification. The authors found that larger heads resulted in distinctly larger k-values. Their result is in agreement with the results of Galvin and Hanrahan, who found smaller k with increasing suction.

Ingram *et al.* (1974) also reported non-linearities in piezometer tests on Dun Moss in Scotland. k-values calculated from data of the first minutes of the tests often were larger by about an order of magnitude than those calculated from measurements 3-10 hours after the test was started. A linear relationship of $\ln y_0/y(t)$ versus t was found only in fresh *Sphagnum* peat with a degree of humification of 1-2 on the Von Post scale. The non-linearity increased with increasing degree of humification. Rising head tests yielded smaller values of k than falling head tests. The latter is in agreement with the previously mentioned results reported by Galvin and Hanrahan. Constant head experiments with imposed heads of some 0.50 m showed a decrease of apparent k in time by a factor of about 5 during the first 1 or 2 hours of the test. After this period an almost time independent value of k was obtained.

Similar effects, also from Dun Moss, were reported by Rycroft *et al.* (1975b). An important observation was that in falling head tests, regardless of the initial level, the curves tended asymptotically towards the same conductivity value. In constant head tests the final result remained dependent on the imposed head with larger heads resulting in larger conductivities.

Waine *et al.* (1985) submitted undisturbed *Sphagnum-Eriophorum* and *Spagnum Eriophorum-Calluna* peat samples from Dun Moss to constant head laboratory permeameter tests. They found only small reductions of the calculated k in time. When a copper compound was added to the infiltrating water the value recovered. From this phenomenon the authors concluded that the change had been caused by biological activity during the tests rather than by a direct physical process. However, the same authors found that measured *k* increased with the gradient, but the effects obviously were less spectacular than in field tests reported from previous literature. An increase of the gradient from 5 to 15 caused an increase of the measured *k* by 30-40%. Increasing the mean head by a factor of 4 resulted in an increase of the measured *k* by about 10% only.

The results found by Waine *et al.* (1985) might to a certain extent confirm a remark made by Chason and Siegel (1986), who did not find non-linearities in their laboratory experiments on peat cores taken in Lost River Peatland, a fen and raised bog complex in Northern Minnesota. They supposed this could have been caused by the relatively small differences in head they used. They applied a falling head test during which the head was allowed to drop by 20% of the initial value. From their description of the test, gradients of 7, 5 and 3 can be derived. Another and maybe more likely explanation could be that the authors reported that their peat cores contained relatively many rootlets and woody parts and that the average *k* of the samples was around 1 $m\,d^{-1}$, which is a large value for catotelm peat. They concluded from these data that to a certain extent "micro-piping" could have occurred. This could be a similar process as observed by Ingram *et al.* (1974), that no non-linearity was found in young moss peat of humification degree 1-2, which is more fibrous and has larger pores than more decomposed peats.

Ingram *et al* (1985) reported about some piezometer test results from Upton Fen near Norwich, England. In oxidised and strongly decomposed fen peat they found that non-linearity during the piezometer test occurred, but to a lesser extent than in tests made on Dun Moss and other places. Unfortunately the authors did not give any details as to consolidation which, based on their description of the material, could have been considerable and could have influenced the hydraulic properties of the peat.

The observations presented above do not necessarily lead to the assumption of non-linear, *i.e.* non-Darcyan flow in peat soils. Peat has a flexible matrix that may react to imposed forces, which results in a relatively large elastic storativity. Hemond and Goldman (1985) argued that such an elastic storativity could explain non-linearities observed during piezometer tests in peat without the need to assume a head dependent *k*. This would explain a few things:

- why the probably more consolidated peat soils of Upton Fen showed a more linear behaviour than other peats
- why the phenomenon is hardly mentioned in the extensive German mire literature, because most *k*-values in that country have been measured in drained and cultivated peats where a considerable consolidation has occurred as e.g. described by Eggelsmann (1990b)
- why laboratory measurements with small samples enclosed in rigid containers apparently tend to show less effects of non-linearity than peats in field tests.

It does not explain, however, why during constant head tests different imposed heads yielded different k-values as observed by Rycroft *et al.* (1975) and Waine *et al.* (1985). However, one should realise that gradients, imposed during k-measurements, hardly ever occur in natural flow processes in peat. It justifies the conclusion of Hemond and Goldman that there are no good reasons to put a satisfactory applicability of Darcy's law in doubt.

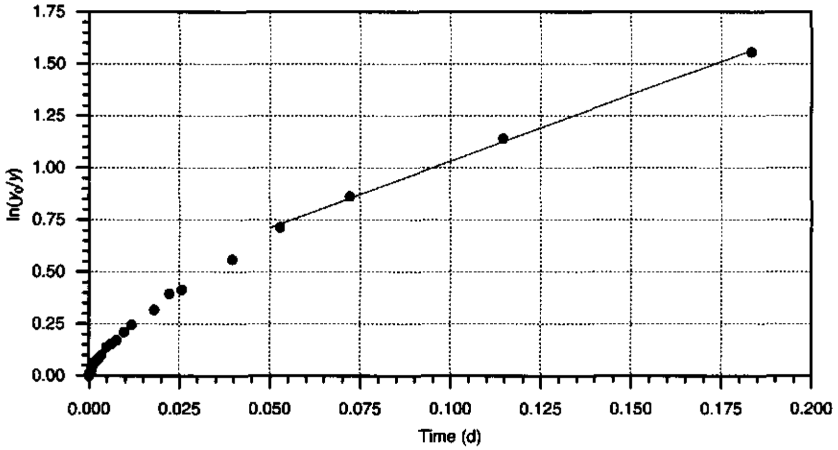

Fig. 3.19. ln $y_0/y(t)$ versus time t from a falling head test on Clara Bog. The initially imposed head y_0 was 16 cm. Hydraulic conductivity k was calculated from the line fitted through the four rightmost points. The apparent k during the first two minutes of the test is about 5 times as large as k calculated from the last four points.

However, the above conclusions do have some implications as to the application of Luthin and Kirkham's piezometer method in peat soils:

- Constant head tests should preferably not be applied, because the imposed head is the distance between water table at equilibrium and the top of the tube, which in most cases leads to imposed heads of 30-50 cm. This causes much larger gradients than occur in peat under natural conditions. Another problem is the usage of Mariotte vessels that are needed to maintain the constant head. Because the temperature of the open air is variable, expansion and shrinkage of the enclosed air in the vessel causes water losses resulting in an overestimation of k.
- Variable head tests should be continued until $\ln y_0/y(t)$ versus t shows an approximately straight line. The value of k is then obtained from the slope of the straight part of the curve (Fig. 3.19). *As to k-values obtained from the initial part of the curve, it seems appropriate to speak of "apparent k".* If the observation by Rycroft *et al.* (1975b), that the initial head has no influence on the eventual result, is generally valid, special care in this respect need not be taken. Because irreproducibility in con-

stant head tests was not a feature mentioned anywhere in the quoted literature (at least some authors repeated their tests) reproducibility probably is a safe assumption.

- Even in tests with a small imposed head of a few cm the system should be allowed time to reach the stage of "linear" behaviour. In falling or rising head tests this will lead to problems resulting from the increasing relative error in the measurement of the head. Therefore the initial imposed head should be sufficiently large to have a remaining head of a few cm during the "linear" stage.

3.9.5. Testing and modifying the piezometer method

Fig. 3.20. Piezometer filter screen as used in the tests (variant with stopper, which also keeps filter cloth in place).

To find which variant of the piezometer method could best be applied, it was tested on Raheenmore Bog. The test was also necessary because no equipment was available to do piezometer tests according to the recipe of Luthin and Kirkham: insert a tube with a loose bottom into the soil and then lift it over a certain distance to create a cavity. This might have been possible at small depths, but not at depths of 5-8 m or more. Instead, piezometers were constructed with a filter screen that was pressed down into the peat to the required depth. The filter screen was a section of the tube in which holes had been drilled with a 6-mm drill. It was covered with nylon geotextile cloth. The lower end of the tube was closed by capping it with a ferrule or by a stopper with the same diameter (1") as the outer diameter of the tube (Fig. 3.20).

Questions as to the following points had to be answered:

- whether a constant, falling or rising head method should be applied
- influence of the imperfect perforation of the filter screen
- effects of sealing with a cork or a ferrule, because the diameter of the ferrule was about 5 mm larger than the tube diameter; this might cause the effective "cavity" to be longer than the actual filter screen length
- effects of filter screen length on apparent *k* as reported by Dai and Sparling (1973).

Tests on 16 piezometers installed on an area of 4x4 m with combinations of a ferrule/cork sealing, filter screens of 10 and 20 cm long and a perforation percentage of 10 and 20% were performed. Sijtsma and Veldhuizen (1992) described the test, the results and the analysis in full. The results can be summarised as follows:

- Similar non-linearities as reported by different authors were encountered in the moving head tests
- The rising head, falling head and constant head methods yielded significantly different results. The smallest values of k were obtained from the rising head method. The geometric means of all values from the falling head method were 50% and those from the constant head method about 250% larger
- After removal of the two most extreme results of each method the k values of the rising head method lay between 5 and 35 mm d^{-1}, those of the falling head method between 7 and 25 mm d^{-1} , and those of the constant head method between 10 and 60 mm d^{-1}
- No effect of the degree of perforation could be found. Probably the cloth cover transmitted enough water to annihilate possible influences of the partial perforation
- No direct effect of the sealing on the result was found, but there was a significant interaction with filter screen length
- The filter screen length of 10 cm gave a significantly larger k than the length of 20 cm. This may have been the result of a certain leakage along the tube which of course has a larger influence on a short filter than on a long one. The interaction with sealing, mentioned in the previous point, also suggested such an effect with the ferrule sealed tubes.

These results led to the following modifications to the piezometer method:

- The falling head method was adopted as a standard. Values of k should be calculated from the last, approximately straight part of the curve of $\ln y_0/y(t)$ versus t as shown in Fig. 3.19;
- Initial imposed heads should all be in the range of 15 to 20 cm for reasons of repeatability;
- Ready made filters covered with a nylon geotextile cloth as shown in Fig. 3.20 replaced cavities based on the original Luthin/Kirkham recipe;
- Filter screen lengths of 20 cm were applied;
- Ferrules were not used as a sealing device. Corks or rubber stoppers, not protruding outside the outer diameter of the tube were applied instead.

k-values were measured at different depths per site to allow estimation of both transmissivity and vertical resistance of the catotelm. On Raheenmore Bog the depths were 0.5, 1, 2, 3, 4, 7, 10 m and the largest possible depth over 10 m below the bog surface. Positions are shown in Fig. 3.21. Depths on Clara Bog West were 1, 2, 3.5, 5, 6.5, 8.5 m and the largest possible depth >8.5 m. Positions are shown in Fig. 3.21 (Raheenmore) and Fig. 3.22 (Clara). The largest depth to which a piezometer could be pressed down was assumed to be the peat depth.

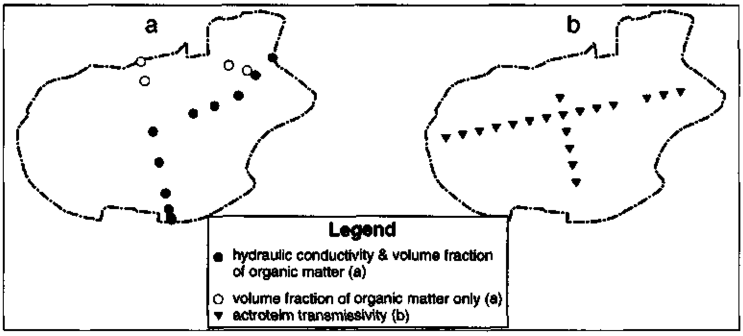

Fig. 3.21. Positions of the measuring sites of hydraulic conductivity k (a), volume fraction of organic matter ϕ_o (a) and acrotelm transmissivity T_a (b) on Raheenmore Bog.

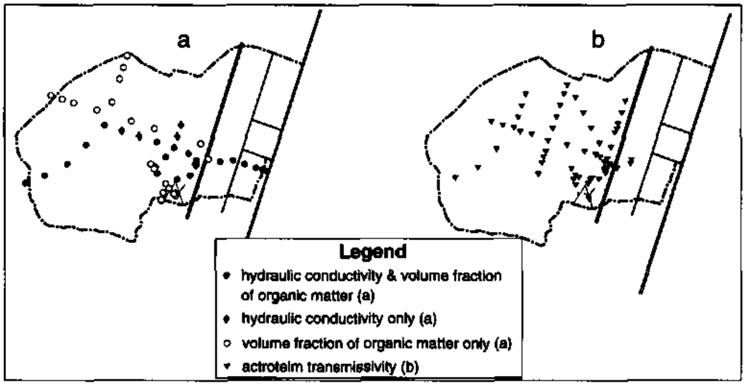

Fig. 3.22. Positions of the measuring sites of hydraulic conductivity k (a), volume fraction of organic matter ϕ_o (a) and acrotelm transmissivity T_a (b) on Clara Bog West.

3.10. Volume fraction of organic matter, degree of humification

3.10.1. Introduction

Measurements of the organic matter content were basically done to assess the possible surface subsidence. An attempt was also made to find a statistical relationship with hydraulic conductivity k and the degree of humification H according to Von Post. *Organic matter was assumed to be identical to solid matter.* Data of Galvin (1976) and Hammond (1981) showed that the peat of Irish Midland bogs contains *negligible amounts of mineral matter.*

When a mire surface subsides as a result of drainage, this is because it loses part of its water content. Subsidence caused by natural oxidation of organic matter is a much slower process, as was found in section 2.7. In the case of Clara and Raheenmore Bog this allows an estimate to be made of surface subsidence under the assumption that oxidation losses are negligible and thus the original volume of organic matter has remained.

Without laboratory facilities the volume fraction of organic matter ϕ_0 in a peat sample cannot be determined directly. However, it can be derived from the mass fraction if the mass density ρ_0 of the organic matter in peat is known and the sample does not contain substantial amounts of other components but organic matter and water. Ombrotrophic peat that does not receive anything else but rainwater satisfies this condition. In underlying fen peat the situation might be different.

Information on the mass density of the organic matter in Irish peats is available from a publication by Galvin (1976). He found a value for ρ_0 of 1.36 g cm^{-3} in ombrotrophic peat and 1.36-1.38 g cm^{-3} in fen peat samples taken from the lower strata of raised bogs. The credibility of these results is confirmed by data from Skempton and Petley (1970), who extrapolated a value of about 1.4 g cm^{-3} for some British fen peats at 100% ignition loss.

The ash content of the fen peat material could be a problem. Ombrotrophic peat has a low ash content by definition because it is only fed by precipitation water. Galvin found an ash content of 1.0-1.6% of the oven dry weight in his moss peats and one of 7.5% in his fen peat samples. Because the analysis was based on dry combustion at 500 °C, these values contain an unknown component of atmospheric oxygen bound during the combustion process, whilst some losses because of evaporation might also have occurred. If ρ_0 is assumed to be 1.35 g cm^{-3} and the same value for ash at 2.6 g cm^{-3} (approximate value for silicates), ρ of a peat sample with a 10% mass fraction of ash would be 1.42. From a statistical analysis of data from western Finland, Karesniemi (1972) extrapolated an average ρ_0 of 1.43 g cm^{-3} for ash free samples. However, for ash contents below 4% of the dry matter (by weight) his results varied rather randomly between 1.33 and 1.53 g cm^{-3}, which raises some doubts as to the accuracy of his (unspecified) method. A reasonable assumption for the density of fen peat would therefore probably be 1.40 g cm^{-3}. This value was confirmed by Hammond (personal communication) and by H. Okruszko (personal communication).

If fen peat samples are analysed without a check on other components than organic matter and water, the samples, particularly those from the lower parts of the peat must be examined carefully on traces of mineral soil material. The value of the dry matter content that results from the analysis must be checked with other values on unusual differences to make sure they do not contain disturbing amounts of mineral soil material. However, the presence of mineral soil material in a fen peat that has formed under lacustrine conditions in an isolated lake basin is not very likely, except maybe in a narrow zone along the margin.

3.10.2. The measuring technique and the measuring sites

Samples were taken at depth intervals of 0.5 m using a Russian type of peat corer that takes almost undisturbed half-cylindrical samples (Fig. 3.23) with a diameter of 5 cm.

Fig. 3.23. Taking a sample from the peat corer (Raheenmore Bog, December 1991)

From the middle of each core of 0.5 m long, a 5 cm long sample was cut and stored in an aluminium box. The Von Post degree of humification H was determined of immediately adjacent and similar material in the same core. The boxes were closed immediately after having been filled. The samples were weighed on the same day and dried at 105 °C until constant weight. This took about 24 hours. The samples were then weighed again. The result gave the volume of water in the sample and the weight of the organic matter. Dividing the weight of the organic matter by its mass density yielded its volume. The technique can only be used if the sample is saturated, *i.e.* the sample has to be taken below the phreatic level. Even in a disturbed bog this condition is usually satisfied, except sometimes in the upper metre of the margin zone. The volume of water in a sample is calculated from:

$$V_w = \frac{m_w - m_d}{\rho_w} \tag{3.5}$$

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 can be calculated from m_d by

$$V_o = \frac{m_d}{\rho_o} \tag{3.6}$$

where

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

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

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

$$V_s = V_w + V_o \tag{3.7}$$

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

$$\frac{V_{s0}}{V_{s1}} = \frac{\phi_{o1}}{\phi_{o0}} \tag{3.8}$$

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 [1]

ϕ_{o1} = actual volume fraction of organic matter [1]

Because shrinkage of peat in a bog means mainly shrinkage in the vertical direction, the symbols for volume in Eq. (3.8) can be replaced by symbols for layer thicknesses D:

$$\frac{D_0}{D_1} \approx \frac{\phi_{o1}}{\phi_{o0}} \tag{3.9}$$

where

D_0 = original layer thickness [L]

D_1 = actual layer thickness [L]

Eq. (3.9) is the basic equation to estimate subsidence caused by water loss, as long as other causes such as losses by methane production may be neglected. The main problem is to find a value for ϕ_{o0}. In almost any case the only way is to use a reference profile which is assumed to be unaffected by human activities and in a similar situation as the profile being examined. This cannot be proven, except maybe in an exceptional case. Therefore the method should be applied with much care.

The positions of the sampling sites on Raheenmore Bog are shown in Fig. 3.21, those on Clara Bog West in Fig. 3.22. No work was done on Clara Bog East.

3.10.3. Comparing profiles

Fractional depth

Because the thickness of the peat differed considerably between the sampled spots, the sampling depths in different profiles could not be compared directly. Therefore in some comparisons between profiles with different depths, the sampling depth was transformed to a dimensionless fractional depth, defined as:

$$d_f = \frac{d_s}{D_p} \qquad (3.10)$$

where

d_f = fractional depth [1]

d_s = sampling depth below the surface [L]

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

There may also be differences between margin and central sites. Sijtsma and Veldhuizen (1992) and also Ten Dam and Spieksma (1993) found that the peat near natural margins of both Raheenmore and Clara Bog generally contains more organic matter per volume than in the central areas, even if compaction by surface subsidence was taken into account. The phenomenon can be explained by differences between physical conditions at natural raised bog margins and those in the central part. In bog literature, little information is available on this phenomenon. One of the few sources is Früh (1897). In his inventory of 30 bog bursts[1] of which 25 had occurred in Ireland, he concluded that often the interior part of the bog flows out, whilst the original margin stands out as a ring-wall after the burst. This also indicates a difference in consistency between margin peat and peat of the central area. Therefore a distinction is made between margin sites and "central" sites in some comparisons.

Margin sites can in general be described as sites that show clear effects of drainage in both the vegetation (more *Calluna vulgaris* and *Scirpus caespitosus* than in the central area, for example) and in the stiffer consistency of the peat at the surface, compared to the wet central areas. Other "margin" areas are caused by face banks left by turf cutting, by the Clara-Rahan road or by subsidence combined with the presence of local elevated parts in the underlying mineral formations. The latter includes the ridge W of Shanley's Lough and a small mound to the NW of piezometer site 206 on Raheenmore Bog. An

[1] A bog burst is a sudden landslide-like outflow of peat from a raised bog. A recent example is the burst of la Vraconnaz in the Swiss Jura in September 1987 (Feldmeyer-Christe and Mulhauser, 1994).

entirely objective distinction cannot be made, however. The positions of the margin and central sites on both bogs are shown in Fig. 3.24.

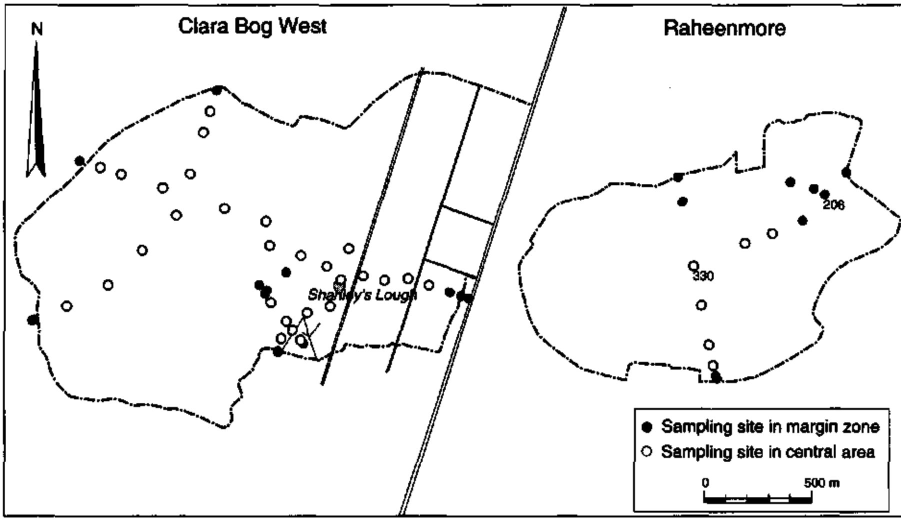

Fig. 3.24. Margin and central sampling sites on Clara West and Raheenmore.

Partial thickness of organic matter in a peat profile

The method of assessing subsidence as described in 3.10.2 basically estimates the total amount of organic matter in each sampled peat profile or layer. The volume of organic matter in a profile may be expressed as the total thickness the material would occupy without pores. This value will further be named *partial thickness* D_{op} of organic matter. D_{op} allows a comparison of the amounts of peat in different profiles in a bog. It is defined by

$$D_{op} = \int_{-D_P}^{0} \phi_o(z)\mathrm{d}z \tag{3.11}$$

where

D_{op} = partial thickness of the solid matter [L]
D_P = total peat depth [L]
ϕ_o = volume fraction of organic matter [1]
z = vertical position [L] (0 at the surface and negative downwards)

When estimated from a sampled profile, Eq. (3.11) is approximated by

$$D_{op} \approx -\phi_{o_1}\frac{z_1 - z_2}{2} + \phi_{o_n}\left(D_P + \frac{z_{n-1} + z_n}{2}\right) + \sum_{i=2}^{n-1}\phi_{o_i}\frac{z_{i-1} - z_{i+1}}{2} \tag{3.12}$$

where

n = the number of samples taken in a peat profile [1]

The samples are counted from the surface downwards. For peat layers that do not comprise an entire profile, the term 'partial thickness' will be used with symbol D_o. Apart from referring to a part of a profile, there is no fundamental difference with D_{op}.

3.11. Evapotranspiration

Evapotranspiration ET is normally the most important loss term in the long-term water balance of most Irish Midland raised bogs. Values can be calculated from meteorological data or measured directly from lysimeters.

The nearest official meteorological stations that produce all the data necessary to calculate potential evaporation rate from open water E_o using the Penman equation are Birr and Mullingar (positions indicated in Fig. 3.1). Both stations are situated at considerable distances from Raheenmore Bog (60 km and 20 km, respectively) and from Clara Bog (45 km and 35 km, respectively).

A recording weather station of University College Galway was installed on Clara Bog in late 1991. Data from this station, allowing calculation of open water evaporation are available from winter 1992 onwards.

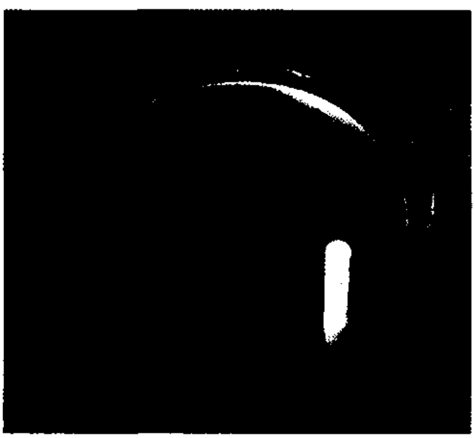

Fig. 3.25. Weighable lysimeter on Raheenmore Bog (August 1991). The vegetation is dominated by *Sphagnum magellanicum*. The diameter of the lysimeter is 40 cm. The tube is used to measure "phreatic" levels in the lysimeter.

Because E_o was expected not to represent ET from a bog, small weighable lysimeters were operated during one year on each bog. The lysimeters were circular in horizontal cross section and had a surface area of 0.125 m^2. The lysimeters were of the type described by Schouwenaars and Vink (1992). A lysimeter with *Sphagnum magellanicum* dominated vegetation cover is shown in Fig. 3.25. The lysimeters were sealed at the bottom and were filled with an undisturbed peat monolith with a length of 0.45-0.50 m with its original vegetation cover. The column was cut by pressing down a bottomless lysimeter container and removing the surrounding peat with a spade. After the container was filled, the monolith was separated from the underlying peat with the spade, lifted carefully while the bottom was supported to ensure that the column would remain in the ring. Then the ring was placed on top of a lysimeter container with a bottom and the monolith was forced into it by gently shaking the ring. All lysimeters were then transported to the same location on the bogs (Fig. 3.13 and Fig. 3.14) where they were dug in until their surface was at the same level as the bog surface. They were weighed approximately weekly (Fig. 3.26). Evapotranspiration *ET* over the preceding week was calculated from the difference in weight and the precipitation recorded over the same period.

The lysimeters contained the most important elements of the vegetation cover of the bogs. The phreatic levels in the lysimeters were kept at approximately the same level as in the vegetation elements on the bog area they represented. The measuring periods were 7 April 1991 to 13 April 1992 on Raheenmore Bog and 24 July 1992 to 28 July 1993 on Clara West.

The vegetation elements in the test on Raheenmore Bog were

- *Calluna vulgaris*
- *Narthecium ossifragum* lawn
- *Eriophorum vaginatum* tussock
- *Sphagnum* sp.; mostly *S. magellanicum* and *S. papillosum.*

Each vegetation element had a variant with a well and a poorly developed acrotelm. Every variant was represented in two lysimeters, making a total of 16. The *Sphagnum* lysimeters with the poorly developed acrotelm mainly had *S. magellanicum*; in those with a well-developed acrotelm the dominating species was *S. papillosum.* All lysimeters except the *Sphagnum* dominated ones contained additional species with different *Sphagna* and *Hypnum jutlandicum.*

The vegetation elements in the Clara Bog lysimeters were:

- *Calluna vulgaris* from a burnt spot
- *Calluna vulgaris* from an unburnt spot
- *Molinia caerulea* tussock
- *Eriophorum vaginatum* tussock
- *Sphagnum* sp.

Because the lysimeters on Raheenmore bog had not shown a clear difference in *ET* between poor and good acrotelm variants, this differentiation was abandoned in the test on Clara Bog. Instead, three lysimeters per element were used, making a total of 15. The *Sphagnum* lysimeters contained mainly *S. magellanicum* and *S. capillifolium.* Here also the water levels in the lysimeters were kept at the approximate level measured at the places where they had been cut. Weighing procedures were the same as on Raheenmore Bog.

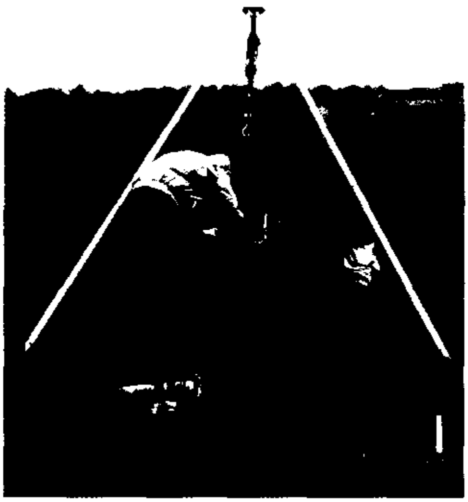

Fig. 3.26. Weighing the lysimeters on Clara Bog (November 1992).

Leaf area indices (LAI) were determined in both the tests on Raheenmore Bog and Clara Bog. As to the *Narthecium ossifragum* lawns, the *Eriophorum vaginatum* and the *Molinia caerulea* tussocks, the LAI was measured in the classic way, *i.e.* as the area of living leaves per surface area. As for the *Sphagnum* lysimeters, the fraction of the total lysimeter area that was covered by living *Sphagnum* capitula was estimated. In the *Calluna* lysimeters the estimating procedure consisted of estimating the surface area per cm branch length on four branches and multiplying the result by the total branch length with green leaves.

3.12. Storage coefficients

Storage coefficients μ were needed to assess the storage term in the water balance and in the methods developed for measuring acrotelm transmissivity T_a in section 3.14. The change of μ with depth of the phreatic level was expected to give information on the transition of hydrophysical properties from acrotelm to catotelm. Two measuring techniques were applied:

- From the lysimeters. Each lysimeter was equipped with a 1" diameter piezometer (Fig. 3.25) that allowed measuring the changes of the phreatic level inside. Storage coefficients μ can be calculated from changes in weight and simultaneous changes of the phreatic level in the lysimeter
- By combining precipitation data from the recording gauges and changes in the phreatic level on the bog, recorded by automatic level recorders.

The recording rain gauges and the level recorders have been described in 3.7 and 3.4, respectively.

3.13. Acrotelm depth

Because the acrotelm is the main aquifer in a raised bog, its depth is an indicator of the hydrological conditions in the part of the bog the value was measured. It will be used to assess effects of drainage and surface slope.

In a survey of acrotelm depth D_a as part of a hydrological study, a reproducible and hydrologically relevant definition is essential. This point was discussed in 2.8. The definition "the top layer of the peat with a degree of humification H of 4 or less on the Von Post scale" was applied in the Raheenmore Bog survey. First results were presented by Van't Hullenaar and ten Kate (1991).

However, T_a-tests that were analysed after the survey of Raheenmore Bog showed that the hydraulic conductivity k in peat with a degree of humification H=4 was so low that an upper value of 3 would be more appropriate from a hydrological point of view. Using the descriptions by Van 't Hullenaar and ten Kate, their acrotelm depth values could be corrected accordingly for the analyses made in this thesis. In the acrotelm survey of Clara Bog the modified definition was applied.

In both bogs the D_a was measured in the hollows. On Raheenmore Bog, at each point of the 100x100 m level grid the top metre was sampled with the peat sampler. The top 50 cm was rechecked with a spade. On Clara Bog measurements were done in a similar way, but also between the grid points whenever a change seemed to occur. A D_a-map of Clara Bog was presented by Van der Cruysen *et al.* (1993).

3.14. Acrotelm transmissivity

3.14.1. Introduction

Measurement of acrotelm transmissivity T_a at different phreatic levels was done to

- assess the dependence of T_a on phreatic level
- to check the validity of Ivanov's empirical equation (Eq. 2.3) under Irish Midland conditions.
- find possible correlations of Ivanov's parameters with D_a and position on the bog.

No field method was available for a proper measurement of T_a. A laboratory method described by Bragg (1982, cited by Ingram and Bragg, 1984) on peat monoliths could not be applied because laboratory facilities were not available. Because a correlation with data from the depth survey was one of the objectives, the number of sampled sites would have been unacceptably small anyway, because of the amount of work involved in the method.

The auger hole method cold not be applied for reasons mentioned in 3.9.1. To measure large transmissivity values (over 10 to 20 $m^2 d^{-1}$) a semi-steady state method had to be developed. For smaller values the pit bailing method of Healy and Laak (1973, cit. Bouwer and Rice, 1983) was modified. Both the semi-steady state and the modifications to the pit baling method are described below.

3.14.2. The semi-steady state method.

The method is based on the drawdown of the water level in a well. In our case it was a pit in the acrotelm that was cut with a spade (Fig. 3.27).

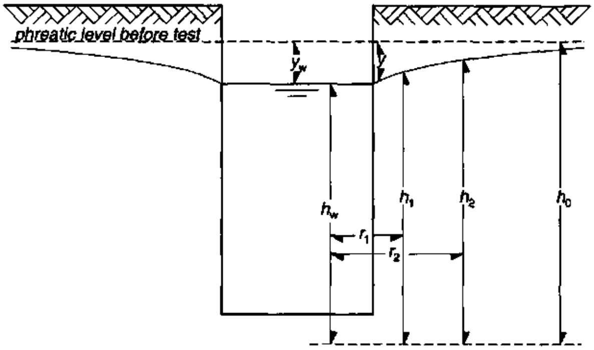

Fig. 3.27. Acrotelm transmissivity test (schematised).

Water was pumped out by a low capacity pump of 1-3 l.min^{-1} until the draw-down does not change visibly during 15 to 60 s, depending on de previous duration of the test.

The basic equation is the Thiem equation:

$$Q = \frac{2\pi T_a (h_2 - h_1)}{\ln \frac{r_2}{r_1}} \qquad (3.13)$$

where

Q	=	well discharge (pumping rate) $[L^3T^{-1}]$
T_a	=	acrotelm transmissivity $[L^2T^{-1}]$
h_1	=	phreatic level at a distance r_1 from the well [L]
h_2	=	phreatic level at a distance r_2 from the well [L]
r_1	=	see h_1 [L]
r_2	=	see h_2 [L]

Eq. (3.13) holds approximately if

(a) the extent of the acrotelm aquifer is much larger than the distance to which the phreatic level is noticeably affected by the drawdown in the well

(b) the aquifer is homogeneous in the horizontal direction over the area in which the phreatic level is noticeably influenced by the drawdown in the well

(c) the phreatic level was approximately horizontal immediately before the test

(d) the discharge rate has been constant

(e) the well fully penetrates the acrotelm aquifer

(f) the flow is horizontal

(g) 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 (a), (c), (d) and (e) are normally satisfied. Condition (b) is mostly satisfied if the site is properly chosen. Conditions (f) and (g) can be satisfied reasonably well by keeping the drawdown in the well small, preferably less than 5% of the acrotelm depth.

In Eq. (3.13) both r_1 and r_2 are unknowns. The radius r_1 can be replaced by the well radius r_w. Let h_2 be the phreatic level immediately before the test. Then r_2 is the distance to which the effect of the pumping has extended (theoretically it is infinite) and the difference h_2-h_1 is the drawdown in the well.

Substitution of r_1, h_1 and h_2 in Eq. (3.13) and writing T_a explicitly yields:

$$T_a = \frac{Q \ln \frac{r_2}{r_w}}{2\pi y_w} \qquad (3.14)$$

where

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

Because the horizontal cross-section of the spade-dug wells was approximately square, an effective radius had to be found. This can be done by either calculating 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

$$r_w \approx \frac{\frac{L}{\sqrt{\pi}} + \frac{2L}{\pi}}{2} \approx 0.6L \qquad (3.15)$$

where

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

Now the only remaining unknown, apart from T, is r_2. r_2 can be estimated as the radius of the depression cone that can be calculated from the volume of water V [L^3] removed from the well:

$$V = Qt \qquad (3.16)$$

where

t = pumping time [T]

If the pumped water is discharged at a sufficient distance from the well, V is approximately equal to the sum of the loss of water volume from the well and the water volume released from the depression cone around the well. An additional assumption is the immediate release of the drainable water above the water table. The value of r_2 is then determined by

$$Qt = \pi r^2 y_w + 2\pi\mu \int_{r_w}^{r_2} r y(r) \mathrm{d}r \tag{3.17}$$

where

μ = storage coefficient [1]

$y(r)$ = drawdown at a distance r from the centre of the well [L]

An expression for y is found from Eq. (3.14):

$$y(r) = \frac{Q \ln \frac{r_2}{r}}{2\pi T_a} \tag{3.18}$$

Substituting $y(r)$ in Eq. (3.17) using (3.18) yields:

$$Qt = \pi r_w^2 y_w + \frac{\mu Q}{T_a} \int_{r_w}^{r_2} r \ln \frac{r}{r_2} \mathrm{d}r \tag{3.19}$$

This implies the assumption that the flux Q is independent of r. This assumption is reasonable if the drawdown in and near the pit has become approximately constant. Solving the integral yields:

$$Qt = \pi r_w^2 y_w + \frac{\mu Q}{4T_a}(r_2^2 - r_w^2 - 2r_w^2 \ln \frac{r_2}{r_w}) \tag{3.20}$$

Eqs. (3.20) and (3.14) form a system of two equations with two unknowns T_a and r_2 if μ is known. Substituting T_a in Eq. (3.20) using Eq. (3.14) yields:

$$Qt = \pi r_w^2 y_w + \frac{\mu \pi y_w}{2 \ln \frac{r_2}{r_w}}(r_2^2 - r_w^2 - 2r_w^2 \ln \frac{r_2}{r_w}) \tag{3.21}$$

If the ratio r_2/r_w is replaced by the symbol n_w, Eq. (3.21) can be simplified to

$$t = \frac{\pi r_w^2 y_w}{Q}\left(1 + \frac{\mu(n_w^2 - 2\ln n_w - 1)}{2 \ln n_w}\right) \tag{3.22}$$

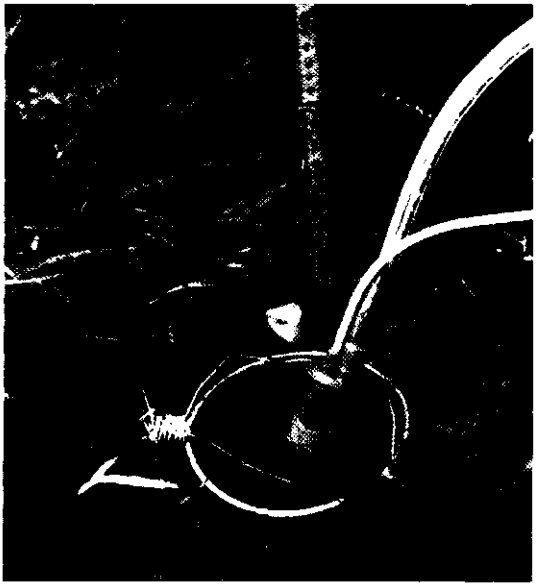

Fig. 3.28. Field measurement of acrotelm transmissivity T_a (Raheenmore Bog, August 1991). The pump is a 12V powered centrifuge type (in the sieve) as used in caravans. The household sieve prevents coarse particles from entering the pump. The ruler is used for reading the levels. The top of the white plastic tube represents the average surface level.

The value of n_w cannot be found directly from Eq. (3.22), but it can either be found graphically by plotting n_w versus t for a known Q, μ and y_w or by iteration, using the following procedure.

Step 1: estimate a value of n_w. Step 2: calculate the pumping time t_{est} using Eq. (3.22). Step 3: multiply the estimated value of n_w by t_{real}/t_{est}, where t_{real} is the real pumping time. Step 4: repeat steps 2 and 3 until the difference between t_{est} and t_{real} has become sufficiently small.

10 iterations are usually sufficient to obtain values equal in the four or five most significant decimals.

Eq. (3.22), but not its derivation, was presented earlier by Van der Schaaf *et al.* (1992).

With known n_w, T_a is then found from the modified Eq. (3.14):

$$T_a = \frac{Q \ln n_w}{2\pi y_w} \tag{3.23}$$

Fig. 3.28 shows the field test setup

3.14.3. 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. After equilibrium has been reached, water is removed from the pit. The basic equation, which is also based on the Thiem equation, reads

$$k = \frac{r_w^2 \ln n_w}{(h_0^2 - h_w^2)} \frac{dh}{dt} \tag{3.24}$$

where

h_0 = water level before water removal [L]

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

Healy and Laak (1973, cited by Bouwer and Rice, 1983) assumed n_w=4. Bouwer and Rice compared the pit bailing and the piezometer method. They concluded that the pit bailing method and the piezometer method give comparable results as long as the distance between the bottom of the pit and an underlying impervious layer is not 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

$$D_a \approx \frac{h_0 + h_w}{2} \tag{3.25}$$

if h_0 and h_w are taken relative to the level of the acrotelm bottom. Because $T_a=kD_a$ and $y_w=h_0-h_w$, Eq. (3.24) can be reduced to

$$T_a = -\frac{r_w^2 \ln n_w}{2y_w}\frac{dy}{dt} \tag{3.26}$$

If the test is done as a recovery after the semi-steady state test, the initial value of n_w is known from that test. However, while 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, y_w, r_w and μ. From Eq. (3.22) one can derive simply:

$$V = \pi r_w^2 y_w \left(1 + \frac{\mu(n_w^2 - 2\ln n_w - 1)}{2\ln n_w}\right) \tag{3.27}$$

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

Alternatively, if the change of ln n_w during the recovery is relatively small and thus may be assumed constant, a curve fitting procedure can be followed. For this purpose Eq. (3.26) must be integrated. Integration and solving the integration constant for recovery time t_r=0 yields:

$$T_a \approx \frac{r_w^2 \ln n_w}{2t_r}\ln\frac{y_{w0}}{y_w} \tag{3.28}$$

where

t_r = recovery time [T]

y_{w0} = drawdown in the well [L] at the beginning of the recovery where t_r=0

Eq. (3.28) strongly resembles Eqs. (3.3) and (3.4), applying to the piezometer method. Dividing both sides of Eq. (3.28) by D_a, followed by eliminating k using Eq. (3.3) or (3.4), would in fact yield an equation from which the shape factor A_p can be approximated. It means that using the equation of the piezometer method to calculate T_a implies the assumption of a constant n_w. Results of the piezometer method and the pit bailing method (the latter with time-dependent n_w) will be compared in 6.3.2.

Eq. (3.28) may be solved graphically by plotting $\ln y_{w0}/y_w$ against t. The tangent of the angle of the line and the t-axis is the value of $2T_a/\left(r_w^2 \ln n_w\right)$. Linear regression is another possibility, but a graph should be made to check whether the curve sufficiently approaches a straight line.

In situations in which the transmissivity is too low to apply the semi-steady state test, the pit bailing methods is the only option. The volume of water is then removed from the pit instantaneously and in fact a classic pit-bailing test is done. However, n_w can still be found from Eq. 3.24.

A reasonably reliable value of the storage coefficient μ is needed in all cases. It was estimated from the lysimeter tests. The practical size of the pits was approximately square with sides between 17 and 27 cm and depths around 40 cm.

3.15. Discharge

Discharges Q_a were recorded because discharge is the second largest loss component of the water balance of both bogs and the expected relationship of T_a and Q_a was one of the research questions.

All Q_a were calculated from level recordings upstream of a measuring weir. The three weirs that were installed in 1989 and 1990 had an analogue recorder supplied by the Geological Survey of Ireland from September 1990. Like the analogue groundwater level recorders, the discharge recorders had a one-month chart. The charts were processed in exactly the same way as those of the level recorders (section 3.4).

On Raheenmore Bog, discharge measurements were done at one single site at the north-eastern margin, using a 90° Rossum weir and an analogue recorder with a one month chart. The Rossum weir was originally described by Boiten (1985). A temporary collector drain of about 70 m long was cut in the bog, approximately parallel to and a few m from the margin. Continuous recordings with a few minor gaps caused by instrument failure are available from 18th September 1990 until 19th July 1993. Gloudemans (1990) presented rating curves of the weir. The position of the site is shown in Fig. 3.13.

Fig. 3.29. Replacing the chart of the level recorder in the collector drain at discharge gauging site CWD1, *Clara Bog West* (December 1991). The recorder stands on PVC pipes filled with concrete that are anchored in the mineral subsoil. The weir is a Rossum type (background with gauging staff).

On no part of Clara Bog West Q_a is concentrated in one point as it is on Raheenmore Bog. Discharge measuring sites were initially installed in two old drains SW of Shanley's Lough, but after a few rainy periods in the winter of 1990 it became clear that an unacceptably large part of the water flew around the weirs. In the autumn of 1990 screens with additional collector drains were installed to divert the flow towards the weirs (Fig. 3.31). An integrating flow meter that was originally installed in the eastern drain did not work satisfactorily and was replaced by a Thomson weir, constructed and installed by the Office of Public Works.

Fig. 3.30. Thomson weir, constructed by OPW with level recorder CWD2 on *Clara Bog West* (April 1991). The steel construction was anchored in the mineral subsoil.

Both the 90° Rossum weir (Fig. 3.29) in the Western collector drain and the Thomson (Fig. 3.30) were equipped with a new analogue recorder by the Geological Survey of Ireland. Their positions, marked "CWD1" and "CWD2" are shown in Fig. 3.14.

Recording at the Rossum weir started on 11th September 1990, at the Thomson on 13th November 1990. Rating curve data of the Rossum are given by Gloudemans (1990); on the Thomson the standard Kindsvater-Shen equation according to ISO1438-1975 (ISO, 1983) was applied.

Fig. 3.31. Collector drain with screen to prevent acrotelm flow around the measuring weir on *Clara Bog* (April 1991).

4. HYDROLOGICAL PROPERTIES OF THE CATOTELM

4.1. Introduction

The main hydrological features of the catotelm are

- it is permanently saturated with water, except in disturbed bogs where the upper few decimetres may be intermittently or permanently unsaturated;
- its surface shape largely determines the hydraulic gradients in the acrotelm;
- the elasticity of its material and changes in storage cause changes in the surface level
- in undisturbed bogs the vertical and horizontal outflows remain sufficiently small to limit seasonal changes of the surface levels to an extent that they have no substantial influence on hydraulic gradients.

The small outflow of water from the catotelm is essential for it to sustain. Thus saturated hydraulic conductivity k and its derived quantities -vertical resistance C_c and catotelm transmissivity T_c- are essential catotelm properties. The k-value of peat may be related to peat type, state of decay (degree of humification) and compaction.

Such relationships may be useful to estimate k-values in the catotelm, because the quantities involved can be measured or estimated more easily. Because the different quantities could not be measured at exactly the same point on the bog, variability of peat properties in the horizontal and vertical direction may affect relationships inferred from available field data.

This chapter discusses

- spatial patterns of humification H, compaction and k in the vertical and horizontal direction
- hydrophysical relationships: relations between peat type, k, H, and depth d .

The actual flow processes will be discussed in Chapter 5.

4.2. Spatial patterns of some peat properties

4.2.1. Introduction

A catotelm contains peat of different botanical composition, age, compaction and state of decay. As these factors are likely to influence the k in the catotelm, they are also likely to affect the flow process of water through the catotelm.

The main pattern consists of the main strata of the peat in Irish Midland raised bogs. They are the ombrotrophic peat ("bog peat") and the underlying minerotrophic fen peat. In the ombrotrophic peat of Irish raised bogs, Mitchell (1976) distinguished an upper layer of "Fresh *Sphagnum* Peat" overlying "Highly Humified *Sphagnum* Peat". Other authors (Barry *et al.*, 1973, Hammond 1984) used the terms "Younger *Sphagnum* Peat" and "Older *Sphagnum/Eriophorum* Peat" respectively. We shall use Mitchell's terminology. For reasons of convenience the names "Fresh *Sphagnum* Peat", "Highly Humified *Sphagnum* Peat" and "Fen Peat" will be abbreviated to "FSP", "HSP" and "FP", respectively. In the "True Midland Type" of bog to which Raheenmore Bog and Clara Bog belong (Hammond, 1981), the FSP consists of a layer of a few m thick with a Von Post degree of humification H=1-4, overlying the HSP with H=5-7 (Hammond, 1978).

In both Clara and Raheenmore Bog, the FP and the HSP can be distinguished visually by the recognisable plant remains they contain. The transition from FSP to HSP can usually be discerned in fresh core samples by a somewhat deeper brown colour and the presence of a larger amount of remains of *Calluna vulgaris* in the latter.

Table 4.1 shows estimated mean depths of the boundaries between the main strata FSP, HSP and FP, their standard deviation, range and average thickness of each stratum.

Table 4.1. Averages (m) of thickness (m) of Fresh *Sphagnum* Peat FSP, Highly Humified *Sphagnum* Peat HSP and Fen Peat (FP), fractional depths d_f of the lower boundaries of FSP and HSP, average peat depth D_p (m) and their standard deviations. n is the number of profiles.

Bog, position	Layer	n	Average thickness	Average depth of lower boundary	Standard deviation	Range of depth of lower boundary
Raheenmore,	FSP	9	2.2m	d_f=0.36	0.10	0.25 → 0.56
margin	HSP	9	1.9 m	d_f=0.70	0.16	0.47 → 0.91
	FP	9	1.6 m	D_p=5.6 m	2.1 m	3.5 m → 10.7 m
Raheenmore,	FSP	6	6.1 m	d_f=0.54	0.06	0.48 → 0.65
central area[1]	HSP	6	3.2 m	d_f=0.80	0.05	0.71 → 0.88
	FP	6	2.3 m	D_p=11.5 m	2.3 m	7.8 m → 14.3 m
Clara West,	FSP	9	2.1m	d_f=0.31	0.13	0.10 → 0.54
margin	HSP	12	0.9 m	d_f=0.47	0.16	0.24 → 0.75
	FP	13	3.2 m	D_p=6.1 m	1.3 m	2.9 m → 7.8 m
Clara West,	FSP	25	4.1 m	d_f=0.45	0.11	0.20 → 0.65
central area	HSP	25	2.1 m	d_f=0.69	0.11	0.40 → 0.88
	FP	25	2.8 m	D_p=9.0 m	1.2 m	6.8 m → 11.0 m

In the central parts of both bogs the FSP occupies about half the total peat depth, slightly more in Raheenmore Bog and slightly less in Clara Bog. In the margin zones the proportion of bog peat is considerably smaller than in the central areas. Another remarkable feature is the larger proportion of FP in Clara Bog, compared to Raheenmore Bog.

---

[1]Values based on estimated peat depths in the centre of the bog (at sites 327, 330 and 333)

More details are shown in Appendix A with three transects of profiles across Clara Bog and two across Raheenmore Bog. Other transects were presented by Bloetjes and Van der Meer (1992). They differ little from those shown in Appendix A.

Differences and spatial patterns may be related to

- different speeds of decay in the catotelm;
- increasing pressure on the peat matrix as it is covered by an increasing layer of younger peat;
- variations in climatic conditions during the development of a bog, affecting rates of growth and decay;
- differences in peat forming conditions at the surface in pools, lawns, hummocks and hollows[1]
- differences in physical conditions imposed by the position on the bog

Spatial patterns of botanical composition, humification H and volume fraction of organic matter ϕ_o, may affect the spatial pattern of k in the peat. Because palaeobotany was not included in the field research, only H and ϕ_o will be examined in relationship with hydraulic conductivity.

Originally the measurements were not intended for use in the kind of analyses made in this section. Data on volume fraction of organic matter were intended for an assessment of subsidence. The estimates of H were made as an addition to field descriptions, just in case they would be needed. The measurements of k were made to allow vertical water losses from the catotelm to be estimated. At sites where peat samples were taken for ϕ_o and where k-values were measured, the horizontal distance between both was up to about 5 m. Samples had a volume of 40-50 cm^3. The sample volume of hydraulic conductivity measurements can be estimated at approximately 5 dm^3. Since the project was basically a field project with limited laboratory facilities, the methods applied did not allow measuring k, H and ϕ_o in one and the same sample. For these reasons, the available data do not allow a full picture of spatial patterns and variabilities to be drawn. However, a reasonable outline can be obtained from what is available.

To visualise differences in both the vertical and horizontal directions and possible relations with surface slope and peat thickness, the majority of available sampling sites was arranged into five transects: three on Clara West and two on Raheenmore Bog. Their positions, those of individual sites and the results for all sites in the transects are shown in Appendix A (humification and volume fraction of organic matter). Appendix B

[1] Terminology after Gore (1983). Hollows and pools differ in that pools contain water all year round in most years, whereas the presence of water in hollows depends on seasonal conditions.

shows results of two large transects of hydraulic conductivity profiles, one on each bog, and another small one on Clara Bog.

4.2.2. Spatial patterns of humification

Introduction

The process of humification in a bog implies a slow weakening and breakdown of fibres into smaller particles. Therefore, the lowest degrees of humification *H* may generally be expected close to the surface. This does not imply a monotonous increase of *H* with depth.

Deviations may be related to

- stratification of peat types,
- stratification within peat types,
- spatial and temporal variations of conditions at the mire surface when the peat was formed.

Stratification and lateral differences in humification

In the FP of Clara and Raheenmore Bog often stratification from sedge peat at the top to reed and wood peat at the bottom was found. Generally, little correlation between humification and botanical composition was noted during the fieldwork. However, according to Van der Molen *et al.* (1992), microtope differentiation in the FP occurs. The bog peat also showed variations in botanical composition with depth. Such differences may reflect varying conditions during the process of peat formation. According to Moore (1986) they are at least in part related to differences in humification.

During the analysis of the field descriptions of corings it became clear that the subdivision into FSP and HSP was not clearly correlated with vertical variations in humification. This is illustrated in Fig. 4.1. It shows three humification profiles taken less than 5 m apart at site 330 on Raheenmore Bog and described at depth intervals of 5 cm (normally samples were taken and described at depth intervals of 0.50 m). The site position is shown in Fig. 3.7 and Fig. 3.24. The original descriptions, including humification values *H*, were made by Sijtsma and Veldhuizen (1992).

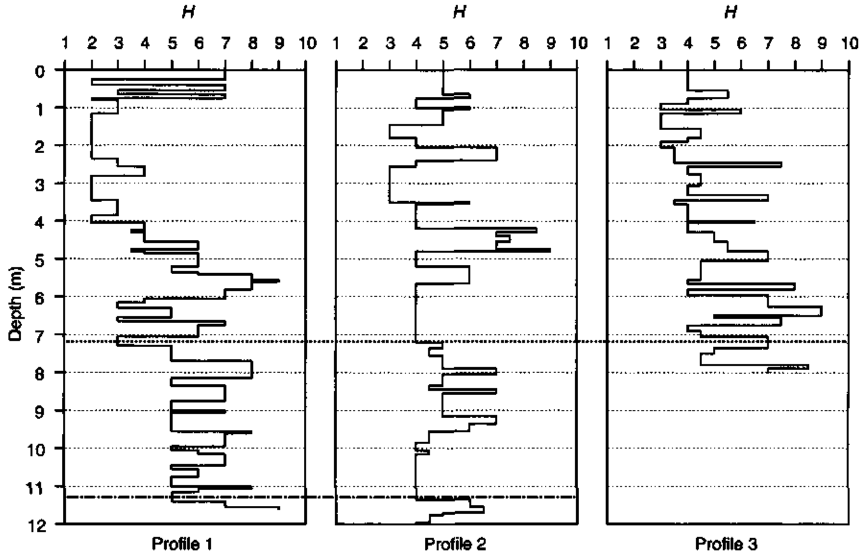

Fig. 4.1. Degree of humification H (-) versus depth (m) at three profiles near piezometer site 330 in the centre of Raheenmore Bog. Dotted lines indicate the transition from FSP to HSP, dash-dot lines from HSP to FP.

Only profile 1 shows a pattern that matches the stratification to some extent. However, the transition from FSP to HSP as it was identified in the field does not coincide with the transition from lower to higher values of H. Apart from this transition and a slight tendency in profile 3 of H to increase with depth, H seems to be distributed almost randomly over the profiles.

The profiles in Fig. 4.1 look poorly correlated, in spite of their mutual distance of only a few m. The correlation can be quantified. Because H is a rank variable, a non-parametric test is appropriate. Hence Spearman's rank correlation coefficient was used as a test variate. Because of the limited number of values H can assume, the data contain ties (equal rankings). Preferably the data should be corrected for ties. The method described by Kendall (1962) was applied.

Levels of significance were calculated after applying the transform described by Sachs (1982):

$$\hat{t}_{n-2} = |r_S| \sqrt{\frac{n-2}{1-r_S^2}} \tag{4.1}$$

where

$\hat{t}_{n-2}$ = estimate of Student's variate with n-2 degrees of freedom

r_S = Spearman's rank correlation coefficient

n = number of data pairs

According to Sachs, the transform can be applied safely for $n \geq 30$. Table 4.2 shows the result.

Table 4.2. Correlation matrix of the humification profiles of Fig. 4.1. Spearman rank correlation coefficients r_S with numbers of data in parentheses in the right hand (upper) triangle, corresponding levels of significance (two-tailed) in the left hand (lower) triangle.

Profile→ ↓	1	2	3
1		0.295 (232)	0.412 (160)
2	<0.001		-0.035 (160)
3	<0.001	0.66	

The correlation of the profile pairs 1-2 and 1-3 is weak in the sense that the pattern in one profile is a poor predictor of the pattern in the other. However, the levels of significance are a strong evidence of the existence of a correlation. The profile pair 2-3 shows no relationship at all. The profiles and the test show that degrees of humification in the peat profiles do not only vary strongly in the vertical direction, but also within horizontal distances of a few metres.

The variability of H in the vertical direction as described above was found in almost all corings of both Raheenmore and Clara Bog. It is in agreement with the findings of Barry (1954), who stated that in Irish ombrotrophic peat "...there is vertically, a marked irregularity or, even, alternation in the degrees of humification, at any boring point". It does not confirm the ranges of H per stratum as specified by Hammond (1981). Mitchell (1976) mentioned the existence of lateral variations over short horizontal distances which he tried to explain at least in part by the theory of lenticular rejuvenation, developed by Kulczynski (1949). The genesis if the strong spatial variability of humification might have bearings on relationships with hydraulic conductivity and volume fraction of organic matter that will be developed later in this chapter. For this reason a study of available literature on raised bog development was made, which is summarised below.

Backgrounds of the vertical and lateral variability of humification

Mitchell's stratification resembles the one described by Weber (1900, 1907) for raised bogs occurring between Elbe and Weser. It comprises a differentiation into less humified Younger *Sphagnum* Peat (*jüngerer Torfmoostorf* or *Weißtorf*), with subjacent more strongly humified Older *Sphagnum* Peat (*älterer Torfmoostorf* or *Schwarztorf*). The strata were separated by the strongly humified *Grenzhorizont* or briefly *Grenz*. Weber assumed the high degree of humification of the *Grenz* to have been caused by increased humification near the surface in a period with a relatively dry climate, which he estimated at about 800-500 BC. Whether such strongly humified layers really represent one and the same climatic period, has been subject to a long lasting discussion on natural regenerative processes in bogs (e.g. Potonié, 1909; Sernander, 1910; Weber, 1926 and 1930; Granlund, 1932). Sernander (1910) noted that the *Grenz* was not very pronounced and often not continuous in raised bogs in Holstein. Granlund (1932) made a similar remark about raised bogs in Southern Sweden. Apparently, the *Grenz* was never identified in Ireland. This may be related to climatic differences with northern Germany. Weber's stratification is too simple to describe and explain the strong variability in humification found in both Raheenmore and Clara Bog.

The theory of recurrence surfaces (*rekurrensytor*) developed by Granlund (1932) postulates a periodical standstill of peat growth with an increased humification at the surface, caused by a period of relatively dry climatic conditions. During subsequent wetter conditions, a cycle of renewed peat growth was assumed to follow. Granlund identified and dated 5 such cycles, including the *Grenz*. Tansley (1939) presented two borings from Irish Midland raised bogs, near Athlone and Edenderry, respectively (i.e. one west of Clara Bog and one east of Raheenmore Bog), taken by Osvald in 1935, in which he reconstructed 7 cycles of regeneration. The profiles with a total peat depth of 7.7 and 8.7 m, had *H*-values of 1-9 in the upper 2 m. This contradicts Hammond's scheme, but it is in agreement with what was found on Clara and Raheenmore Bog during the fieldwork. Nilsson (1964) even identified 9 cycles for a raised bog in Skåne, southern Sweden. Such a process would result in alternating more and less humified layers in a similar pattern in different bogs and would therefore be a more likely explanation of the vertical variability described above than Weber's theory. As many such "recurrence levels" cannot be traced back in different bogs or even in different profiles within the same bog (cf. the low correlation between the profiles of Fig. 4.1), Moore and Bellamy (1974) concluded that at least part of them "may be dismissed as an expression of local drainage features in the course of the history of the mire". The low correlation between the profiles of Fig. 4.1 does not support recurrence.

Another attempt to explain alternating layers of slightly and strongly humified peat was the theory of lenticular rejuvenation, devised by Kulczynski (1949). It implies rejuvenation in hummock-hollow structures by postulating a stagnation of the growth of hummocks by lack of water in their upper part and a subsequent peat growth in the hollows. Thus new hummocks are supposed to form at the place of the hollows, thus turning places that once were hummocks into hollows and causing an inversion of the microrelief. As both weathered hummock tops and hollows may be expected to produce a more strongly humified peat than the lower parts of the hummocks, the theory would explain both horizontally and vertically alternating slightly and strongly humified peat. These ideas go back to an interpretation by Sernander (1910) of descriptions of peat profiles by earlier authors. The theory does not contradict the theory of recurrence, because the lenticular system can be regarded as a system of subcycles, controlled by local hydrological conditions within a climatically controlled recurrence cycle. Lenticular rejuvenation would be a more likely explanation to Fig. 4.1 than recurrence.

Walker and Walker (1961), who investigated face banks left by cutting on eight Irish bogs including Clara Bog, found little evidence of lenticular rejuvenation. They often found that hummocks had persisted when their surroundings were overgrown by *Sphagnum*. Casparie (1969, 1972) confirmed their findings in his study on a large remnant of the Bourtangermoor near Emmen (The Netherlands). Barber (1981) concluded there is no conclusive theory on periodicity of bog growth. Van der Molen *et al.* (1992) found the hummock-hollow systems of Clara Bog to be self-perpetuating until disturbed by external factors. A similar conclusion was drawn earlier by Hulme (1986) for a raised bog in southwest Scotland. Van der Molen *et al.* also concluded that hummock-hollow complexes have larger production and decay rates in the hollows and lower rates in the hummocks. Such differences may be expected to lead to differences in H: low values of H in the hummocks and higher ones in the hollows. Clymo (1984, 1992) attributed horizontal variability largely to variations in growth and decay conditions near the bog surface over horizontal distances in the order of magnitude of a metre or more. According to both Clymo (1983) and Lütt (1992), the rate of decay of different species also varies. Thus vegetation patterns may also have left their traces in horizontal variations of H.

A quick test was done by the author in April 1996 during a short visit to Clara Bog in the hummock and hollow area described by Van der Molen *et al.* 20 sets of 2 augerings of 1 m deep with a peat sampler were made in hummocks and neigbouring hollows. The hummocks had an upper layer of slightly humified material ($1 \le H \le 3$) of 15-40 cm thick, overlying more strongly humified material ($5 \le H \le 8$). The hollows had a shallower layer of 5-25 cm of unhumified to slightly humified material ($1 \le H \le 2$), also overlying humified material with $5 \le H \le 8$. The height of the hummocks was 30-40 cm above the bottom of the hollows. This supports two conclusions of Van der Molen *et al.* (1992):

- the regeneration of the wet vegetation in this part of the bog may be of a rather recent date (2nd half of the 19^{th} century)
- the hummocks have mostly developed on the higher parts of the bog surface and the hollows in the lower parts.

The conclusion from the above is that humification patterns of bog peat on Clara and Raheenmore Bog in both the vertical and the horizontal direction are probably mostly related to differences in height of the bog surface, including hummock/hollow complexes. The horizontal scale is up to a few m. It is in agreement with conclusions drawn by Grosse-Brauckmann (1990) that

- humification patterns are mainly determined by spatially variable conditions in the uppermost part of the peat;

- humification patterns become stable features as soon as they have become part of the deeper layers.

Thus lateral differences in humification may continue over larger depths than the height of a hummock (about 40 cm). The growth of such a system may be interrupted by local hydrological changes and/or minor climatic fluctuations. This set of mechanisms fully explains differences as shown in Fig. 4.1 and similar patterns on Clara Bog and other Irish bogs as shown by Walker and Walker (1961). An extensive discussion on the topic, of course without reference to more recent sources in literature, was given by Overbeck (1975).

Patterns related to depth and position on the bog

The positions of the coring sites on Raheenmore and Clara Bog are shown in Fig. 3.24.

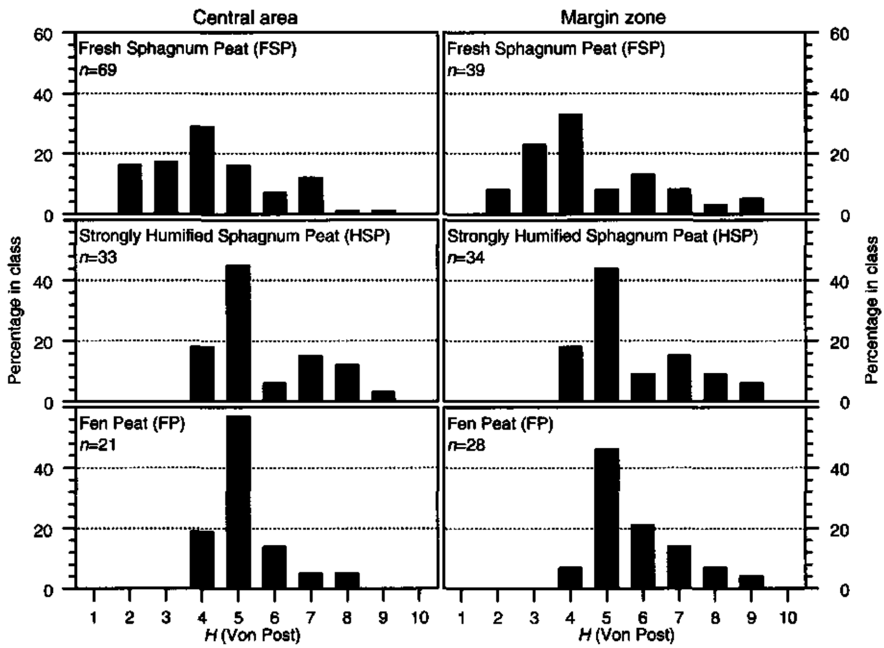

Fig. 4.2. Frequency distributions of degree of humification *H* in FSP, HSP and FP in the central and margin area of *Raheenmore Bog*.

The vast majority of the sites is part of the transects presented in Appendix A. Samples were mostly taken at depth intervals of 0.5 m. From the profiles along the transects shown in Appendix A in figs. A.7, A.8 (Raheenmore Bog) and A.9-A.11 (Clara Bog West), the following conclusions can be drawn:

- Low degrees of humification (*H*<4) occur mostly in the upper part of the FSP and rarely in the HSP and the FP. It is the only pattern-like feature in most profiles.

- High degrees of humification (H=5-9) occur in all three main strata.
- There are no clear differences between margin sites and sites in the central part of the bogs.
- Raheenmore Bog tends to have lower degrees of humification than Clara Bog West.

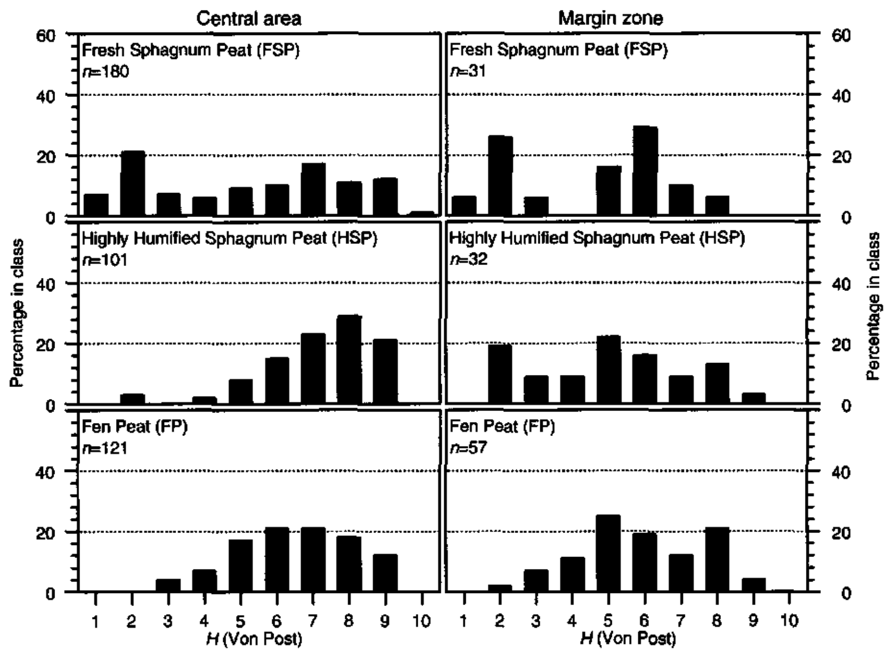

Fig. 4.3. Frequency distributions of the degree of humification H in FSP, HSP and FP in the central and margin areas of *Clara Bog West*.

Fig. 4.2 shows frequency diagrams of H for the three main strata on Raheenmore Bog, for both central and margin sites.

Fig. 4.3 shows them for Clara Bog West.

The frequency distributions of H in the FSP of both Raheenmore Bog and Clara West in Fig. 4.2 and Fig. 4.3 do not contradict the profiles shown by Tansley (1939) and Barber (1981). The range of values of H in the FSP of both bogs is much wider than suggested by Hammond (1981). In the HSP, the distribution agrees rather well with Hammond's range. The values of H in the FP are similar to those in the HSP, although the FP is older and subjacent to the latter.

The differences in H between FSP and HSP seem to reflect a gradual downward change rather than a difference between strata. As a test, the FSP of the central part of both bogs was divided into three depth intervals: d_f<0.2, 0.2< d_f<0.4 and d_f>0.4. The number of samples from margin sites was insufficient for a useful comparison. For Clara

West, the distribution of H in the upper part of the HSP with d_f<0.6 was added; for Raheenmore the limit was defined as d_f<0.7, because of the larger average d_f of the transition from FSP to HSP, compared with Clara Bog (Table 4.1). Fig. 4.4. shows the result.

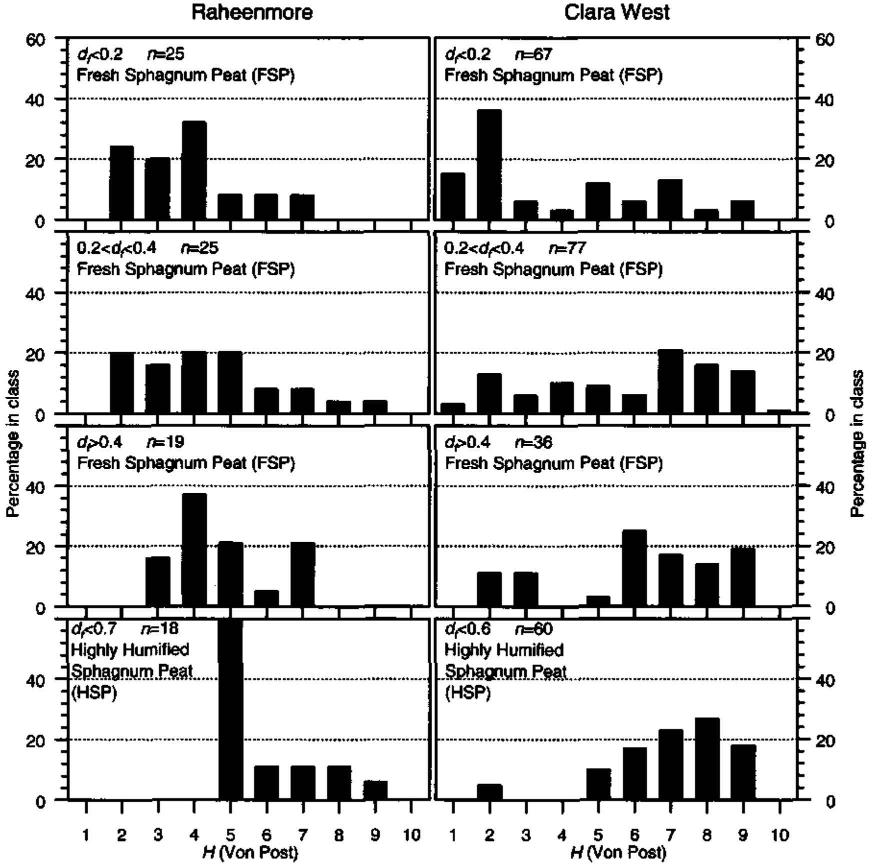

Fig. 4.4. Frequency distributions of humification H in different intervals of fractional depth d_f in the FSP and the upper HSP of the central areas of *Raheenmore Bog* and *Clara Bog West.*

Fig. 4.4 shows a gradual change in humification with depth rather than a sudden one from FSP to HSP. Hence it must be concluded that a vertical trend of H exists rather than a relationship with the stratum. The trend can be visualised by plotting the means of d_f and their confidence intervals versus H (Fig. 4.5). Confidence intervals were calculated with (Snedecor and Cochran, 1989):

$$\bar{d}_f - t_{n-1;0.05}\frac{s}{\sqrt{n}} < \bar{d}_f < \bar{d}_f + t_{n-1;0.05}\frac{s}{\sqrt{n}} \qquad (4.2)$$

where

$\bar{d}_f$ = arithmetic mean of the fractional depth within the humification class [1]

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

s = estimated sample standard deviation of d_f [1]

n = the number of data values within the class [1]

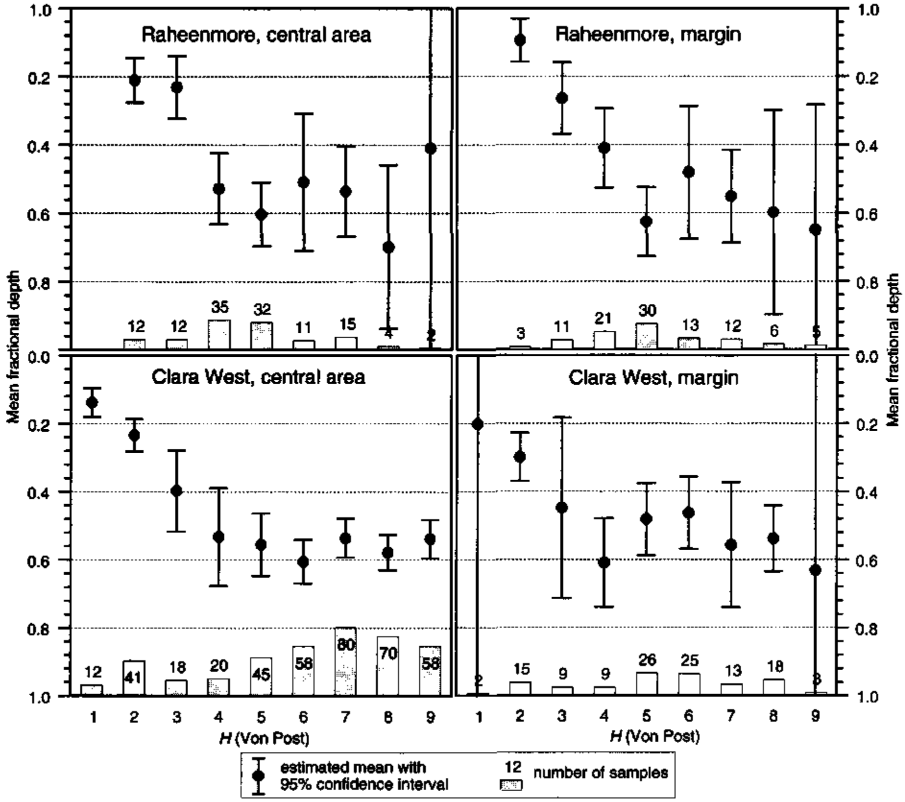

Fig. 4.5. Mean fractional depths and their confidence intevals per humification class *H*.

It should be noted that Eq. (4.2) assumes d_f to be normally distributed. It is not, but the results can be used as a reasonable indication as to whether the means differ significantly.

Fig. 4.5 shows that the tendency of *H* to increase with (fractional) depth is mainly based on the lower classes of *H* that occur in the upper half of the profiles. This is in agreement with the almost equal distributions of *H* in the HSP and FP, shown in Fig. 4.2 and Fig. 4.3.

The existence of a vertical trend in H can also be verified in a quantitative statistical way by Spearman's rank correlation coefficient r_S. Tables A.1 through A.5 in Appendix A show r_S per profile in the transects as shown in Fig. A.1. The variation between the profiles is large with values of r_S ranging from -0.6 to +0.9, almost randomly distributed along the transects without marked differences between sites in margin zones and those in central areas. It confirms the picture drawn in Fig. 4.1.

Conclusions

As to the patterning and variation of H the following conclusions can be drawn:

- H may vary by several points over vertical distances of a decimetre and over horizontal distances of a few metres;
- The FSP shows a range of $1 \leq H \leq 9$. At increasing depth, the share of values ≥ 5 in the FSP tends to increase at the expense of those ≤ 2;
- With a few exceptions, the HSP shows a range of $4 \leq H \leq 9$ for Raheenmore Bog and the central part of Clara Bog and an even wider range in the margin sites of Clara Bog.
- The frequency distribution of H in the FP is comparable to the one in the HSP;
- There is no significant relationship between humification and the three main strata.
- The vertical trend of H to increase with depth is mainly based on the range $H \leq 5$ and thus restricted to the FSP and the upper part of the HSP;
- Variations of H in the horizontal direction are related to a large extent to processes of production and/or decay, related to differences in local hydrological conditions at the bog surface and possibly also to varying climatic conditions;
- Variations of H in the vertical direction are related to processes mentioned in the previous point. The vertical trend in H is related to a process of gradual decay in the catotelm that slows down substantially if $H \geq 5$.

4.2.3. Spatial patterns of the volume fraction of organic matter

Introduction

After having been formed, peat in a living mire is buried gradually deeper as a result of the continuing production of new peat material at the surface. Thus the pressure exerted by the overlying material increases with ageing. The processes of peat accumulation may therefore be expected to cause compaction of the peat with increasing depth.

Spatial patterns in the horizontal direction may be expected in the form of a transition from the central area to the margin zone of the bog. In margin zones subsidence resulting from drainage may be expected to have caused higher values of the volume fraction of organic matter ϕ_o than in the central areas. No data are available that allow a direct assessment of patterns or variability over horizontal distances of a few m.

This section deals with the relationship of ϕ_o with depth and position on the bog.

Results

Table 4.3 shows the estimated correlation of ϕ_o with fractional depth d_f. Because the degree of humification H was found to depend on depth to some extent, the correlation of H and d_f is also shown in the table. For reasons of comparability, Spearman's rank correlation coefficient corrected for ties was used for both, although both ϕ_o and d_f are physical quantities. Student's variate $\hat{t}_{n-2}$ was estimated using Eq. (4.1).

Table 4.3. Rank correlation coefficients r_S of volume fraction of organic matter ϕ_o, degree of humification H and fractional depth d_f, with number of data pairs n, estimated Student variate $\hat{t}$ and derived level of significance α, based on a two-tailed test.

		ϕ_o & H		ϕ_o			H	
Bog	Position	n	r_S	$\hat{t}_{n-2}$	α	r_S	$\hat{t}_{n-2}$	α
Raheenmore Bog	Margin zone	101	0.388	4.19	<0.001	0.352	3.75	<0.001
	Central area	123	0.656	9.56	<0.001	0.376	4.46	<0.001
Clara Bog West	Margin zone	120	0.255	2.87	0.005	0.241	2.70	0.008
	Central area	401	0.572	13.92	<0.001	0.292	6.11	<0.001

The differences between ϕ_o and H are small for the margin zones, but substantial for the central areas. This is related with the compaction of the peat in the upper part of some margin profiles and indicates that subsidence along margins is mostly caused by superficial drainage (*cf.* 2.7). Such drainage is not necessarily caused directly by drains, but may also be the result of an increased surface slope, resulting from by subsidence at the margin. It is in agreement with observations described by Segeberg (1951), Uhden (1960) and Eggelsmann (1990a), who found that subsidence as a result of drainage mainly occurs in the upper part of the peat. It also is at least a partial explanation of the relatively small part of the total peat depth that is occupied by the bog peat in the margin zones. The processes involved will be discussed in more detail in Chapter 7.

Detailed information on differences and similarities can be found in the transects of that have been worked out in Appendix A (Figs. A.12-A.16). In both bogs, most profiles shows an increase of ϕ_o with depth. This is a logical consequence of the process of gradual compaction by increasing overburden. The increase is often largest in the deepest 1-2 m of the peat, particularly at some sites of Raheenmore Bog, where it often was sharper than in the deepest layers of Clara Bog. In most profiles of Raheenmore Bog where the phenomenon was not found, the bottom of the peat was not reached. The consistency in the relationship of ϕ_o and d_f in most individual profiles seems to be considerably larger than the consistency of the relationship of H and fractional depth.

No clear change of ϕ_b at boundaries between the main peat strata shows up in the profiles. This means, there is no evidence of a direct relationship of ϕ_b with main peat stratum, which is similar to what was found for H.

To illustrate the relationship of ϕ_b with depth and position on the bog, Tables A.1 through A.5 in Appendix A show average values of ϕ_b and the correlation coefficient of ϕ_b and depth for all individual profiles along the transects as they are shown on the maps of Fig. A.1. The average values of ϕ_b increase from centre to margin. This can be explained in part by the compaction peat has undergone at drained secondary margins[1]. It will be shown later that close to natural bog margins the increase must have been caused in part by other processes. The values in the transect A'-A, southwest of Shanley's Lough on Clara West are particularly high, probably indicating a rather severe subsidence in the area (an increase of ϕ_b from 0.04 to 0.06 means a shrinkage by one third of the original peat volume). The averages of ϕ_b in the surroundings of Shanley's Lough are large, compared to the rest of the central area of Clara Bog West. It suggests a subsidence in the area of Shanley's Lough. This matter will be worked out in more detail in Chapter 7. The smallest values of ϕ_b were found in the central areas of Raheenmore Bog and the western part of Clara Bog West.

Many margin profiles show an increase of ϕ_b towards the surface. Examples are sites 201, 317 and 313 and 342 on Raheenmore Bog and 78, 84, 92 and 112 on Clara Bog West. This confirms subsidence in the top layer, caused by superficial drainage and explains the low values in Table 4.3 of $r_S(d_f, \phi_b)$ of margin sites, compared to sites in the central areas.

The (non-)existence of large variations of ϕ_b over horizontal distances of a few m as found for H could not be checked. However, the results of the two borings at site 330 on Raheenmore Bog do not show very striking differences (figs. A.12 and A.13). There is a clear trend in ϕ_b, averaged over individual profiles, from margin to centre. The variation of the correlation coefficient of ϕ_b and depth between profiles is rather large, but negative values are only found at margin sites where their existence reflects the effects of physical processes inherent to margin areas. Therefore the existence of large variations in ϕ_b over short distances, comparable with those in H is rather unlikely. This means that the spatial variation of values of ϕ_b and H largely depend on different processes.

---

[1] By "secondary margin" a margin is meant that has been created by human influence. Usually, such margins originate from peat cutting; on Clara Bog they also include the subsidence zone along the Clara-Rahan road.

Conclusions

- There is a clear and significant tendency of ϕ_b to increase with depth in most profiles of the central areas. It is less clear but still significant in margin profiles. The difference is caused by shrinkage of the upper peat layers, resulting from drainage;
- The increase of ϕ_b with depth is more consistent than the increase of H with depth;
- In many profiles, particularly on Raheenmore Bog, the strongest increase of ϕ_b with depth was found in the lowest 1-2 m of the profile;
- The average value of ϕ_b per profile decreases from bog margins to the central part. In the upper 1.5 m of central sites the value usually lies between 0.03 and 0.04. It increases to 0.05-0.08 in surface peat at margin sites and to 0.05 to 0.12 at the peat bottom, regardless of the horizontal position on the bog;
- The value of ϕ_b depends at least in part on other processes than does the value of H. The main factors that determines ϕ_b are the weight of overlying peat and reduced pore pressure in drained (margin) zones, both combined with the flexible matrix that is inherent to peat soils.
- No direct relationship exists between ϕ_b and main stratum (FSP, HSP of FP) in either bog.

4.2.4. Hydraulic conductivity

Introduction

Spatial patterns of the saturated hydraulic conductivity k may be important in assessing both vertical and horizontal outflow in raised bogs.

One of the assumptions in Ingram's groundwater mound theory is a constant value of k throughout the catotelm body (Ingram, 1982). Variations at a vertical scale of a few decimetres and a horizontal scale of a few metres do not affect the theory because they are negligible at the scale of a bog which is several metres in the vertical and usually several hundreds or thousands of metres in the horizontal direction. If a vertical or horizontal trend of k occurs like those for ϕ_b in the previous section, this would seriously affect the theory.

A vertical trend would mean the dismissal of the usage of k in Ingram's equations. Instead, catotelm transmissivity T_c with a non-linear relationship with the thickness of the catotelm should be applied. A horizontal trend from centre to margin means that k becomes a function of the distance r from the centre. This would be a serious complication.

The variability of k over horizontal distances of a few metres may be relevant in the assessment of relationships with H and ϕ_b later in this chapter. It will be discussed first.

Appendix B shows the position of *k*-transects (Fig. B.1), profiles of *k* versus depth per site (Figs. B.2-B.4) and tables with geometric means of *k* and the correlation coefficient of log *k* with depth per profile.

Variability over horizontal distances of a few metres

Although the topic was not researched in a systematic way, an indication can be obtained from an analysis of different piezometer test variants described by Sijtsma and Veldhuizen (1992). It can also be used in a test on spatial variability of *k* over distances of a few metres.

The test was done on 16 piezometers placed in a square grid with a mesh size of 1 m, positioned about 300 m north-west of site 206 (Fig. 3.7 or Fig. 3.24) on Raheenmore Bog. The lower end of the filter screens was 2.60-2.70 m below the surface in *Phragmites* peat with some *Alnus* wood remains and *H* varying between 4 and 6. As eventually the falling head test was adopted for all tests, its results are used here after correction for significant interaction effects of filter screen length and tube sealing (*cf.* 3.9.5). The resulting values of *k* are shown in Table 4.4.

Table 4.4. Saturated hydraulic conductivity values *k* resulting from falling head permeability test on Raheenmore Bog. *k* is expressed in $\mathrm{m\,d^{-1}}$. *x* and *y* are the coordinates of the piezometer grid. On bottom row in parentheses: average and standard deviation after removing outlier at position (3,2).

x (m) / *y* (m)	0	1	2	3
3	$7.30*10^{-3}$	$1.40*10^{-2}$	$7.70*10^{-3}$	$8.87*10^{-3}$
2	$1.06*10^{-2}$	$7.20*10^{-3}$	$1.29*10^{-2}$	$8.09*10^{-2}$
1	$2.10*10^{-2}$	$8.00*10^{-3}$	$1.13*10^{-2}$	$6.76*10^{-3}$
0	$2.45*10^{-2}$	$9.20*10^{-3}$	$5.08*10^{-3}$	$2.46*10^{-2}$
	Average:	$1.62*10^{-2}$ $(1.19*10^{-2})$	Standard deviation:	$1.83*10^{-2}$ $(6.41*10^{-3})$

A consequence of assuming normality of *k* is to accept the possibility of negative hydraulic conductivities, which are impossible on physical grounds. Assuming normality of log *k*, identical to assuming lognormality of *k*, excludes such probability. Analyses involving *k* will therefore be based on $\log_{10} \frac{k}{\mathrm{m\,d^{-1}}}$, denoted as $\log_{10} k$. A consequence is that differences in *k* must be expressed as ratios. The analysis deals with both *k* and $\log_{10} k$.

Table 4.4 has one outlier at position (3,2). It originates from a piezometer in which the water loss showed a sudden increase during a previous test (Sijtsma, personal communication). Probably a disturbance had developed in the piezometer. Therefore the value was discarded.

Semivariances for each available distance L were calculated by (Isaaks and Srivastava, 1989):

$$\gamma(L)=\frac{1}{2n(L)}\sum_{(i,j)|L_{i,j}=L}(k_i-k_j)^2 \qquad (4.3)$$

where

γ = semivariance [dimension of k^2]

L = distance [L] between data points

$L_{i,j}$ = distance [L] between data points i and j

$n(L)$ = number of data pairs [1] with distance L

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

Replacing k in Eq. (4.3) by $\log_{10} k$ gives the semivariance of $\log_{10} k$. Fig. 4.6 shows both semivariograms with fitted straight lines.

In the fitting process, the points were given weights according to the corresponding number of data pairs. Both graphs show an increase of the semivariance with distance. The level of significance of the existence of the relationship based on the F-test (Snedecor and Cochran, 1989) with 13 degrees of freedom (the number of observations the semivariances have been derived from minus 2) for Fig. 4.6a and -b is 0.01 and 0.09, respectively. Thus the semivariogram of k (Fig. 4.6a) gives a more significant result than the one of $\log_{10} k$ (Fig. 4.6b).

As to the spatial variability of k or its logarithm, it can be concluded that inaccuracy of the method and spatial variability have contributed approximately equally to the differences in k as obtained from the 15 piezometers. The contribution of the combination of the measuring method and the medium to the standard deviation of $\log_{10} k$ can be estimated from the intercept of the fitted line. This yields a standard deviation of about 6 mm d^{-1} for Fig. 4.6a and 0.25 for Fig. 4.6b. The conclusion as to the reproducibility of the piezometer method in FP is that errors in measured k, exceeding a factor 2, occur at about 1 out of 5 occasions if a lognormal distribution of k is assumed. In view of the different peat types and conditions involved in the measurements made on the bogs, this is an indication rather than a robust figure.

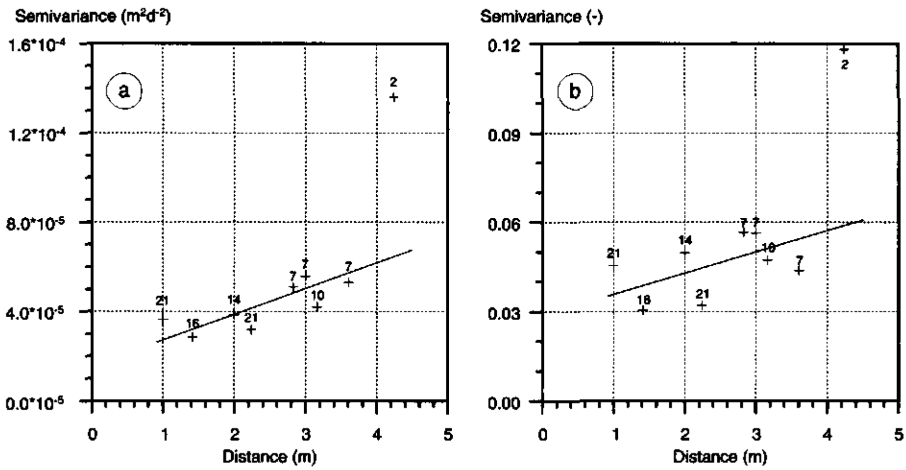

Fig. 4.6. Semivariograms of hydraulic conductivity *k* and of $\log_{10}k$ (a and b, respectively) of the *k*-test on Raheenmore Bog. Figures at the data points give the number of data pairs with the corresponding distance *L* (*cf.* Eq. 4.3).

Patterns related to depth and horizontal position on the bog

Compaction and humification are likely to cause a decrease of hydraulic conductivity with increasing depth. It may be interpreted as the continuation of the decrease of hydraulic conductivity with depth in the acrotelm. Table 4.5 shows the general relationship of the hydraulic conductivity with d_f for the central and margin areas of Raheenmore Bog and Clara Bog West. To allow a comparison with Table 4.3, Spearman's rank correlation coefficient was applied.

Table 4.5. Rank correlation coefficients r_S of hydraulic conductivity *k* and fractional depth d_f with number of data pairs *n*, estimated Student variate $\hat{t}$ and derived level of significance α, based on a two-tailed test.

Bog	Position	*n*	r_S	$\hat{t}_{n-2}$	α
Raheenmore Bog	Margin	21	-0.825	6.36	<0.001
	Central area	43	-0.087	0.56	0.58
Clara Bog West	Margin	31	-0.474	2.90	0.007
	Central area	89	-0.735	10.10	<0.001

The negative values of r_S show that the value of *k* tends to decrease with increasing depth. The central part of Raheenmore Bog, however, shows no significant relationship. At the margin sites a significant increase was found, even though the number of measurements was relatively small. The actually calculated level of significance was $4.3*10^{-6}$. This justifies the indication of "<0.001" in the table, in spite of the fact that applying Eq. (4.1) may give incorrect results at levels of n<30.

All r_S in Table 4.5, except the one of the central part of Raheenmore Bog, have larger absolute values than the corresponding values in Table 4.3, but as a result of the smaller n, the significance in Table 4.5 may be less.

The transects in Appendix B (Fig. B.2-B.4 and Tables B.1-B.3) show more detail than Table 4.5. Generally, the correlation of k and d_f is strong with some exceptions, notably the central area of Raheenmore Bog (*cf.* Table 4.5). Over the sampled depths, individual profiles in the central part of Raheenmore Bog hardly show a sign of a decrease of k with increasing depth.

No clear relationship between mean stratum (FSP, HSP and FP) and the value of k shows up in Figs B.2-B.4. The values of k close to the surface generally lie around 10^{-1}-10^{-2} m d^{-1} in the central areas of both bogs. In the margin sites of Clara Bog they are in the range of 10^{-2}-10^{-3} m d^{-1}; in Raheenmore Bog there is little difference between margin and central area in this respect.

Another difference between the bogs is the average value of k over the profiles, which generally is about an order of magnitude larger in Raheenmore Bog than in Clara Bog (Tables B.1-B.3 in Appendix B). Only the values of the western part of Clara Bog (sites 96-98) are at about the same level as those of the central part of Raheenmore Bog. In both bogs, the mean of k per profile tends to decrease from centre to margin.

A third difference is the decrease of the correlation of log k and depth from margin to centre on Raheenmore Bog that was not found on Clara Bog. Clara Bog shows a decrease of the correlation from the area near Shanley's Lough towards the Clara-Rahan road. This is probably caused by compaction of the peat at the surface during the process of subsidence that has continued over about 175 years. No such change was found at the face bank in the SW (sites 77 and 78) where subsidence has also occurred, but only over one or two decades.

Conclusions

- k usually varies by half an order of magnitude or less over horizontal distances of a few metres and by 3-4 orders over a bog;
- The inaccuracy of the piezometer method for determining k is in the order of a deviation by a factor 2 or more in about one out of 5 measurements;
- No direct relationship between k and main peat strata (FSP, HSP and FP) could be found;
- The average k per profile on Raheenmore Bog is about an order of magnitude larger than on Clara West, except the on westernmost part of Clara Bog, where the values do not differ much from those of Raheenmore Bog.
- The value of k tends to decrease with depth; the average difference between values measured at depths of about 0.50-0.75 m and those near the bottom of the peat is

about 2 orders of magnitude. Exceptions are the central area of Raheenmore Bog and some sites near the Clara-Rahan road on Clara West, where trends of k with depth are insignificant (but the average values differ by about two orders of magnitude between both areas);

- Except in the central part of Raheenmore Bog, the correlation of k with depth is stronger than of H and ϕ_o with depth;
- The mean k per profile tends to decrease from centre to margin; differences between centre and margin are about an order of magnitude;

The last three conclusions are in disagreement with assumptions of the Groundwater Mound Theory.

4.2.5. Discussion and conclusions on spatial patterns

In 4.2.2 to 4.2.4 spatial patterns of humification H, volume fraction of organic matter ϕ_o and hydraulic conductivity k have been discussed.

For none of these quantities, a direct relationship with peat stratification could be found. Hence the classical stratification of FSP, HSP and FP must be regarded as irrelevant to the quantitative hydrology of the catotelm of both Raheenmore Bog and Clara Bog. Differences in H, ϕ_o and k between the three strata are the result of a diagenetic process rather than of the stratification itself. The latter is merely based on botanical composition.

H varies strongly over horizontal distances of a few metres and vertical distances of a few decimetres. This variation can probably be explained by the self-perpetuating conditions at the bog surface -although within climate imposed limits-. The trend of H to increase with depth is significant for $H \leq 5$ only. For larger values of H, the peat material seems to be stable. Thus trends in H are limited to the upper half of the peat profile.

More significant trends than the one of H with depth are those of ϕ_o and k with depth. An exception is the trend of k with depth in the central area of Raheenmore Bog, for which no evidence was found. Apart from this exception, k tends to decrease and ϕ_o to increase with depth. Unlike H, no evidence for strong variations of k and ϕ_o at a horizontal scale of a few m was found.

In the data sets, values of ϕ_o vary from 0.02 to 0.12. The first value was only found in the upper m, the latter in the deepest 0.5 m of Raheenmore Bog. For Clara Bog a range of 0.03-0.09 was found, again with the smaller values prevailing in the upper part and the larger in the deepest parts of the peat. Values of k varied from about 1 to about 10^{-5} m d^{-1}, *i.e.* by 5 orders of magnitude. The larger values occur in the upper part of the peat and the smallest in the deepest layers. Where clear vertical trends in k and ϕ_o occur, they tend to continue over the entire peat profile. Thus it must be concluded that variations in k and ϕ_o to a large extent depend on other processes than variations in H.

Similar differences occur between margin and central sites. The larger values of ϕ_o and the smaller values of k were found at the margin sites, the smaller values of ϕ_o and the larger values of k in the central areas. This suggests a relationship of ϕ_o and k via the process of compaction. ϕ_o of Raheenmore Bog often showed abrupt increases in the deepest 1-2 m. In margin areas the trend of ϕ_o to increase with depth is less significant. Generally, the average values of ϕ_o per profile are considerably larger at margin sites than at those in central areas. Thus shrinkage of peat in the upper part of margin profiles must have been larger than in the deeper parts. This is in agreement with results of German studies on peat shrinkage caused by drainage. No clear differences in H were found between margin and central positions. This is yet another indication that the processes that cause variations in H are at least partly different from those behind variations in k and ϕ_o.

4.3. Hydrophysical relationships

4.3.1. Introduction

From Poiseuille's law one can derive that hydraulic conductivity k is proportional to the square of pore size, expressed as a radius (e.g. Koorevaar *et al.*, 1983). Thus pore size distribution is a major determining factor for k. The main processes in peat that affect pore size are compaction and humification.

Compaction implies a decrease in average pore size. Humification may have a similar effect, since it is a process of breakdown of fibres into smaller particles.

Hence, all possible relationships between ϕ_o, H and k were expected to be possible. In view of the conclusions of 4.2, strong relationships of H with k and ϕ_o are least likely. Because of its hydrological meaning, k is the central quantity and therefore direct relationships of H and ϕ_o with k are of main interest. However, all three relationships will be discussed.

4.3.2. Volume fraction of organic matter and humification

Introduction

As ϕ_o is an indicator of the compaction of peat, compaction may be related in part to strength of the peat matrix and matrix strength is likely to be affected by humification, a relationship between H and ϕ_o was expected. The expectation was supported by literature from Germany (Segeberg, 1952) and Finland (Päivänen, 1969; Karesniemi, 1972) who found strongly positive correlations of H with dry bulk density over the full range of humification in *Sphagnum* peats. Boelter (1969) also found an increasing dry bulk density with decreasing fibre content in peat samples.

Results

In Fig. 4.7, means of ϕ_o and their confidence intervals as calculated using Eq. (4.2) have been plotted for each class of *H*.

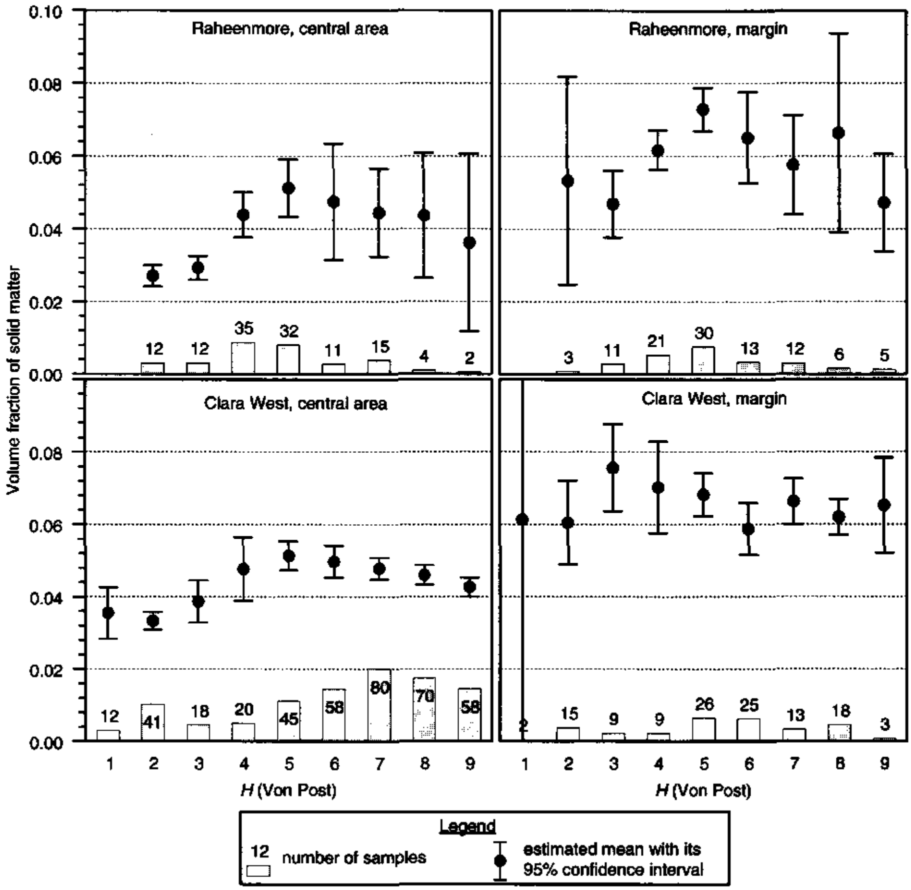

Fig. 4.7. Means and 95% confidence intervals of volume fraction of organic matter ϕ_o per humification class *H* with numbers of samples per class.

The result is rather unexpected. A positive correlation of *H* and ϕ_o for $H \leq 5$ seems to turn into a negative one for $H \geq 5$. A more rigid statistical analysis is given in Table 4.6 ($H \leq 5$) and Table 4.7 ($H \geq 5$). They show Spearman rank correlation coefficients of *H* and ϕ_o with estimated Student variate and level of significance based on Eq. (4.1). Corrections for ties were made using Kendall's correction method (Kendall, 1962).

Table 4.6. Spearman rank correlation coefficients r_S of degree of humification H and volume fraction of organic matter ϕ_o with number of data pairs n, estimated Student variate $\hat{t}$ and level of significance α for $H \leq 5$, based on a two-tailed test.

Bog	Position	n	r_S	$\hat{t}_{n-2}$	α
Clara Bog West	Margin	61	0.130	1.00	0.32
	Central area	135	0.539	7.37	<0.001
Raheenmore Bog	Margin	64	0.575	5.53	<0.001
	Central area	91	0.619	7.44	<0.001

Table 4.7. Spearman rank correlation coefficients r_S of degree of humification H and volume fraction of organic matter ϕ_o with number of data pairs n, estimated Student variate $\hat{t}$ and level of significance α for $H \geq 5$, based on a two-tailed test.

Bog	Position	n	r_S	$\hat{t}_{n-2}$	α
Clara Bog West	Margin	85	-0.062	0.562	0.58
	Central area	310	-0.206	3.69	<0.001
Raheenmore Bog	Margin	66	-0.349	2.98	0.002
	Central area	64	-0.186	1.49	0.07

The significance for $H \leq 5$ is stronger than for $H \geq 5$ in all areas. All correlation coefficients for $H \geq 5$ are negative, but with a weaker significance than for $H \geq 5$. For the margin zone of Clara Bog, the relationships are insignificant. This cannot only be related to the process of compaction, because the margin zone of Raheenmore Bog gives a significant result. Probably the larger diversity in conditions at margin sites of Clara Bog, compared to those of Raheenmore Bog have obscured relationships that would have been found in a more homogeneous set of profiles.

Discussion and conclusions

The results in Table 4.6 and Table 4.7 do not confirm the strongly positive correlations presented by the authors quoted in the introduction. Because the results for three out of four areas are significant and consistent and the lack of significance in the fourth area is likely to have been caused by differences in conditions at individual sites, there should be a physical explanation to the described phenomenon.

One theoretical possibility is that during stages of decay with $H \geq 5$, the peat keeps losing material. According to Naucke (1990), *Sphagnum* peat loses almost 20% of its mass during decay from H=3 to H=10, mainly in the form of carbon dioxide and water. Naucke did not take loss of methane into account, which, according to Clymo (1984) and other authors, is an important source in the carbon flux from bogs into the atmosphere. If no further compaction occurs for $H \geq 5$, loss of carbon dioxide and water from the solid peat matter could approximately explain the reduction of ϕ_0 for $5 \leq H \leq 9$. However, because the postulate that compaction ends when H exceeds a value of 5 seems rather odd, such a process is considered unlikely.

Another and probably more likely explanation may lie in the kind of forces that bind water in peat. As in mineral soils, adhesive and cohesive forces probably prevail in the pores between peat fibres. As decay continues, the share of fine particles in the peat material increases at the expense of fibres. The share of colloids also increases during the process of humification. They are mainly electrostatically stabilised (Aldén and Forsberg, 1987) and thus contribute to osmotic binding of water in a way that is comparable to clay soils. Saturated clay soils, for example, usually have a considerably larger water content than sandy soils (*cf.* Wösten *et al.*, 1994), which is for a large part related to such bindings which do not or hardly occur in sands.

The coincidence that the process of humification seems to slow down considerably at $H \approx 5$ and the transition from a positive to a negative correlation of H and ϕ_0 at about the same level of H might -or might not- be based on causality. Testing this would require rather extensive laboratory research for which no facilities were available.

4.3.3. Hydraulic conductivity and volume fraction of organic matter

Introduction

As pointed out in 4.2.4, $\log_{10} k$ is used in the analyses instead of k. Because pore size is reduced by compaction of peat, a relationship was likely. Hanrahan (1954) indeed found a reduction of the hydraulic conductivity of a "partly humified" peat sample from $3.5*10^{-1}$ to $7*10^{-6}$ m d^{-1} when ϕ_0 increased from 0.08 to 0.18 under load. The relationship was confirmed by Hanrahan (1964) for Irish Midland bog peat. Baden and Eggelsmann (1963a) showed a strong dependence of k in *Sphagnum* peat on ϕ_0 for $\phi_0 > 0.035$, but little dependence below this value. Päivänen (1973) derived statistically significant linear relationships between log k and dry bulk density for both *Sphagnum* and *Carex* peats.

Because ϕ_0 and k are quantities with a continuous probability distribution, the statistical analyses of their possible relationship will be made in the form of regression by the method of least squares. The F-test will be used to test the mere presence of a relationship. Because the F-test is sensitive to non-normality of the data (Sachs, 1982), some care should be taken in judging significance. An estimate of the 95% confidence interval of the model parameters will be derived as described by Draper and Smith (1981).

Because the process of reduction of pore size by compaction includes compaction at margins and the number of data points is rather limited, the data points of margin and expanse sites have been used in one statistical analysis per bog. To allow margin and expanse points to be distinguished in the plots, they are shown with different markers in the diagrams.

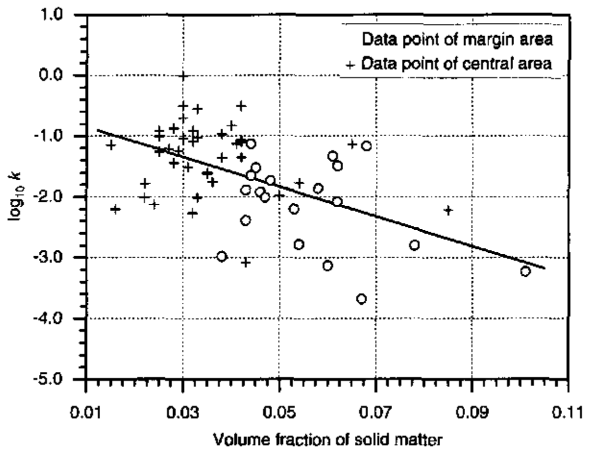

Fig. 4.8. $\log_{10} k$ versus volume fraction of organic matter ϕ_o with fitted straight line for *Raheenmore Bog.*

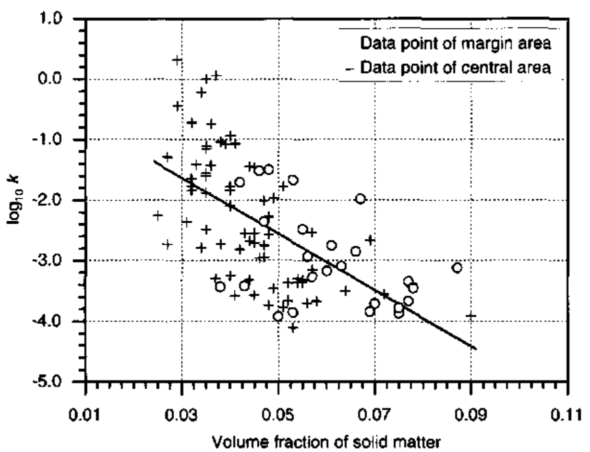

Fig. 4.9. $\log_{10} k$ versus volume fraction of organic matter ϕ_o with fitted straight line for *Clara Bog West.*

Results

Fig. 4.8 shows the points and a fitted straight line for Raheenmore, Fig. 4.9 for Clara Bog. In both diagrams, the positions of the data points of the margin zone are more concentrated towards the right than those of the central area, illustrating that the largest values of ϕ_o tend to occur in the margin zones. The two groups of points overlap in both diagrams. There is no indication of a change in the trend from one group to the other. It justifies their usage in one analysis per bog.

Non-linear models gave no substantial improvement of the fit over linear ones. Omitting the smallest values of ϕ_o (<0.030) gave slightly higher correlations. This supports the conclusions of Baden and Eggelsmann (1963a), quoted in the introduction. An analysis of variance of the fitted models is given in Table 4.8.

Table 4.8. Analysis of variance of log10 k versus volume fraction of organic matter for Clara and Raheenmore Bog.

Model		$\log_{10}\frac{k}{\mathrm{m\,d^{-1}}} = a + b\phi_o$						
Bog		Sum of squares	d.f.	Mean squares	*r*	*F*	*a*	*b*
Raheenmore	Total	32.34	57				-0.61	-24.5
n=58	Model	9.07	1	9.07	0.529	20.9	95% confidence intervals	
	Residual	23.28	56	0.416	α<0.001		-1.07<*a*<-0.15	-34.9<*b*<-14.1
Clara Bog West	Total	105.62	94				0.25	-46.3
n=95	Model	40.84	1	40.84	0.622	58.6	95% confidence intervals	
	Residual	64.78	93	0.697	α<0.001		-0.85<*a*<0.36	-58.3<*b*<-34.3

Discussion and conclusions

The relationships are significant for both Raheenmore and Clara Bog. In both cases, the regression coefficient b and the intercept a show a considerable uncertainty. The 95% confidence bandwidth of the expectation value of the estimated $\log_{10} k$ varies in the range of 0.35 - 1.1, depending on the value of ϕ_o. The 95% estimation bandwidth (Hahn, 1989) of $\log_{10} k$ is around 3.3 for Clara West and 2.6 for Raheenmore Bog. If the estimated reproducibility of k-values from the piezometer method in peat in 4.2.4 is approximately correct, most of the uncertainty in the model must have come from uncertainties in the value of ϕ_o and in the relationship itself. The measuring method of ϕ_o has probably contributed little to the confidence bandwidths as it is basically a gravimetric method. Unknowns are the spatial variability of ϕ_o over distances of up to about 3 m (although it is probably too small to contribute substantially to uncertainty in the relationship) and possible other effects such as an interaction with H, that may affect the relationships of log k and ϕ_o.

The difference between the relationships for Clara West and Raheenmore Bog is statistically significant because the 95% confidence intervals of the estimated regression coefficients hardly overlap. A possible explanation of the difference could be the larger average degree of humification on Clara West, if H interacts in the relationship of k and ϕ_o. The large variability of H might then provide a (partial) explanation of the scatter of the data points in Fig. 4.8 and Fig. 4.9. To prove (or disprove) this would require an extensive and precise sampling scheme. The available data are insufficient for such an analysis because of the distance of some metres between the sample points for ϕ_o and the sites for k and the number of available data (a split into 9 humification classes would be needed).

Although the statistical analysis shows a highly significant relationship between k and ϕ_0, their mutual predictive power is small, at least for individal values. This does not necessarily mean that transmissivities and vertical resistances that result from a number of values in a profile, cannot be estimated with acceptable reliability. This matter will be discussed in Chapter 5.

4.3.4. Humification and hydraulic conductivity

Introduction

Baden and Eggelsmann (1963a), Boelter (1965, 1969), Päivänen (1973), Rycroft *et al.* (1975), Ivanov (1981) and Korpijaakko (1988) found a negative correlation of H and k, i.e. a decrease of k with increasing H. Baden and Eggelsmann indicated a decrease of k by 2-3 orders of magnitude with H increasing from <3 to >8 for all kinds of peat except wood peat. Päivänen found a decrease of k by 2 orders of magnitude with H increasing from 1 to 10. His relationship was statistically significant (α<<0.001) for *Sphagnum* peat, but weak for *Carex* peat. Ivanov indicated a decrease in k by about four orders of magnitude for bog peat from slightly to strongly humified peat and slightly smaller effects for fen peat for a similar range in H.

Where at the measuring depth of k no sample for H was taken, the value of H was estimated by interpolating between the H-values at the nearest depth above and below it.

Results

In Fig. 4.10 k has been plotted against H in the same way as ϕ_0 in Fig. 4.7.

The diagrams show no relationships for the margin of Clara Bog West and the central area of Raheenmore Bog. The relationships for the central area of Clara Bog West and the margin of Raheenmore Bog are weak. The latter two indicate a decrease of k by about two orders of magnitude with an increase of H from 2 to 8, but with a wide margin of uncertainty. This and the results presented in section 4.3.3 indicate that compaction has a stronger effect on hydraulic conductivity than humification.

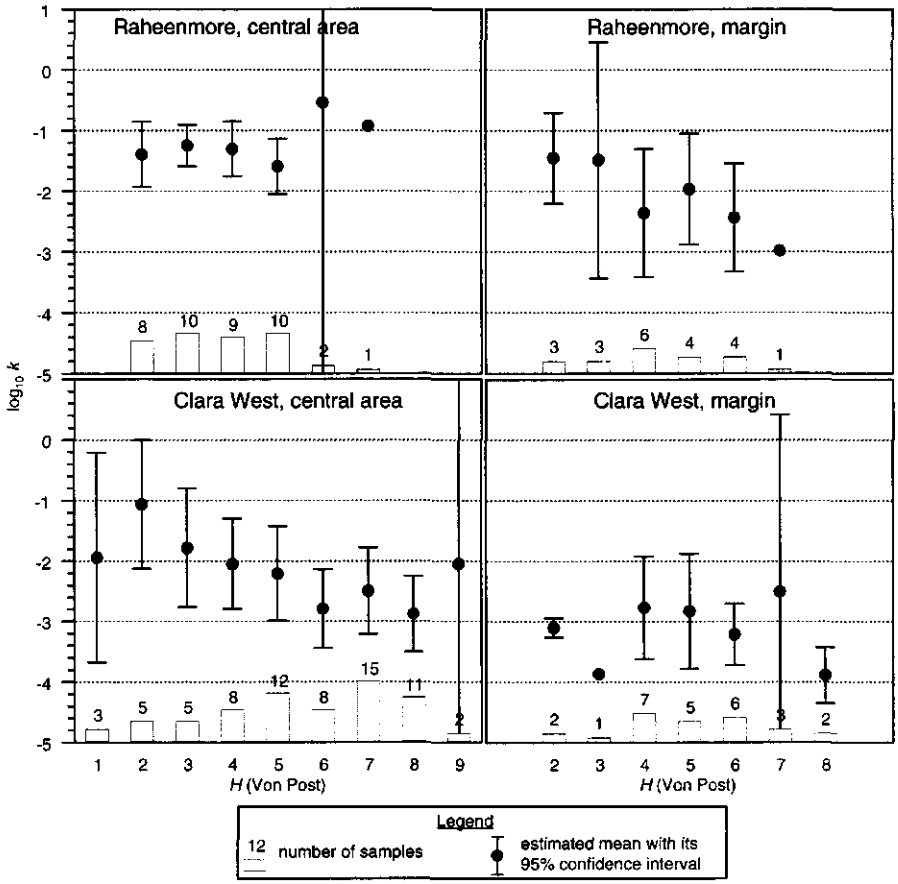

Fig. 4.10. Means and 95% confidence intervals of hydraulic conductivity k, expressed as $\log_{10} k$ (k in md^{-1}) per humification class H with numbers of measurements per class.

Table 4.9 shows Spearman rank correlation coefficients, corrected for ties and levels of significance, calculated with Eq. (4.1). It confirms the picture of Fig. 4.10.

Table 4.9. Rank correlation coefficients r_S of degree of humification H and hydraulic conductivity k with number of data pairs n, estimated Student variate $\hat{t}$ and level of significance α, based on a two-tailed test.

Bog	Position	n	r_S	$\hat{t}_{n-2}$	α
Clara Bog West	Margin	26	-0.161	0.80	0.43
	Central area	69	-0.384	3.40	0.001
Raheenmore Bog	Margin	21	-0.552	2.89	0.01
	Central area	40	0.004	0.02	0.98

The relationship is fairly significant for the central area of Clara West and rather doubtful for the margin of Raheenmore Bog because of the small number of data. The central area of Raheenmore Bog and the margin of Clara West show no significance at all. Hence the strong relationship of H and k as suggested by Baden and Eggelsmann, Päivänen and Ivanov is dismissed for both Clara and Raheenmore Bog.

The weak relationship of H and k is in disagreement with most other results presented in peat literature. It is indeed hard to believe that humification with its breakdown of fibres into smaller particles and even gelatinous peat has as little effect on hydraulic conductivity as suggested by Fig. 4.10 and Table 4.9. Because all samples have been used in the analysis, regardless of their ϕ_o, a possible relationship may have been obscured by the relationship of ϕ_o and k, found in 4.3.3. This and the weak curvilinear relationship of ϕ_o and H found in 4.3.2 could possibly have had such an effect. An indication as to whether a relationship of H and ϕ_o could have interfered with the test can be obtained by dividing the measuring results into classes of ϕ_o and repeating the test for each class. Because the margin zones and central areas of both bogs differ mainly by their values of ϕ_o and to obtain classes with a reasonable amount of measurements, no distinction was made between centre and margin. Because on Raheenmore Bore a larger proportion of samples with a low value of ϕ_o was taken than on Clara Bog West, the class boundaries for Raheenmore were chosen 0.005 lower than those for Clara. The correlation coefficient r_S was not corrected for ties.

Table 4.10. Spearman's rank correlation coefficient r_S of degree of humification H and hydraulic conductivity k for 4 classes of the volume fraction of organic matter ϕ_o, mean and standard error of the mean of $\log_{10} k$, the range of H. n in the third column is the number of samples per class.

Bog	Class of ϕ_o	n	r_S (H,k)	Mean of $\log_{10} k$	Standard error of mean of $\log_{10} k$	Range of H
Raheenmore Bog	all ϕ_o	61	-0.21	-1.59	0.10	$2 \leq H \leq 8$
	$\phi_o \leq 0.030$	16	0.39	-1.22	0.14	$2 \leq H \leq 6$
	$0.030 < \phi_o \leq 0.040$	14	-0.34	-1.46	0.17	$3 \leq H \leq 8$
	$0.040 < \phi_o \leq 0.050$	16	-0.16	-1.59	0.15	$2\text{-}3 \leq H \leq 7$
	$\phi_o > 0.050$	15	-0.48	-2.10	0.22	$2 \leq H \leq 6\text{-}7$
Clara Bog West	all ϕ_o	95	-0.29	-2.49	0.11	$1 \leq H \leq 9$
	$\phi_o \leq 0.035$	16	0.23	-1.37	0.23	$1 \leq H \leq 9$
	$0.035 < \phi_o \leq 0.045$	30	-0.37	-2.12	0.18	$1 \leq H \leq 9$
	$0.045 < \phi_o \leq 0.055$	24	-0.58	-2.86	0.17	$3 \leq H \leq 8\text{-}9$
	$\phi_o > 0.055$	25	-0.02	-3.29	0.09	$2 \leq H \leq 8\text{-}9$

Table 4.10 shows the results with mean and standard error of the mean of $\log_{10} k$, the range of H and the number of samples within each class. A positive correlation is found

of H and k for the peats with the smallest volume fraction of organic matter ϕ_o and a negative one for the others. However, the negative values for the other classes are not consistent. The value for ϕ_o>0.055 on Clara Bog is even close to 0. Therefore local factors -possibly botanical composition- may also have had effects on ϕ_o and/or k. The physical background of the positive correlation values for the lower values of ϕ_o is not clear. The relationship of ϕ_o and k shows up clearly in the columns referring to $\log_{10} k$.

Discussion and conclusions

Contrary to the relationship between H and ϕ_o, where measurements could be made in the same core samples, the hydraulic conductivity measurements were made at a distance of some metres from the sites where corresponding values of H were measured. This and the poor correlation of H at a horizontal scale of a few metres could mean that a negative result of a test on the existence of a relationship is no evidence of the non-existence of a relationship. However, the likely small variation of k over small horizontal distances as found in 4.2.4 contradicts this. The difference in spatial patterning between H and k also makes a statistically strong relationship unlikely.

Although some evidence was found for an interaction with ϕ_o of the relationship of H and k, it is not convincing enough to attribute differences in H and k between Raheenmore and Clara Bog to an interaction with ϕ_o, which quantity also differs between both bogs.

4.3.5. Discussion and conclusions on hydrophysical relationships

As found in section 4.2, there are no indications of a direct relationship of the mean strata of the peat with hydrophysical properties, even though in some literature differences between *Sphagnum* and *Carex* peat was mentioned. Decay and compression may have caused a gradual reduction of the differences to such an extent that they were no longer detectable by the methods applied in the work described here.

The relationships of H with both ϕ_o and k are weak. This conclusion seems to be in disagreement with conclusions in literature on peat properties. However, the differences in horizontal patterning between H on one hand and ϕ_o and k on the other as they were found in both bogs, make a strong relationship unlikely. The curved relationship of H and ϕ_o with a positive correlation for $H \leq 5$ and a negative one for $H \geq 5$ is a remarkable result. In the literature on the subject that was checked, only positive correlations for all H were mentioned. The most likely explanation of the phenomenon, but not for the discrepancy with conclusions in literature, is a difference in water binding between slightly and highly humified peat. Whether the level of $H \approx 4$-5 at which the process of decay seems to slow down, has a causal relationship with this or is a mere coincidence, remains unclear.

For values of ϕ_b, smaller than 0.30-0.35, H and k were positively correlated, albeit with a poor level of significance. For larger values the correlation was negative, but with varying values. This may indicate an interaction of ϕ_b and H in their relationship with k.

The relationship of k and ϕ_b is statistically significant. Its physical background is the decrease of pore size -rather than pore space-, resulting from peat compaction. The relationship is (near) linear for log k. However, as the prediction bandwidth is about two orders of magnitude, the predictive value is limited. Probably most of the uncertainty lies in the relationship itself rather than in the measuring methods for k and/or ϕ_b.

For ϕ_b<0.3, the relationship with k is weaker than for larger values of ϕ_b. Because over a similar range of ϕ_b weakly positive correlations in the relationship of H and k occurred, it must be concluded that for small values of ϕ_b -and thus in relatively loose peat material- hydrophysical relationships are generally weaker than in denser peat.

5. FLOW IN THE CATOTELM

5.1. Introduction

In this chapter the flow process in the catotelm is discussed and worked out for Clara and Raheenmore Bog. This will eventually result in estimates of the lateral and vertical outflow of water from the catotelm. Together with the description of lateral outflow, attention will be given to the applicability of Ingram's Groundwater Mound Theory (further referred to as GMT) on both bogs.

First a conceptual model for catotelm flow is developed where the concepts of transmissivity T_c and vertical resistance C_c of the catotelm are defined, followed by a section on estimating techniques for T_c and C_c. Lateral and vertical outflow ("exfiltration") from the catotelm are quantified in the last two sections.

5.2. Concepts

The flow in a raised bog can be divided into different components. Together, they form the bog's water balance. The bog system is fed by the precipitation excess P_e, which is defined as the difference of the precipitation rate P and the evapotranspiration rate ET [LT^{-1}]:

$$P_e = P - ET \tag{5.1}$$

In the bog body, P_e is divided into different flow components. The process is schematised in Fig. 5.1.

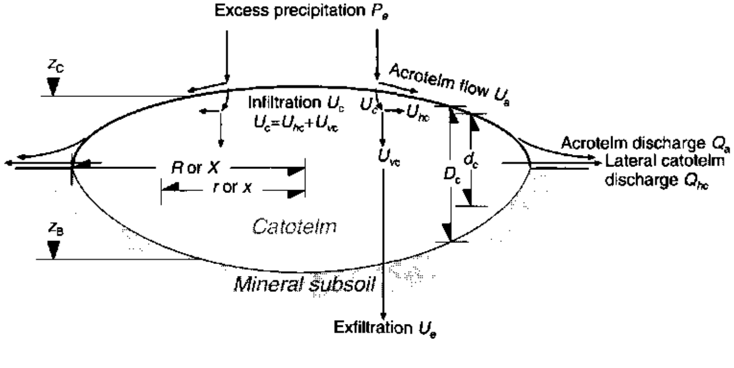

Fig. 5.1. Terms and symbols denoting flow in the acrotelm and catotelm of a raised bog some symbols used for distance and position. Because of its small depth, the catotelm is not shown as a layer but as a thicker line.

At the transition from acrotelm to catotelm, P_e splits up into the acrotelm flow rate U_a and infiltration rate into the catotelm U_c. U_c is divided into a horizontal and a vertical component, U_{hc} and U_{vc}. At the base of the catotelm, U_{vc} is identical with exfiltration U_e. All U are defined as flow rates with dimension [LT^{-1}]. Integrating any U over a bog area with size A turns it into a discharge flux Q with dimension [L^3T^{-1}]:

$$Q = \oint_A U dx dy \tag{5.2}$$

Specific discharge v with dimension [LT^{-1}] is defined as the *average* flux density of a flow component over an *area*:

$$v = \frac{Q}{A} \tag{5.3}$$

The suffixes of the flow components U as given above and in Fig. 5.1 are also used for the corresponding Q and v. The water balance of the catotelm over a bog area may now be written in terms of v as:

$$v_c + v_e + v_{hc} = \frac{dS_w}{dt} \tag{5.4}$$

where

S_w = specific storage [L]

v_e is U_e, averaged over a bog area (Eqs. 5.2 and 5.3 combined). U_e may be estimated from the difference in piezometric level between two vertical positions z_1 (deepest) and z_2 in the catotelm and the local vertical resistance C_c (dimension [T]) between z_1 and z_2:

$$U_e \approx \frac{h(z_1) - h(z_2)}{C_c} \tag{5.5}$$

where

$h(z_1)$, $h(z_2)$ = piezometric levels at vertical positions z_1 and z_2 in the catotelm [L]

Assuming the Dupuit-Forchheimer assumption holds approximately, the specific horizontal discharge v_{hc} of the catotelm between two points P_1 and P_2 on the same flow line and a distance ΔX apart, is estimated by:

$$v_{hc} \approx \frac{T_c\big(h(P_1) - h(P_2)\big)}{x\Delta X} \tag{5.6}$$

where

T_c = catotelm transmissivity between P_1 and P_2 [L^2T^{-1}]

$h(P_1)$, $h(P_2)$ = phreatic levels at points P_1 and P_2

Values of T_c and C_c can be estimated from available values of the hydraulic conductivity k, whether measured or estimated from ϕ_0.

Assuming perfect horizontal layering[1] and isotropy of any infinitesimally small volume of catotelm peat, the relationship of k with T_c, when k varies with depth, is defined as

$$T_c = \int_{z_B}^{z_C} k(z)\mathrm{d}z \qquad (5.7)$$

where

z = vertical position [L]

z_C = vertical position of the surface of the catotelm [L] (Fig. 5.1)

z_B = vertical position of the base of the catotelm [L] (Fig. 5.1)

In a similar way the relationship of k with C_c is defined as

$$C_c = \int_{z_B}^{z_C} \frac{1}{k(z)}\mathrm{d}z \qquad (5.8)$$

If k is known at n different levels z and assumed isotropic at these levels (in fact over the entire length of the filter screen), Eqs. (5.7) and (5.8) can be approximated by

$$T_c \approx \sum_{i=1}^{n} k_i \Delta z_i \qquad (5.9)$$

and

$$C_c \approx \sum_{i=1}^{n} \frac{\Delta z_i}{k_i} \qquad (5.10)$$

where

$$\Delta z_i = \frac{z_i + z_{i+1}}{2} - z_B \quad \text{for} \quad i = 1 \qquad (5.11a)$$

$$\Delta z_i = \frac{z_{i-1} + z_{i+1}}{2} \quad \text{for} \quad 1 < i < n \qquad (5.11b)$$

$$\Delta z_i = z_C - \frac{z_{i-1} + z_i}{2} \quad \text{for} \quad i = n \qquad (5.11c)$$

where i=1 at the base and i=n at the top of the catotelm.

[1] Perfect horizontal layering implies a changing k in the vertical direction only. Consequences of imperfect layering are not considered here. For a treatise on the subject and related implications for groundwater flow, one is referred to Zijl and Nawalany (1993).

The effective k_h in the horizontal and k_v in the vertical direction (dimensions [LT^{-1}]) are defined as

$$k_h = \frac{T_c}{D_c} \quad (5.12)$$

and

$$k_v = \frac{D_c}{C_c} \quad (5.13)$$

The variables to be compared in statistical tests are k_h and k_v, not C_c and T_c. The advantage over a comparison of C_c and T_c is that profile depth -which depends on the horizontal position on the bog- is not directly involved. Substituting C_c and T_c in Eqs. (5.9) and (5.10) using Eqs. (5.12) and (5.13), respectively, yields

$$k_{hm} \approx \frac{1}{D}\sum_{i=1}^{n} k_{m_i} \Delta z_i \quad \text{and} \quad k_{he} \approx \frac{1}{D}\sum_{i=1}^{n} k_{e_i} \Delta z_i \quad (5.14)$$

and

$$k_{vm} \approx \left(\frac{1}{D}\sum_{i=1}^{n} \frac{\Delta z_i}{k_{m_i}} \right)^{-1} \quad \text{and} \quad k_{ve} \approx \left(\frac{1}{D}\sum_{i=1}^{n} \frac{\Delta z_i}{k_{e_i}} \right)^{-1} \quad (5.15)$$

where

k_m = measured k [LT^{-1}]

k_e = estimated k according to the relationship of volume fraction of solid matter ϕ_o and k as worked out in 4.3.3: $k_e = f(\phi_o) = 10^{a+b\phi_o}$ m d^{-1}, where a and b are the intercept and regression coefficient in the statistical relationship of k and ϕ_o.

k_{hm} = estimate of the effective hydraulic conductivity k in the horizontal direction, based on k_m [LT^{-1}]

k_{he} = estimate of the effective k in the horizontal direction, based on k_e [LT^{-1}]

k_{vm} = estimate of the effective k in the vertical direction, based on k_m [LT^{-1}]

k_{ve} = estimate of the effective k in the vertical direction, based on k_e [LT^{-1}]

To allow testing the GMT, T_c of individual sites should preferably be known at a level of accuracy that allows estimating a relationship between T_c and position on the bog. The lateral specific discharge v_{hc} of the catotelm is preferably calculated from a model that takes trends in T_c from centre to margin into account (v_{hc}=U_{hc} if U_{hc} is spatially constant). The exfiltration rate v_e can be calculated as an average of U_e at individual spots. Thus a calculation of v_{hc} is more demanding in terms of errors in T_c than one of v_e at the scale of a bog in terms of errors in C_c.

Data on phreatic levels were available from all dip well sites. Because in both Raheenmore Bog and Clara Bog West average phreatic levels were less than 10-20 cm above or below the surface (except in a zone, 5-50 m from the margin, *cf.* Chapter 7), they could often be derived from surface levels. In the high and relatively flat part of the bogs, ground levels from the 100 x 100 m grid of the OPW surface level survey were available. Because the OPW data were average ground levels and those available from the piezometer sites represented the bottom levels of surrounding hollows, the OPW levels were adjusted downwards by 10 cm when used as an estimate of average phreatic levels.

5.3. Estimating T_c and C_c from K

5.3.1. Introduction

In section 5.2, equations for estimating k_h, k_v, T_c and C_c have been developed. A decision on whether to use k_e, k_m and/or a mixture of both had to be made as well. Conventional regression as applied in 4.3.3 to develop a relationship between k and ϕ_0 has some disadvantages. They are discussed in 5.3.2, where an alternative method is given. This will be followed by a discussion on the comparability of k_h and k_v (and thus of T_c and C_c), derived from k_e, k_m and mixtures of both. A reference method is selected. A system of conversion between other methods and the reference method is developed.

5.3.2. Estimating k from ϕ_0; method of reduced major axis

In 4.3.3 a statistical relationship of ϕ_0 and k was developed and tested. The method was based on the least squares method with a dependent variable k and an independent variable ϕ_0. When comparing measured quantities as k and ϕ_0, which are both subject to error, there are no reasonable grounds to distinguish between "dependent" and "independent". In statistical terms, both are random variables, drawn from an unknown parent distribution.

Most texts on regression deal with this problem by stating that the variable y can be estimated from x by regression of y on x and that x can be estimated from y by regression of x on y and that one is free to choose between either method. The two ways of regression produce unequal relationships; the difference increases with a decreasing correlation coefficient. This is demonstrated as follows. The regression coefficients for n pairs of data x and y are estimated by

$$b_{yx} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad \text{and} \quad b_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \qquad (5.16)$$

If both regression lines are identical, then

$$b_{yx}b_{xy} = 1 \tag{5.17}$$

The left hand member of Eq. (5.17) can be evaluated using Eq. (5.16):

$$b_{yx}b_{xy} = \frac{\left(\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})\right)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2} = r^2 \tag{5.18}$$

where

r = estimated correlation coefficient [1]

This proves that the product of b_{yx} and b_{xy} only equals 1 if $|r|=1$ and is less (but not less than 0) in all other cases. Thus the values of b_{yx} and b_{xy} are not only determined by the relationship between y and x, but also by their correlation coefficient. Hence conventional linear regression is not very suitable to estimate k from ϕ_b.

An alternative is the so-called *reduced major axis* method, described by Kermack and Haldane (1950) and quoted by Miller and Kahn (1962). It is a variant of a method that uses the major axis of the ellipse of data points as a regression line and based on minimising the sum of products of residuals $|(x-\hat{x})(y-\hat{y})|$ instead of the sum of squares of residuals $(y-\hat{y})^2$. It gives a single regression line for the relationship of x and y. Eqs. (5.19) through (5.22) are based on equations given by Miller and Kahn.

In the reduced major axis method, from now on abbreviated as RMA, the regression coefficient b (slope of the regression line of y versus x) is estimated by

$$b = \frac{|r| s_y}{r s_x} \tag{5.19}$$

where

s_y, s_x = sample standard deviation of y, resp. x

The intercept a is estimated by

$$a = \bar{y} - b\bar{x} \tag{5.20}$$

s_b, the standard error of b, is estimated by

$$s_b = b\sqrt{\frac{1-r^2}{n}} \tag{5.21}$$

and s_a, the standard error of a by

$$s_a = s_y \sqrt{\frac{1-r^2}{n}\left(1+\frac{\bar{x}^2}{s_x^2}\right)} \tag{5.22}$$

The F-test on the presence of a relationship between x and y remains applicable because in simple linear regression, the value of F is related to r by

$$F_{n-2}^{1} = \frac{(n-2)r^2}{1-r^2} \tag{5.23}$$

To demonstrate the difference between RMA and the conventional method of regression, the regression lines for Raheenmore and Clara Bog from both methods are given in Fig. 5.2.

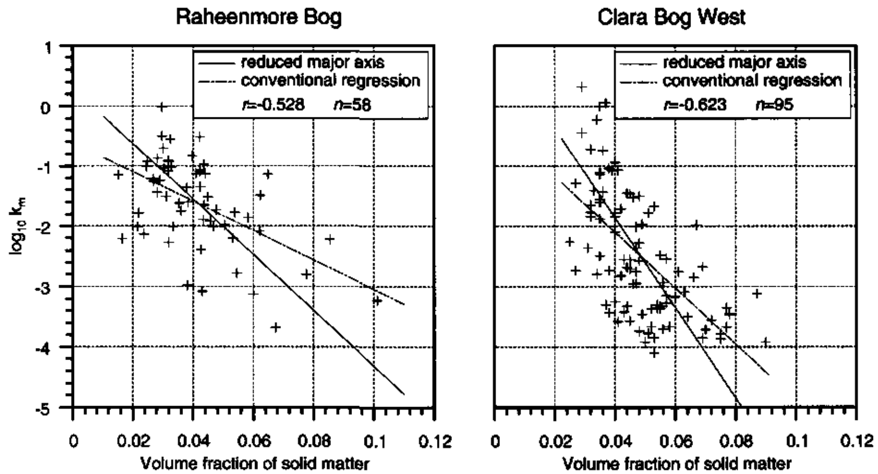

Fig. 5.2. Fitted regression lines of measured hydraulic conductivity expressed as $\log_{10} k_m$ (k_m in m d^{-1}) versus volume fraction of solid matter ϕ_0 from conventional regression (k on ϕ_0) and reduced major axis.

There is another important difference between both methods. Imagine two data sets $x_1..x_n$ and $y_1..y_n$ with $|r|<1$. Regression lines $y = a + bx$ are estimated using both regression methods. An estimated data set $\hat{y}_1..\hat{y}_n$ can be derived from the data set $x_1..x_n$. The mean of $\hat{y}_1..\hat{y}_n$ is equal to the mean of $y_1..y_n$ for either method. However, for the set $\hat{y}_1..\hat{y}_n$, derived from a relationship based on "conventional" regression, the standard deviation around the mean is

$$s_{\hat{y}} = |r| s_y \tag{5.24}$$

whilst for $\hat{y}_1..\hat{y}_n$, derived from a relationship based on the RMA method

$$s_{\hat{y}} = s_y \tag{5.25}$$

Thus the RMA method affects the statistical properties of an estimated set of data to a lesser extent than does conventional regression.

Table 5.1 gives the values and 95% confidence intervals of intercept and regression coefficients of $\log_{10} k_m$ versus ϕ_b for both methods.

Table 5.1. Parameters of the fitted lines in Fig. 5.2 and their 95% confidence intervals.

Bog	Method	*a*	95% confidence interval of *a*	*b*	95% confidence interval of *b*
Raheenmore Bog	Conventional	-0.61	$-1.07<a<-0.15$	-24.5	$-34.9<b<-14.1$
	Reduced major axis	0.29	$-0.17<a<0.75$	-46.2	$-56.6<b<-35.9$
Clara Bog	Conventional	-0.25	$-0.85<a<0.36$	-46.3	$-58.3<b<-34.4$
	Reduced major axis	1.13	$0.53<a<1.73$	-74.6	$-86.5<b<-62.7$

Table 5.1 shows that the derived regression parameters differ significantly. Three out of four confidence intervals do not even overlap and the overlap in the fourth one (*a* of Raheenmore Bog) is negligibly small.

5.3.3. Frequency distributions of measured and estimated *k*

Before methods to estimate k_h and k_v are selected, the frequency distributions of k_m and k_e are given attention. k_e was derived from ϕ_b at sites and depths were k_m was measured. The RMA method as shown in Fig. 5.2 and Table 5.1 was applied. Fig. 5.3 shows the frequency diagrams of both k_m and k_e.

A comparison of the distributions in Fig. 5.3 with the normal distribution using the χ^2 goodness of fit test (*cf.* e.g. Sachs, 1982) showed that with a level of significance $\alpha \leq 0.05$, the hypothesis of normality should be rejected for all sets. The Kolmogorov-Smirnov test (Sachs, 1982) yielded larger values of α and thus a less significant result: 0.45 and 0.11 respectively for k_m and k_e of Raheenmore and 0.15 and 0.38 for k_m and k_e of Clara Bog West. These results may be regarded as an indication that the frequency distributions of Fig. 5.3 have not been drawn from a normal distribution.

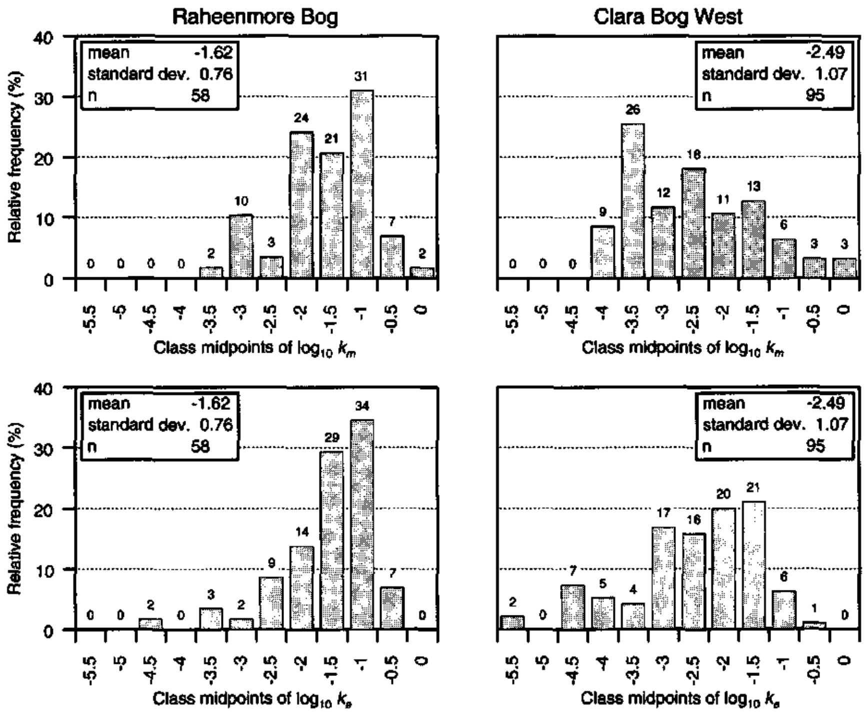

Fig. 5.3. Frequency diagrams of $\log_{10} k_m$ (upper row) and $\log_{10} k_e$ (lower row) for Raheenmore Bog (left) and Clara Bog (right).

The Kolmogorov-Smirnov test can also be used to test whether the distributions of k_m and k_e have equal parent distributions. For Clara Bog the test gave $a<0.02$, which can be regarded as acceptable evidence of different parent distributions of k_m and k_e. For Raheenmore Bog $a \approx 0.29$ was found, which indicates that the parent distributions of k_m and k_e may not differ strongly.

5.3.4. Comparing k_h and k_v, obtained from measured and/or estimated k

Introduction

In addition to Eqs. (5.14) and (5.15), values of k_h and k_v can also be derived from a hybrid set consisting of k_m and k_e. This may be useful in peat profiles where both k and ϕ_b have been measured, because in such profiles the number of values of ϕ_b is 2.5-3 times as large as the number of values of k_m as shown in Table 5.2. The table gives numbers for the upper 6 m of the profiles and for entire profiles. Analyses of the upper 6 m were added, because some relationships for full profiles showed poor levels of statistical significance.

Table 5.2. Average number of values of measured (k_m) and estimated hydraulic conductivity (k_e) of data per profile for Raheenmore Bog and Clara Bog.

	Raheenmore Bog			Clara Bog		
	No. of profiles	No. of k_m per profile	No. of k_e per profile	No. of profiles	No. of k_m per profile	No. of k_e per profile
Entire profile	10	6.0	17.8	19	5.0	13.8
Upper 6 m	10	4.9	11.5	19	3.8	10.2

Therefore, using Eqs. (5.14) and (5.15), one can derive T_c and C_c in different ways:

- Straightforward from k_m
- From available k_m and added k_e at depths where no k_m is available
- Solely from k_e in the case of profiles in which only data of ϕ_b are available.

In the estimating process, two main effects are likely to occur:

- Estimated T_c and C_c become more reliable when calculated from a larger number of k, whether k_e or k_m
- Estimated T_c and C_c become less reliable with an increasing share of k_e at the expense of the share of k_m in the result.

The effects cannot be separated, since in no profile k was measured at depth intervals as small as 0.5 m (as was ϕ_b). Consequently, it remains unclear whether the reliability of estimated T_c and/or C_c in a given profile benefits from adding k_e to the available set of k_m for depths where k_m was not measured and ϕ_b was. Another uncertainty is for which numbers and depths of k_e and k_m an estimate of T_c and/or C_c from (many) k_e is better or worse than one from (few) k_m.

Only indirect methods can be applied. They cannot give an answer to the above questions, but may give an indication of the effects of replacing and/or mixing k_m with k_e. Such indications may be obtained in the following ways:

- The effect on k_h and k_v (or on T_c and C_c) of an increased number of data per profile can be estimated by comparing profiles in which k_m is replaced by k_e, (without adding any additional k_e) with the same profiles in which all available k_e are used;
- Comparing k_h and k_v of profiles where k_m has been only been replaced by k_e with the k_h and k_v derived from k_m, may give some indication as to the error introduced by estimating T_c and C_c from k_e;
- The comparison mentioned in the previous point may also give an indication as to whether the rather poor predictive power of the statistical relationship of k_m and ϕ_b improves when k_h and k_v are estimated from 4 to 7 such values per profile.

Therefore comparisons are made for k_h and k_v, derived by the following methods (*cf.* Fig. 5.4):

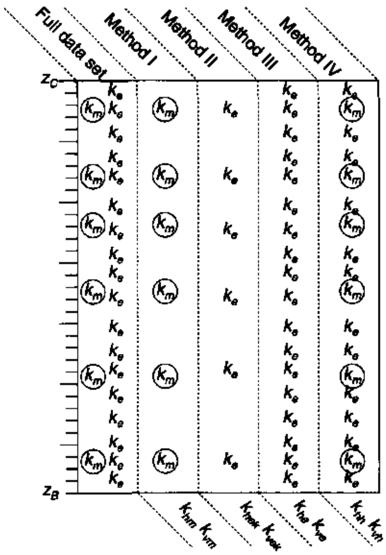

Fig. 5.4. Estimating methods and corresponding symbols of results for the effective horizontal (k_h) and vertical hydraulic conductivity (k_v), using measured (k_m, encircled) and estimated hydraulic conductivity (k_e).

I. from available k_m only; the symbol k_{hm} denotes effective horizontal k, k_{vm} effective vertical k.

II. from all k_m replaced by k_e of the same depth without adding any k_e from other depths; symbols are k_{hek} and k_{vek} for the respective effective horizontal and vertical k.

III. solely from all k_e of the examined profile; symbols k_{he} and k_{ve}.

IV. from available k_m with as many values of k_e added as available with the exception of k_e nearest to each depth at which k_m was measured; symbols k_{hh} and k_{vh}.

Although in 4.3.3 log k had a rather linear relationship with ϕ_b, this does not necessarily mean that in estimating k_h and k_v, a linear model in log k yields better results than one in k. The ways of calculating k_h and k_v, based on a weighted arithmetic and harmonic mean (respectively) of available k per profile, may lead to another optimal relationship. Therefore linear relationships in k instead of log k have been included in the comparison. The first analyses of k_v are done for full profile depths and for the upper 6 m, because some relationship of k_v of full profiles did not always turn out to be usable.

Comparing methods by correlation and standard deviation

In the comparison of methods, both the correlation matrix and the sample standard deviations of the resulting data sets are given. The latter are shown because in the reduced major axis method the ratio of the standard deviations of paired data sets is the estimate of the slope of their regression line. Table 5.3 and Table 5.4 show these values for the data sets of k_h, resulting from the methods I-IV. Table 5.3 shows the results for $\log_{10} k$, Table 5.4 for k.

Table 5.3. Standard deviations and correlation coefficients of data sets of $\log_{10} k_h$ and $\log_{10} k_v$ (k in m d^{-1}) as obtained for Raheenmore and Clara Bog from four estimating methods.

	Standard deviations (-)				Correlation coefficients					
Method	I	II	III	IV	I	I	I	II	II	III
versus method					II	III	IV	III	IV	IV
					Raheenmore Bog (n=10)					
horizontal k	0.566	0.580	0.565	0.459	0.85	0.84	0.95	0.97	0.86	0.91
vertical k (full profiles)	0.708	0.868	0.764	0.637	0.50	0.28	0.39	0.58	0.62	0.95
vertical k (upper 6 m)	0.745	0.900	0.973	1.053	0.63	0.64	0.78	0.98	0.88	0.90
					Clara Bog (n=19)					
horizontal k	0.855	0.808	0.739	0.738	0.75	0.75	0.91	0.96	0.92	0.94
vertical k (full profiles)	0.708	0.868	0.764	0.637	0.41	0.59	0.34	0.83	0.95	0.90
vertical k (upper 6 m)	0.598	1.070	1.286	0.981	0.68	0.60	0.52	0.89	0.95	0.94

Table 5.4. Standard deviations and correlation coefficients of data sets of k_h and k_v as obtained for Raheenmore and Clara Bog from four estimating methods.

	Standard deviations (m d^{-1})				Correlation coefficients					
Method	I	II	III	IV	I	I	I	II	II	III
Versus method					II	III	IV	III	IV	IV
					Raheenmore Bog (n=10)					
horizontal k	0.0718	0.0307	0.0230	0.0277	0.81	0.76	0.94	0.97	0.92	0.90
vertical k (full profiles)	0.0236	0.0238	0.0048	0.0042	0.39	0.32	0.65	0.15	0.28	0.90
vertical k (upper 6 m)	0.0226	0.0328	0.0236	0.1505	0.66	0.63	0.79	0.92	0.22	0.33
					Clara Bog (n=19)					
horizontal k	0.1379	0.0152	0.0265	0.0691	0.73	0.84	0.99	0.89	0.78	0.90
vertical k (full profiles)	0.0024	0.0036	0.0022	0.0815	0.63	0.44	0.56	0.75	0.92	0.69
vertical k (upper 6 m)	0.0078	0.0127	0.0114	0.0081	0.86	0.29	0.23	0.48	0.42	0.98

The logarithmic models show more consistent and on average slightly higher correlations than the linear ones. There also is more consistency in the standard deviations of the data sets that result from the logarithmic model, particularly when k_e replace or are added to k_m. Hence the logarithmic models seem to be a safer basis for further calculations.

The following conclusions, based on the logarithmic model, may be drawn from Table 5.3 and Table 5.4:

- For the resulting k_h, the correlations between data sets based on measured and estimated k are moderate to high. There is an improvement over the correlation of k and ϕ_0. The difference for Raheenmore Bog (0.85 vs. 0.53) is considerably larger than for Clara Bog (0.75 vs. 0.62). This may be related to the better resemblance between the frequency distributions of $\log_{10} k_m$ and $\log_{10} k_e$ of Raheenmore Bog than between those of Clara Bog.

- For the resulting k_v, the correlations between data sets are lower than for k_h and there is little improvement over the correlation of k and ϕ_b. The correlation for the upper 6 m is generally better than for entire profiles. This may be related to the few values of k_m in the lower parts of the profiles, the strong and sudden increase of ϕ_b in the lower parts of some profiles or both. Consequently, using the upper 6 m in estimating exfiltration whenever possible, seems to be a more promising alternative than using entire profiles. However, it will be shown later in this chapter that anisotropy in the upper part of peat profiles may cause a considerable overestimation of exfiltration rates when they are based on k_v (or C_c) of the upper half of a profile.
- k_h shows a slight decrease in the standard deviation, related to the increased number of data values per profile (methods III and IV versus I and II). As for k_v, the picture is inconsistent: Raheenmore Bog shows a small and Clara Bog a large increase, particularly for method III. This suggests that the increase is related to the usage of k_e rather than to the increased number of values. This difference between the bogs may be related to the better resemblance between the frequency distributions of k_e and k_m of Raheenmore Bog.
- Method IV has a better correlation with method III than method I. Method I and IV are well correlated for horizontal k, but moderately to poor for vertical k. The same conclusion can be drawn for the methods I and III. The larger numbers of k_e than k_m used in Method IV are the likely cause of the intermediate position of Method IV between I and III.

The above discussion on estimating methods for k_h and k_v leads to a continuation with full regression analyses along the following lines:

- Method II is not used, because no good reason was found not to use all available k_e.
- Method III is not suitable as a reference method because it uses no k_m.
- Of the methods I and IV, IV is the most practical choice for a reference method because of its intermediate position between I and III. It facilitates a reliable conversion of results of the other two methods. It is also based on a larger number of individual values of k.
- In view of the previous points, the analyses to be made should be IV versus I and IV versus III. They will also provide conversion equations in case method IV is selected as the reference method.

Method IV (hybrid method) versus method I (measured k only)

Fig. 5.5 shows plotted values of k_h and k_v from method IV versus those from methods I and III for both bogs. Comparing data sets of k_v of full profiles from method I and method IV makes little sense in view of the low correlation levels. Therefore the analysis has been omitted.

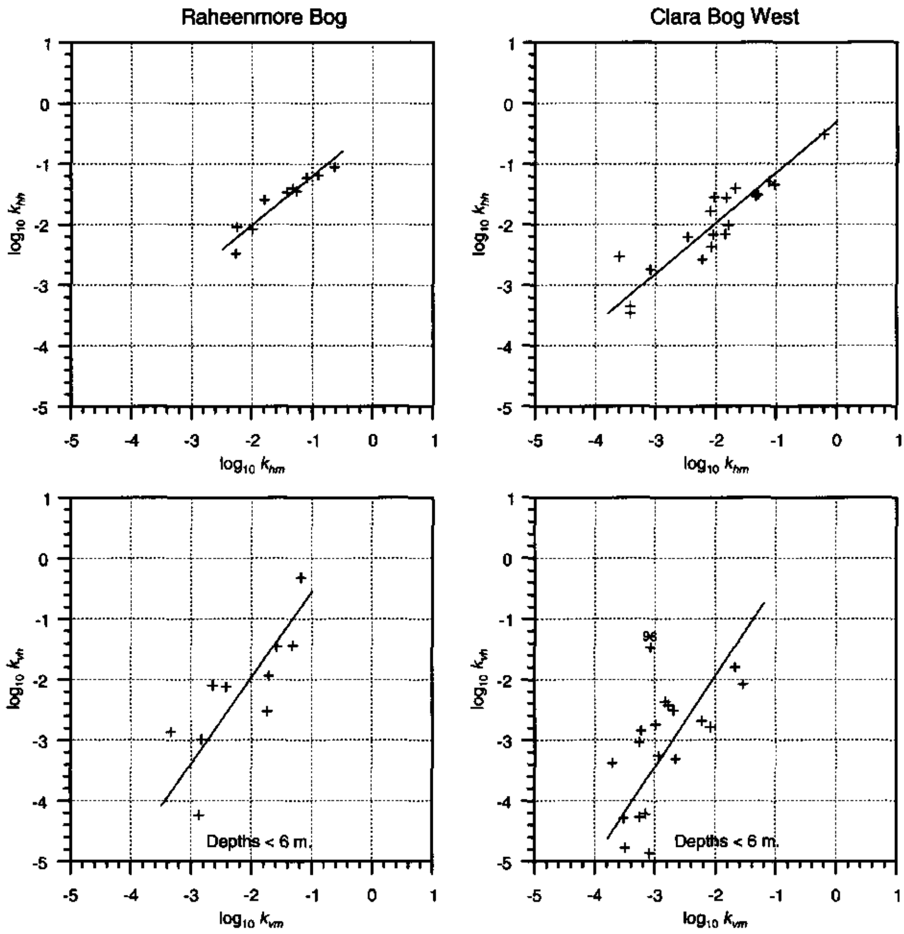

Fig. 5.5. Relationship of effective horizontal hydraulic conductivity from method IV (k_{hh}) and from method I (k_{hm}) in the upper two diagrams and of effective vertical hydraulic conductivity from method IV (k_{vh}) and I (k_{vm}) in the lower two diagrams for Raheenmore Bog (left) and Clara Bog (right). The fitted line for Clara Bog is based on the data without the outlier 96 (see text).

Table 5.5 gives the results of the significance test and fitted parameters of the models.

Table 5.5. Results of significance tests for the diagrams of Fig. 5.5 with model constants and their 95% confidence bounds estimated by the MRA method.

Models	$\log_{10}\frac{k_{hh}}{\mathrm{m\,d^{-1}}}=a+b\log_{10}\frac{k_{hm}}{\mathrm{m\,d^{-1}}}$ and $\log_{10}\frac{k_{vh}}{\mathrm{m\,d^{-1}}}=a+b\log_{10}\frac{k_{vm}}{\mathrm{m\,d^{-1}}}$									
Bog	n	r	F	α	95% lower	a estim.	95% upper	95% lower	b estim.	95% upper
Raheenmore k_{hm} versus k_{hh}	10	0.947	69.7	<0.001	-0.68	-0.39	-0.09	0.63	0.81	0.99
Raheenmore k_{vm} versus k_{vh}, depth<6 m	10	0.784	12.8	0.007	0.55	0.87	2.29	0.80	1.42	2.04
Clara Bog k_{hm} versus k_{hh}	19	0.912	83.7	<0.001	-0.67	-0.31	0.06	0.67	0.83	1.00
Clara Bog k_{vm} versus k_{vh}, outlier 96 removed; depth<6 m	18	0.696	15.0	0.001	-0.49	1.07	2.62	0.97	1.50	2.04

The statistical significance is acceptable for the models dealing with k_v and strong for those dealing with k_h. Initially, a rather low level of significance of the model of k_{vh} versus k_{vm} for Clara Bog was found. This was largely caused by one outlier, marked "96" in Fig. 5.5. It represents the profile of site 96, situated in a small soak system in the western part of Clara West (position shown in Fig. 3.11). The hydrological regime of a soak system differs both quantitatively and qualitatively from the other parts of a raised bog (Cross, 1989). The analysis was therefore repeated without site 96. As a result, the correlation coefficient r increased from 0.598 to 0.696 and the level of significance α reduced from 0.007 to 0.001. Hence the results for k_v in Fig. 5.5 and Table 5.5 are based on the data set without site 96.

The regression analysis shows some interesting results:

- The regression coefficients (b) for k_h are smaller and those for k_v are larger than 1 and all intercepts (a) for k_h are negative whilst those for k_v are positive;
- There hardly is a difference between the lines fitted for both bogs of k_{hh} versus k_{hm} and of k_{vh} versus k_{vm}. The relationships seem almost identical.
- In view of the confidence intervals for the model parameters a and b, the predictive value of the models for k_v is doubtful but probably acceptable if exfiltration is averaged over the bog; for k_h it is acceptable.

Results of the hybrid method (IV) and of estimated k only (method III)

Fig. 5.6 shows plotted values of k_h and k_v from both methods and for both bogs.

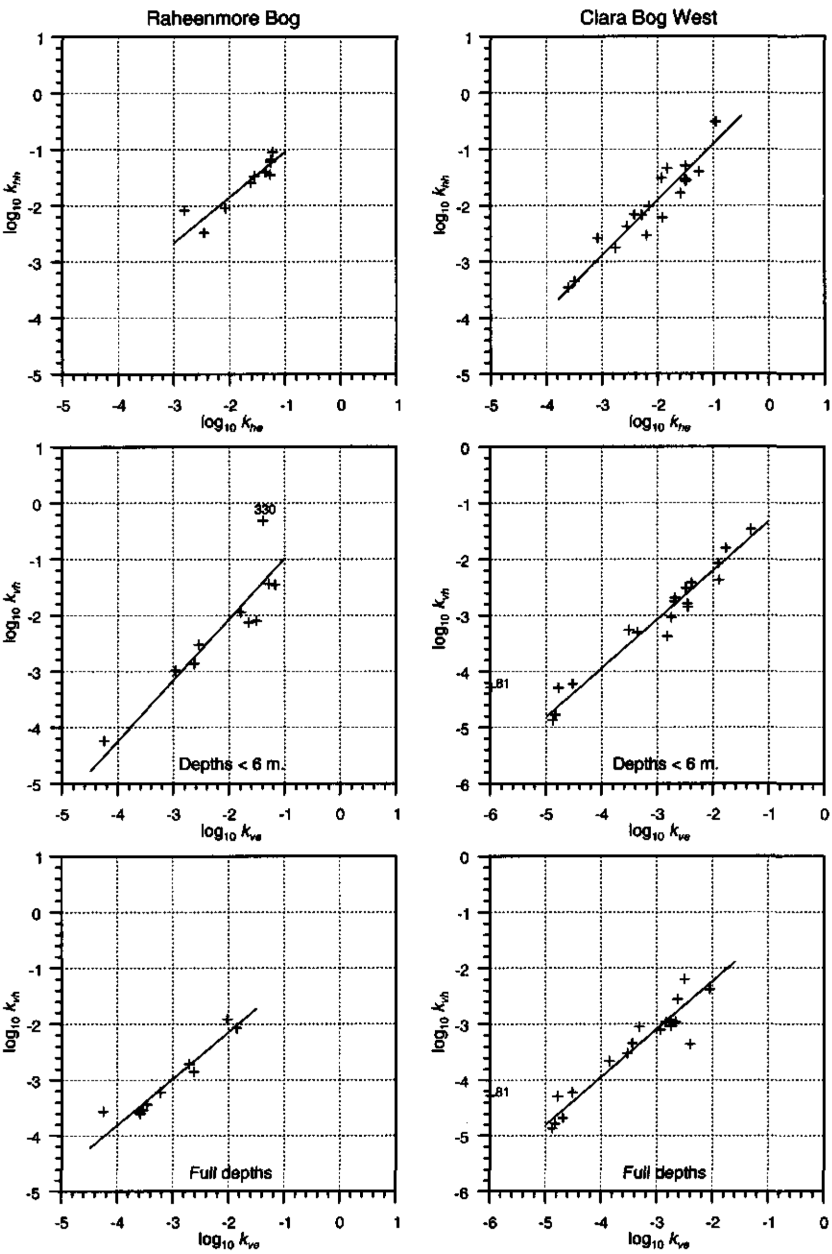

Fig. 5.6. Relationships of effective horizontal hydraulic conductivity from methods IV (k_{hh}) and III (k_{he}) in the upper two diagrams and of effective vertical hydraulic conductivity from method IV (k_{vh}) and III (k_{ve}) in the lower four. Left: Raheenmore Bog. Right: Clara Bog. Marked points (81 and 330) are outliers, discussed in the text.

Table 5.6 gives the results of the significance test and fitted parameters of the models.

Table 5.6. Results of significance tests for the diagrams of Fig. 5.6 with model constants and their 95% confidence bounds estimated by the RMA method.

Models	$\log_{10}\frac{k_{hh}}{\mathrm{m\,d^{-1}}}=a+b\log_{10}\frac{k_{he}}{\mathrm{m\,d^{-1}}}$ and $\log_{10}\frac{k_{vh}}{\mathrm{m\,d^{-1}}}=a+b\log_{10}\frac{k_{ve}}{\mathrm{m\,d^{-1}}}$									
Bog	n	r	F	α	95% lower	a estim.	95% upper	95% lower	b estim.	95% upper
Raheenmore k_{he} versus k_{hh}	10	0.909	38.1	<0.001	-0.65	-0.22	0.20	0.57	0.81	1.05
Raheenmore k_{ve} versus k_{vh}, depth<6 m	10	0.903	35.3	<0.001	-0.66	0.11	0.88	0.76	1.09	1.42
Raheenmore k_{ve} versus k_{vh}, all depths	10	0.951	75.4	<0.001	-1.35	-0.60	0.15	0.56	0.79	1.03
Clara Bog k_{he} versus k_{hh}	19	0.942	133	<0.001	-0.26	0.10	0.46	0.84	1.00	1.16
Clara Bog k_{ve} versus k_{vh}, outlier 81 removed; depth<6 m	18	0.899	71.9	<0.001	-0.76	-0.46	-0.16	0.78	0.87	0.96
Clara Bog k_{ve} versus k_{vh}, outlier 81 removed; all depths	18	0.943	129	<0.001	-1.20	-0.68	-0.17	0.66	0.81	0.96

The statistical significance is high for all analyses. An outlier in the analysis of k_v for Clara Bog is site 81. The point is marked in Fig. 5.6. The site is located in the extremely compressed peat close to the Clara-Rahan road. It was sampled over only half its depth (Fig. A.16 in Appendix A), because of the high resistance of the peat. Therefore the point was not included in the analysis.

In the analysis of k_v for Raheenmore Bog site 330 is an apparent outlier. It is positioned in the centre of the bog. There is no good physical explanation to its position in the diagram. Hence the point was not removed from the set.

The difference between the relationships for k_h of Raheenmore and Clara Bog is small, but larger than in Table 5.5, where they were almost identical. The relationships for k_v also seem strongly related. For the data sets of Clara Bog over depths less than 6 m, the confidence interval of a lies almost and the interval of b entirely within the confidence interval of the corresponding parameter of Raheenmore Bog. For full profiles, the confidence intervals for both a and b of Clara Bog lie within those for Raheenmore Bog, which means that the relationships may be considered (almost) identical.

5.3.5. Discussion and conclusions

A first conclusion is that linear regression in $\log_{10} k$ seems to be more consistent in the significance of relationships and more reliable than regression in k. Therefore, methods based on $\log_{10} k$ are used.

For the following two reasons, the hybrid method (IV) is selected as the reference method for estimating k_h and of catotelm transmissivity T_c

- Its results are better correlated with results from both measured and estimated data than the alternative, the method based on measured data (I) only;
- The relationships for k_h seem reliable enough to estimate T_c of individual profiles with sufficient accuracy for a model of lateral outflow.

This does not mean that the hybrid method is superior to the other two. There is neither evidence of this nor of the contrary.

The relationships for k_v are less reliable. For full profiles, a conversion from values based on measured k to those based on estimated or hybrid sets is not justified by the results of the correlation analysis. There is no alternative but to use the results from measured sets as they are, accepting the likely error caused by the relatively small number of data per profile. For depths up to 6 m the relationship is of moderate quality. The problem only exists for a few profiles of Clara Bog. The relationship seems usable if exfiltration is to be estimated at the scale of the bog as an average of several sites.

Therefore the hybrid method can only be used as a reference method for estimating vertical resistance for profiles less deep than 6 m and for the upper 6 m of deeper profiles. For full profiles deeper than 6 m, there is no reliable conversion from k_{vm} to k_{vh}, but there is no problem in the conversion from k_{ve} to k_{vh}.

Although the respective statistical relationships as found for the two bogs are almost identical in some cases, the equations describing the relationships will be applied as they were found for the individual bogs. They are:

<u>For Raheenmore Bog:</u>

Horizontal k: $$\log_{10}\frac{k_{hh}}{\text{m d}^{-1}} = -0.22 + 0.81\log_{10}\frac{k_{he}}{\text{m d}^{-1}} \quad (5.26)$$

Vertical k, upper 6 metres: $$\log_{10}\frac{k_{vh}}{\text{m d}^{-1}} = 0.11 + 1.09\log_{10}\frac{k_{ve}}{\text{m d}^{-1}} \quad (5.27)$$

Vertical k, full profiles: $$\log_{10}\frac{k_{vh}}{\text{m d}^{-1}} = -0.60 + 0.79\log_{10}\frac{k_{ve}}{\text{m d}^{-1}} \quad (5.28)$$

<u>For Clara Bog:</u>

Horizontal k: $$\log_{10}\frac{k_{hh}}{\text{m d}^{-1}} = -0.31 + 0.83\log_{10}\frac{k_{hm}}{\text{m d}^{-1}} \quad (5.29)$$

$$\log_{10}\frac{k_{hh}}{\text{m d}^{-1}} = 0.10 + 1.00\log_{10}\frac{k_{he}}{\text{m d}^{-1}} \quad (5.30)$$

Vertical k; upper 6 metres: $$\log_{10}\frac{k_{vh}}{\text{m d}^{-1}} = 1.07 + 1.50\log_{10}\frac{k_{vm}}{\text{m d}^{-1}} \quad (5.31)$$

$$\log_{10}\frac{k_{vh}}{\text{m d}^{-1}} = -0.46 + 0.87\log_{10}\frac{k_{ve}}{\text{m d}^{-1}} \quad (5.32)$$

Vertical k; full profiles: $$\log_{10}\frac{k_{vh}}{\text{m d}^{-1}} = -0.68 + 0.81\log_{10}\frac{k_{ve}}{\text{m d}^{-1}} \quad (5.33)$$

The following equation pairs show only minor statistical differences:

- (5.26) and (5.30)
- (5.28) and (5.33)

Eqs. (5.29) and (5.31) of Clara Bog also are nearly identical with their equivalents of Raheenmore Bog. The latter are not given in the conclusions, because they are not needed. The relevant values can be found in Table 5.5. Eqs. (5.27) and (5.32) differ clearly.

5.4. Lateral discharge from the catotelm

5.4.1. Introduction

In this section, lateral catotelm discharge Q_{hc} is estimated from catotelm transmissivity T_c calculated from the equations developed in 5.3 and from horizontal gradients of hydraulic head. Because most values of T_c were determined for sites where observation wells had been installed, direct measurements of phreatic levels were available in most cases. Where such measurements were lacking, surface levels of the OPW grid surveyed in 1991 were used as a surrogate (*cf.* 5.2), except near margins.

One remark on T_c should be made. The catotelm is a concept rather than a well-defined layer and strictly speaking its transmissivity is not well defined. However, almost anywhere on Raheenmore and Clara Bog the transition between the larger k of the acrotelm and the lower k of the catotelm is rather abrupt, often within 10 cm. Therefore usage of the concept of T_c does not seem to be inappropriate.

Considerations as to the validity of the GMT are given. Because the cross sectional shapes of Raheenmore Bog and Clara Bog West differ -Raheenmore Bog is a typical convex raised bog, whilst the western half of Clara Bog is slightly concave- the two bogs are dealt with separately.

5.4.2. Raheenmore Bog

Catotelm transmissivities and -depths

Values of T_c were calculated for 11 sites from hybrid sets of k_m and k_e. At 4 additional sites, T_c could be estimated from k_e. They were converted to "hybrid" T_c using Eq. (5.26). The site positions with T_c and peat depth are shown in Fig. 5.7.

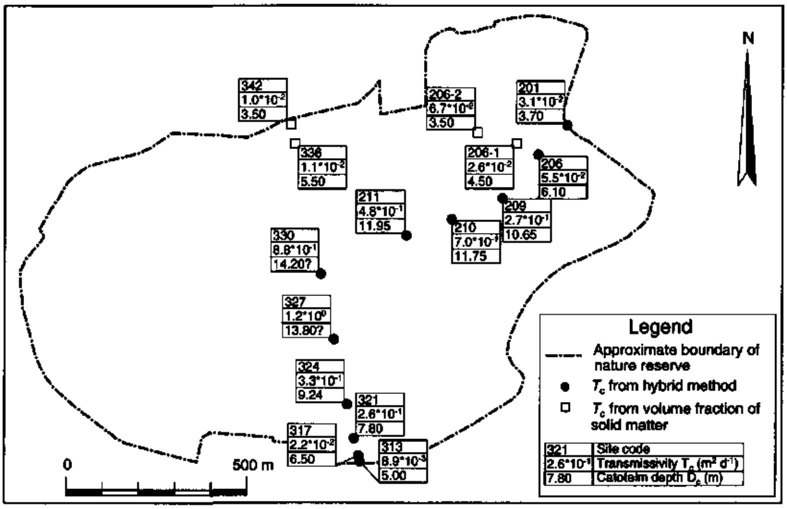

Fig. 5.7. Catotelm transmissivities T_c and catotelm depths D_c of Raheenmore Bog.

Fig. 5.7 indicates a strong decrease of T_c towards the bog margin. The difference between centre and margin is approximately two orders of magnitude. This cannot be caused by differences in peat depth. These may account for up to half an order. This and the vertical variability of k (appendix B) mean that the assumption of the GMT of a spatially constant k is rejected for Raheenmore Bog. Because Raheenmore Bog is a typical dome shaped raised bog, it is unlikely that it differs strongly from other and similarly shaped bogs in this respect. Therefore, the GMT should be expressed in terms of a spatially variable T_c rather than a spatially constant k.

Another question with regard to the GMT is whether it is possible to describe the shape of a raised bog in terms of the lateral component of catotelm flow U_{hc} (Fig. 5.1). In the GMT it is assumed to be spatially constant. For this assumption no good reason is given in any publication on the GMT, known to this author. One may, however, ask oneself how important the assumption really is. One should realise that the horizontal flux across a closed contour towards the bog margin is the integral of Eq. (5.2). In such an integration process, spatial variations on a scale that is small compared to the distance over which the integration takes place, have relatively little effect on the resulting lateral outflow or the spatial distribution of the phreatic level.

Relationships between T_c and position on the bog

To produce a model of lateral outflow in an analytical form, it is necessary to find an expression for the relationship between T_c and position on the bog. For this purpose, the position should preferably be expressed as a single quantity. In a radial flow system this is the distance to the centre or the margin. The surface level contours of Raheenmore indeed suggest an approximately elliptic radial system that slopes downwards towards the ENE.

Fig. 5.8 shows a map of surface level gradients, based on the 100x100 m surface level grid, installed by OPW. It confirms the radial pattern, except for the eastern part of the bog where the pattern is approximately parallel towards the ENE. The large gradients near the margin reflect the elevation of the bog surface above the surroundings. Their absence in some margin areas does not necessarily indicate a less steep margin, but merely the absence of a level point just outside the bog.

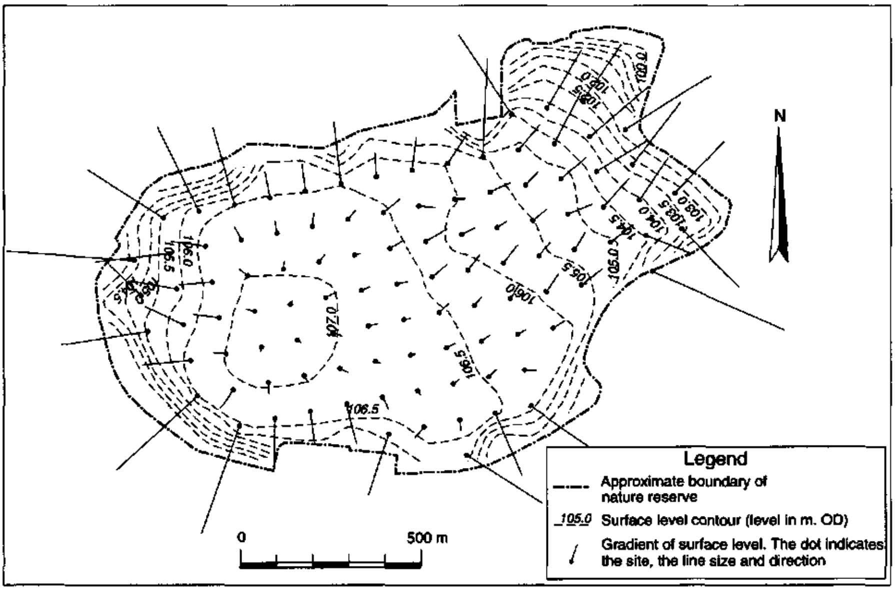

Fig. 5.8. Surface level contours and surface gradients of Raheenmore Bog.

In a radial flow system, a position may be expressed as its position on the flow line through itself from the centre to the margin. To facilitate comparison between different flow lines, it may be expressed as a dimensionless quantity by

$$r_r = \frac{r}{R} \tag{5.34}$$

where

r_r = relative distance to centre [1]

r = distance to centre [L]

R = length of the flow line between centre and margin [L]

For the points shown in Fig. 5.7, the positions of four such flow lines were estimated. Fig. 5.9 shows their positions.

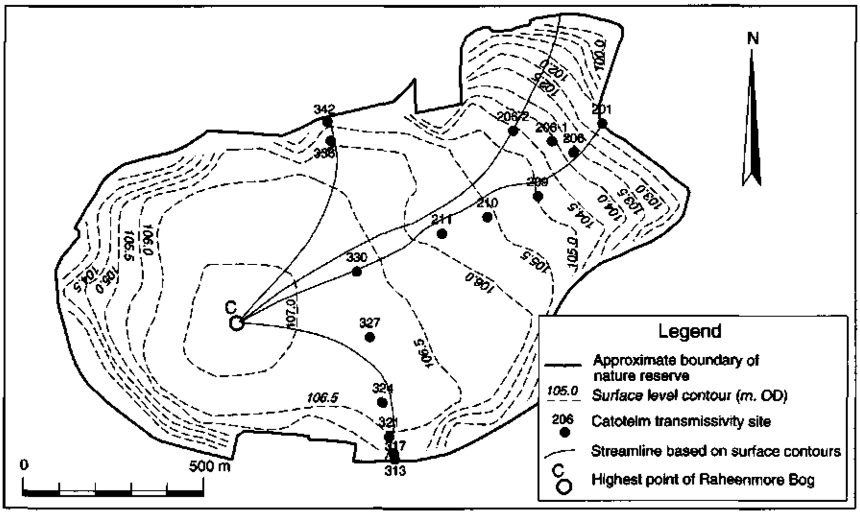

Fig. 5.9. Surface level contours and flow lines along points of Raheenmore Bog for which catotelm transmissivity T_c was calculated

For points that do lie not exactly on one of the flow lines, the position of their perpendicular projection on the nearest flow line was used. The results with two fitted curves are given in Fig. 5.10. Because of the large range of T_c and to avoid negative values of T_c close to the bog margin, the graph and the statistical analysis are based on $\log_{10} T_c$ (formally: $\log_{10} \frac{T_c}{\mathrm{m^2 d^{-1}}}$).

The straight line in Fig. 5.10 is a simple linear regression line of $\log_{10} T_c$ on r_r; the dashed curve follows from a non-linear regression. The fitted models are:

$$\log_{10} \frac{T_c}{\mathrm{m^2 d^{-1}}} = 1.29 - 2.93 r_r \tag{5.35}$$

with correlation coefficient r=0.84, $F^1_{13} = 32$ and a level of significance α<0.001 and

$$\log_{10}\frac{T_c}{\mathrm{m^2d^{-1}}} = 0.087 - 1.98 r_r^{3.34} \tag{5.36}$$

with correlation coefficient r=0.89, $F_{12}^2 = 22$ and a level of significance α<0.001.

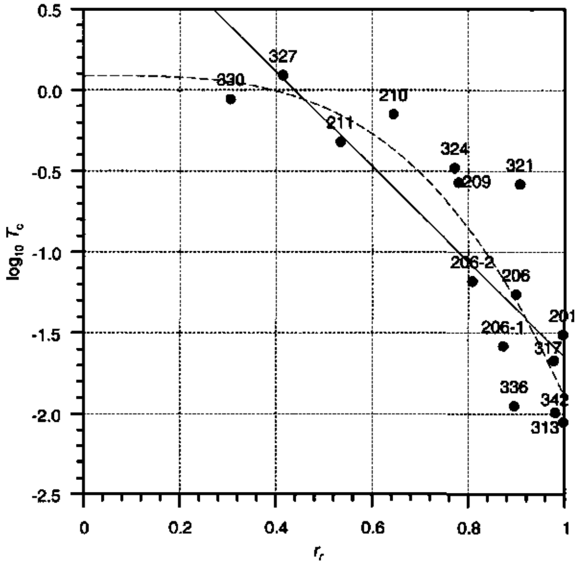

Fig. 5.10. Catotelm transmissivity (as $\log_{10} T_c$) versus relative distance to the centre r_r. Continuous line: the linear model in $\log_{10} T_c$; dashed line: the non-linear model.

The difference between both equations is the power of r_r. For the straight line it is fixed at 1, for the curve it was estimated at 3.34. The curved relationship represents the more likely situation that in the central area the differences between transmissivities are small, as is suggested by the position of the points for which r_r<0.7. For r_r >0.7, the slope of the curve steepens. The physical background is the increase of ϕ_0 towards the margin. This is not only caused by subsidence, but ϕ_0 also tends to increase towards undisturbed bog margins, as will be shown in Chapter 7.

Equations of lateral outflow

For the radial flow system of a theoretical circular raised bog with T_c depending on r, the following basic equations can be written:

$$Q_{hc} = \pi r^2 U_{hc} \tag{5.37}$$

and

$$Q_{hc} = -2\pi r T_c(r)\frac{\mathrm{d}h}{\mathrm{d}r} \tag{5.38}$$

where

Q_{hc} = horizontal flux through the catotelm between two flow lines [$L^3 T^{-1}$]

r = distance to midpoint of bog [L]

U_{hc} = the component of the infiltration, expressed as a lateral flow rate [L T^{-1}], assumed spatially constant

h = phreatic level in the bog [L]

Eliminating Q_{hc} yields:

$$\frac{\mathrm{d}h}{\mathrm{d}r} = \frac{-rU_{hc}}{2T_c(r)} \tag{5.39}$$

In a similar way the following equation for parallel flow can be derived

$$\frac{\mathrm{d}h}{\mathrm{d}x} = \frac{-rU_{hc}}{T_c(x)} \tag{5.40}$$

where

x = the distance from the catchment boundary [L]

Eqs. (5.39) and (5.40) only differ by a coefficient 2 in the denominator. Thus developing an equation for radial flow implies developing one for parallel flow. Writing h explicitly in Eq. (5.39) yields the expression

$$h = -\int \frac{rU_{hc}}{2T_c(r)}\mathrm{d}r \tag{5.41}$$

whose solution depends on the properties of the function $T_c(r)$. Deriving $T_c(r)$ from Eq. (5.36) yields an integral that is difficult to solve. The representativity of the models for other raised bogs is questionable. Nonetheless the models will be worked out for three of the flow lines shown in Fig. 5.9 as a mere example of the bearings of a position dependent T_c upon the GMT. The test will also yield an estimate of the lateral outflow of Clara Bog based on both models.

The function $T_c(r)$ for the linear model of $\log_{10}T_c$ is:

$$\frac{T_c(r)}{T_u} = \exp(a + br_r) \tag{5.42}$$

and for the non-linear one:

$$\frac{T_c(r)}{T_u} = \exp\left(a + br_r^{\ c}\right) \tag{5.43}$$

where T_u is unit transmissivity and a, b and c are dimensionless model parameters. Eq. (5.41) for the linear model becomes:

$$h = -\frac{U_{hc}}{2T_u}\exp(-a)\int r\exp(-b\frac{r}{R})\mathrm{d}r \tag{5.44}$$

and for the non-linear model:

$$h = -\frac{U_{hc}}{2T_u}\exp(-a)\int r\exp\left[-b\left(\frac{r}{R}\right)^c\right]\mathrm{d}r \tag{5.45}$$

Eq. (5.44) is evaluated analytically, the non-linear one will be solved numerically when applied to the flow lines of Raheenmore Bog. Integration of Eq. (5.44) yields (Burington, 1973):

$$h = \frac{U_{hc}R^2\exp(-a)}{2T_u b^2}(b\frac{r}{R}+1)\exp(-b\frac{r}{R}) + K \tag{5.46}$$

The integration constant K is solved for the boundary condition:

$$r = R \Rightarrow h = h_0 \tag{5.47}$$

where

h_0 = the hydraulic head at the bog margin [L]

Hence

$$K = h_0 - \frac{U_{hc}R^2\exp(-a)}{2T_u b^2}(b+1)\exp(-b) \tag{5.48}$$

The solved equation, after substituting $\frac{r}{R}$ by r_r is

$$h - h_0 = \frac{U_{hc}R^2\exp(-a)}{2T_u b^2}\left[(br_r+1)\exp(-br_r) - (b+1)\exp(-b)\right] \tag{5.49}$$

The equivalent for parallel flow reads:

$$h - h_0 = \frac{U_{hc}X^2\exp(-a)}{T_u b^2}\left[(bx_r+1)\exp(-bx_r) - (b+1)\exp(-b)\right] \tag{5.50}$$

where

X = the length from the catchment boundary in the bog to the margin of the flow line through the point [L]

x = distance to the catchment boundary along the flow line [L]

x_r = $\frac{x}{X}$ [1]

Eqs. (5.49) and (5.50) only differ in the value of the coefficient in the denominator. Therefore it is an indicator of the type of flow: radially divergent or parallel. If it is given a symbol, say *f*, the unified equation is written as:

$$h - h_0 = \frac{U_{hc} X^2 \exp(-a)}{f T_u b^2} \left[(bx_r + 1)\exp(-bx_r) - (b+1)\exp(-b) \right] \qquad (5.49a)$$

where

f=2 indicates divergent radial flow

f=1 indicates parallel flow

The system cannot be extended to convergent flow (which occurs on Clara Bog) by assigning a value between 0 and 1 to *f*, because the corresponding equivalent of Eq. (5.39) would have $(R-r)^2$ in the counter and *r* in the denominator. This leads to a different solution of the integral. The value of $\frac{U_{hc}}{f}$ for a flow line can be found by fitting h-h_0 to the real hydraulic heads along the flow line.

Estimating lateral discharge by fitting the models

U_{hc} can be adjusted until an optimal fit to the phreatic levels along the flow line for the models is obtained. This yields a test on the models and an estimate of lateral outflow.

The developed models require a value for h_0. It is available for three out of the four flow lines of Raheenmore Bog shown in Fig. 5.9. Because no measured data exist of *h* at the end of the flow line through site 206-2, this flow line cannot be worked out. On the more upstream parts of the other three, to the W of the line through 342, 330 and 313, no piezometer sites are available. For that area, average phreatic levels have been estimated from ground levels as described in 5.2. For the piezometer sites, average heads over 1991-92 were used.

Fig. 5.11 shows the mean phreatic levels from available data points, the phreatic levels calculated from the models at all points along the flow lines and a fitted ellipse to indicate the levels according to Ingram's GMT.

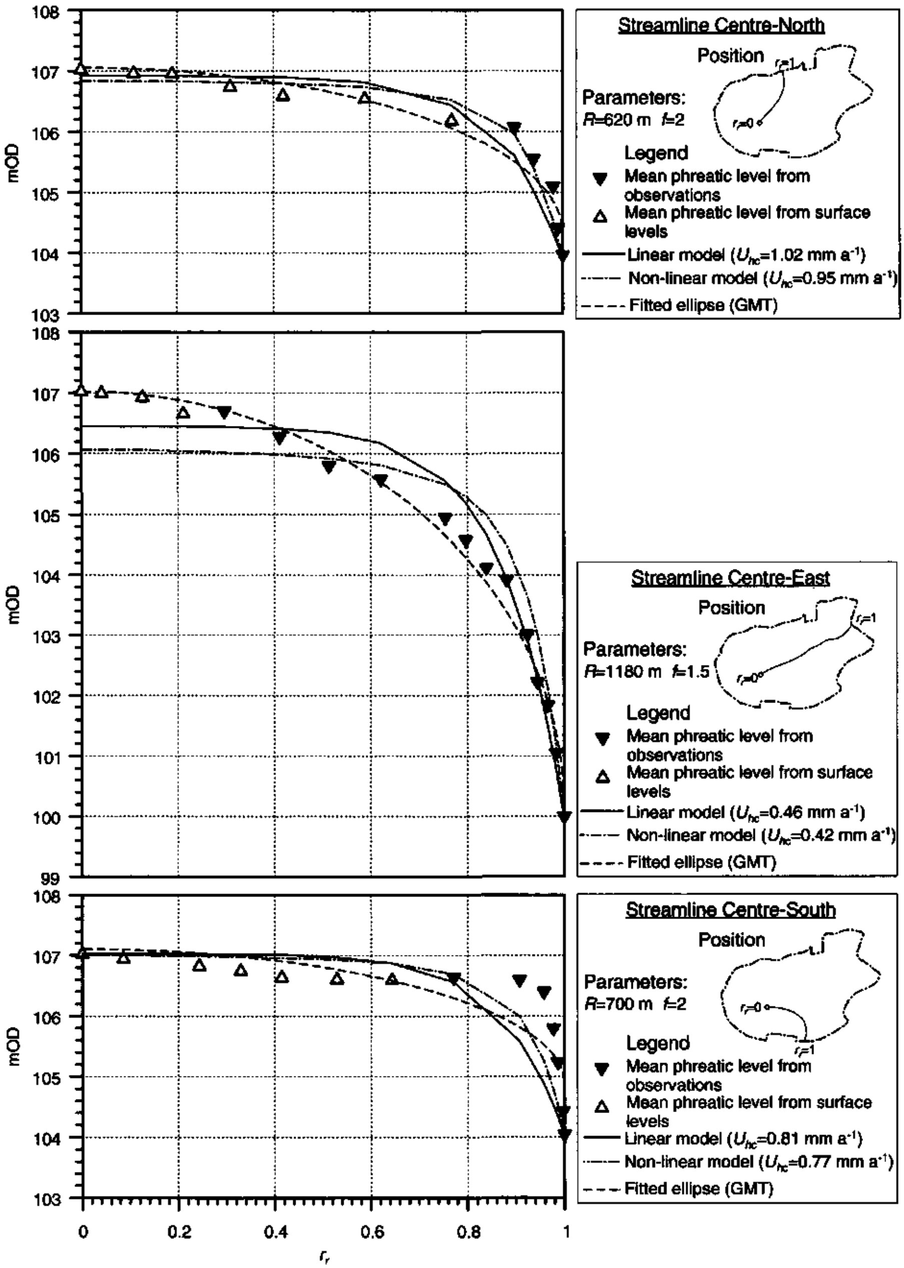

Fig. 5.11. Mean phreatic levels derived from measured groundwater levels and from surface levels versus relative distance r_r along the flow line; estimated values of the lateral outflow component of infiltration U_{hc} according to the linear and the non-linear model in log k, resulting fitted cross-sectional shapes of the mean phreatic level and an elliptical curve according to the GMT in its original form, along three flow lines of Raheenmore Bog.

The values for the linear model were found using Eq. 5.49a. Those for the non-linear model were found by numerical integration of Eq. (5.45). For this purpose, each interval was divided into two sub-intervals on which Simpson's rule for numerical integration was applied.

The values of U_{hc} from the linear and the non-linear approach differ only slightly. Both indicate extremely low lateral outflows. Taking into account the possibility that U_{hc} varies spatially, it should be replaced by the specific horizontal discharge of the catotelm v_{hc}. A safe assumption of the order of magnitude of v_{hc} is 1 mm a^{-1}. It explains observations, such as reported by Verry (1984), that the outflow of raised bogs stops completely when the water table reaches the base of the acrotelm. A similar behaviour was observed in the discharge of Raheenmore Bog, measured at the discharge recording site at the north-eastern margin (position shown in Fig. 3.13).

The best fit of the non-linear model is found along the flow line to the northern margin (upper diagram of Fig. 5.11). It is the most natural one of the three involved. Little or no peat has been cut there as was concluded from the colour of the topsoil of the mineral soils in the field adjacent to the bog. It turned from black to brown within 30 m from the margin, indicating that no peat was ever formed beyond that distance. The 30 m includes the former lagg. The present margin slopes downwards by about 2 metres over the same horizontal distance. The phreatic surface is less steep (points shown in Fig. 5.11). The fit of the non-linear curve is sufficient to support the assumption of U_{hc} being approximately spatially constant. The ellipse, fitted to the available data points, gives the worst fit. It does not even reach the measured level at the margin.

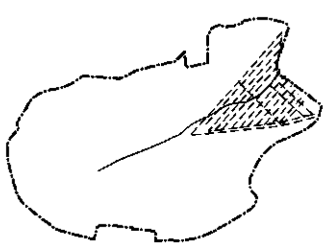

Fig. 5.12. The old ingrown drains of Raheenmore Bog (dashed lines) with position of the flow line to the margin in the ENE.

The long flow line to the northeastern margin (middle diagram in Fig. 5.11) shows the worst fit to the models. For r_r>0.4 the fit is reasonable, especially for the linear model, but the level towards the centre is too low. The explanation may be subsidence along the lower half of the flow line. The part where r_r>0.5 lies in an area with old ingrown drains. Fig. 5.12 shows their position and the position of the flow line. Although the drains are not very effective anymore, they have caused surface subsidence and thus lowered phreatic levels.

Because the flow is radial in the central part of the bog and becomes more parallel towards the margin, the value of f was given a value of 1.5. The good fit of the ellipse is remarkable, because in the original GMT an ellipse is supposed to indicate an undisturbed raised bog.

The flow line to the southern margin shows a poor fit of the ellipse. The curve cannot follow the sharp downward bend of the surface towards the groundwater level at the margin and ends a little lower than halfway between the highest and the lowest level of the flow line. The curves from the other models show a slightly better fit, but do not follow the rather sudden transition from bog level to surrounding level in a proper way. In this part, the peat has been cutover in a zone of 100-150 m (estimated from the colour of the topsoil in the adjacent fields). The poor fit close to the margin could indicate that the process of subsidence caused by the cutting has not yet come to an end. According to Aue (1991, 1992), who studied a partly cutover raised bog in northern Germany, such a margin eventually settles to a shape that resembles the cross section of an undisturbed bog. An additional remark as to this point is made in the conclusions of Chapter 7.

The relatively good fit of the ellipse on the first two flow lines shows that even if an ellipse fits reasonably well, this fact alone is no evidence of the validity of the GMT in its original form. With a spatial trend of k_h and (possibly) a spatially variable U_{hc}, ellipse-like shapes of the phreatic surface may still occur.

The presence of cracks caused by shrinkage and common in peat along facebanks, apparently has little effect on the outflow, because close to the margins in the North and the South the real levels even lie above the calculated ones. In the event of cracks having a considerable effect on lateral outflow, one would rather expect the opposite.

Conclusions

- Application of the GMT to Raheenmore Bog requires that the assumption of a spatially constant k be replaced by a position dependent T_c, because k_h tends to decrease from surface to bottom and from centre to margin.
- The value of T_c was found to vary from about 1 $m^2\,d^{-1}$ in the central part to 0.01 $m^2\,d^{-1}$ at the margin of Raheenmore Bog.
- The fit of the lateral outflow model, based on the modified GMT is best at the least disturbed bog margin, *i.e.* the one in the North; the unmodified "classic" GMT model fits best on the most disturbed part.
- The steep slopes of the phreatic level at the bog margins and the sudden transition to the flat central part require a stronger decrease of T_c towards the bog margin than can be explained by the decline of the surface level in the "classic" GMT.
- For disturbed situations, the assumption of a spatially constant U_{hc} in the GMT should probably be rejected. In undisturbed situations it might hold.
- Even though k_h shows a spatial trend and U_{hc} may depend on horizontal position, it is possible to find an ellipse that fits reasonably well along the phreatic levels of a flow line. This shows that a more or less elliptic cross sectional shape of the phreatic surface of a raised bog is no evidence of the validity of the basic assumptions of the original GMT.

- The specific lateral discharge of the catotelm catotelm v_{hc} of Raheenmore Bog is in the order of magnitude of 1 mm a^{-1} or less.

5.4.3. Clara Bog

Transmissivities and peat depths

T_c could be calculated for a total of 46 sites. 19 were calculated from a hybrid set of k_m and k_e, 21 from k_e and 6 from k_m only. The results of the latter two methods were converted to estimated results of the hybrid method using Eqs. (5.29) and (5.30). The positions of the sites, their transmissivities and peat depths are shown in Fig. 5.13.

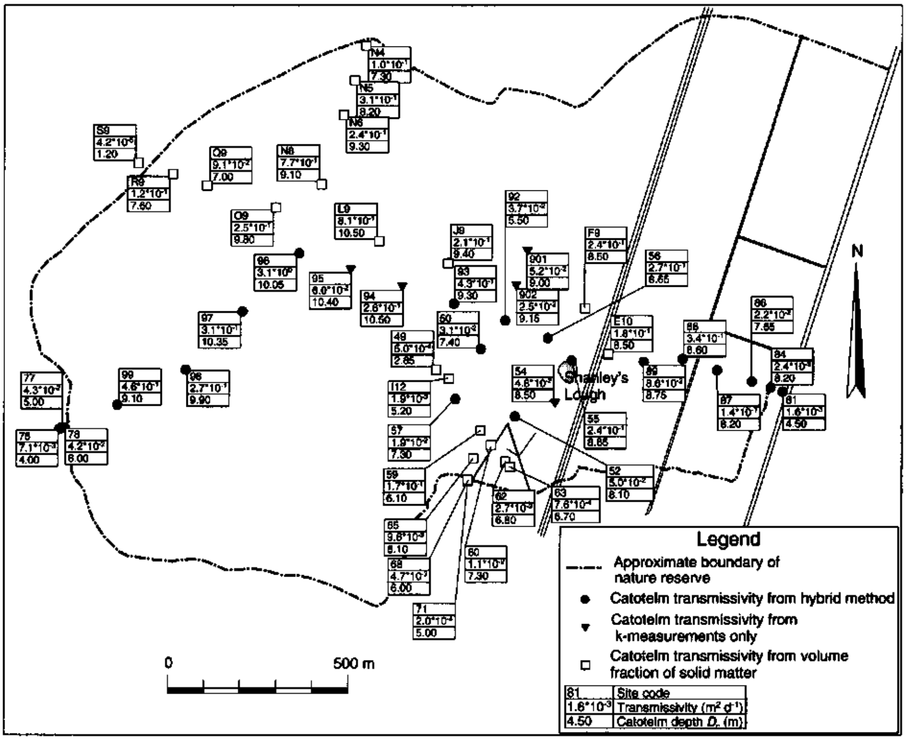

Fig. 5.13. Catotelm transmissivities T_c and catotelm depths D_c of Clara Bog West.

In most of Clara Bog West, peat depths vary between 9.00 m and 10.50 m. Along the margins and in the area around Shanley's Lough, particularly 400-500 m west of the bog lake where the peat overlies a till mound, the peat depths are smaller.

The number of sites is sufficient to make a tentative contour map of catotelm transmissivities of Clara Bog West. It is shown in Fig. 5.14.

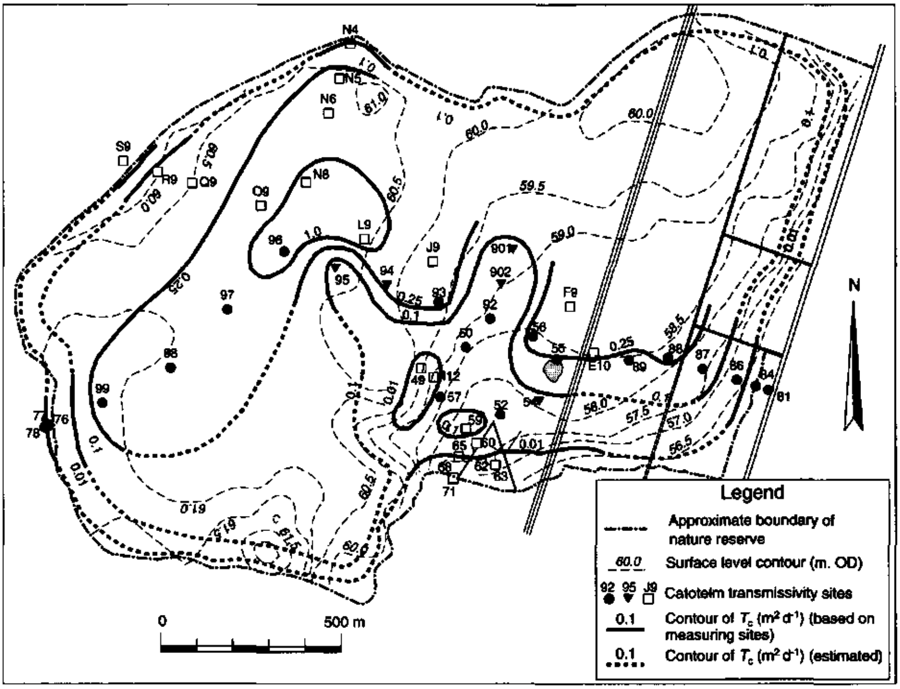

Fig. 5.14. Tentative contour map of catotelm transmissivities T_c of Clara Bog West with surface level contours.

T_c in the central area of the bog varies in the range of 0.25 - 3 $m^2 d^{-1}$. Towards the margins, T_c tends to decrease by two orders of magnitude or more. Most of the decrease occurs in a zone along the margin, approximately 100 metres wide. In these respects, there is no great difference with Raheenmore Bog. To the W and N of Shanley's Lough an area exists with considerably lower T_c, mostly coinciding with smaller peat depths than in the western and northern parts of Clara West. However, the small T_c are not directly to smaller peat depths, but to relatively low values of k. The smallest T_c of lesst than 0.001 $m^2 d^{-1}$ in the central part occur in the peat overlying the mound W of Shanley's Lough of which at least the upper mineral material is glacial till (Bloetjes and Van der Meer, 1992). The surface levels of the peat are about 2 m above those around Shanley's Lough. Parts of the surface slope towards Shanleys Lough are about 1:40, which may be considered steep for the central area of a raised bog. The volume fraction of solid matter of the peat on the slope and on top of the mound is relatively high, as is shown in the profiles of the sites 49, I12 and 57 in Fig. A.14 (Appendix A). This and the surface topography suggest that a considerable surface subsidence has occurred in the area of Shanley's Lough. In Chapter 7 this will be discussed in more depth.

Lateral discharge of the catotelm

Fig. 5.15 is a map of surface level gradients of Clara Bog West. The large gradients along the bog margin mark the steep transition of face banks in the S and W, a mixture of face banks and a possibly near-natural margin in the N and the transition to the Clara-Rahan road in the E. As on Raheenmore, an absence of indicators of large gradients along the margin indicates the absence of level points outside the bog rather than the absence of a steep margin slope.

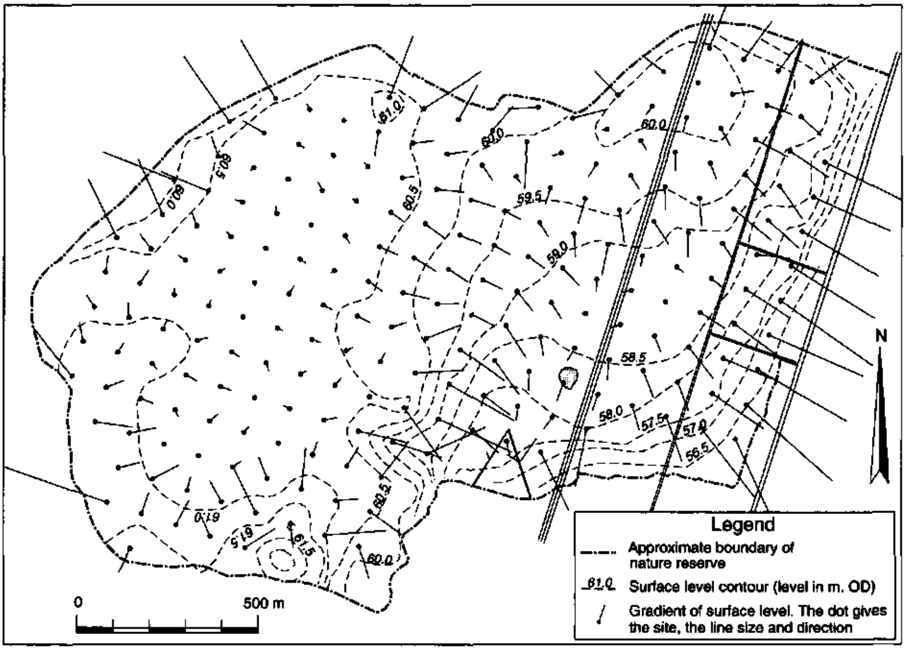

Fig. 5.15. Surface level gradients of Clara Bog West.

The map indicates little diverging radial flow. The western half shows either an unclear pattern or converging flow from the margin area towards the centre (in the SW). In the eastern half, there is one pattern that converges towards the area of Shanley's Lough and another one that indicates a discharge towards the Clara-Rahan road. Although uncommon in Ireland today, converging flow in raised bogs is not unusual in the world. Ivanov (1963, 1981), for example, presented several such flow patterns of raised bog complexes in Western Siberia.

The GMT does not take converging flow into account, neither in its original form nor in the modified version as developed in this chapter. Of course a numerical model for Clara Bog West to assess lateral catotelm outflow could be developed. The negligible amounts found for Raheenmore Bog, the small differences in T_c between both bogs and hence the expected small outflows justify a simpler approach. It is based on seven transects along approximate flow lines across points with known phreatic levels and transmissivities. From the estimated distance to the catchment boundary, hydraulic gradients and T_c, an estimated v_{hc} of the upstream area can be derived as follows.

Let $x_1 ... x_n$ be the distances of n consecutive sites on the transect to the upstream catchment boundary and $h_1 ... h_n$ the corresponding phreatic levels, averaged over a certain period of time. v_{hc} at any site i is then estimated by:

$$v_{hc} \approx -\frac{T_c(i)}{x_i}\frac{\mathrm{d}h(x)}{\mathrm{d}x} \qquad (5.51)$$

where the gradient $\frac{\mathrm{d}h(x)}{\mathrm{d}x}$ is estimated by

$$\frac{\mathrm{d}h(x)}{\mathrm{d}x} \approx \frac{h_i - h_{i+1}}{x_{i+1} - x_i} \quad \text{for} \quad i = 1 \qquad (5.52a)$$

$$\frac{\mathrm{d}h(x)}{\mathrm{d}x} \approx -b_{hx}(i-1, i, i+1) \quad \text{for} \quad 1 < i < n \qquad (5.52b)$$

$$\frac{\mathrm{d}h(x)}{\mathrm{d}x} \approx \frac{h_{i-1} - h_i}{x_i - x_{i-1}} \quad \text{for} \quad i = n \qquad (5.52c)$$

and where

$b_{\bar{h}x}$ = regression coefficient of h on x over the specified range of i [1]

If i is numbered upwards from the upstream catchment boundary to the downstream end, downstream flow is indicated by a minus sign, which is justified by the flow being outwards from the bog.

Fig. 5.16 shows the position of seven transects, the sites and the estimated v_{hc} per site. The transects indicated by the end sites and represent the following situations:

Face banks: transects R16-75 in the SW and 59-71 in the south.

Western flat area: transects R16-O11 and N9-Q9. The upstream ends of the transects M9/N9-F12 and 96-G13 also give information (M9/N9 is the position halfway between the OPW grid pegs M9 and N9).

The flow from the western flat area towards the area of Shanley's Lough: transects M9/N9-F12 and 96-G13.

The sloping area W of Shanley's Lough to the southern margin: transect J12-63.

The flow towards the Clara-Rahan Road: transect D9-81.

Values of h have been either calculated from phreatic levels over 6th February 1992- 4th February 1993 (26 values) or estimated from ground levels as described in 5.2. To avoid large variations of the interval of x in the transects as much as possible, sites with known h but unknown T_c were added when available and needed. Where possible, T_c was estimated by interpolation between neighbouring sites in the transect. Added sites often are OPW grid pegs where only the ground level is available. Such sites are indicated by a character, followed by a number, e.g. J9. Dip well sites are indicated by numbers only.

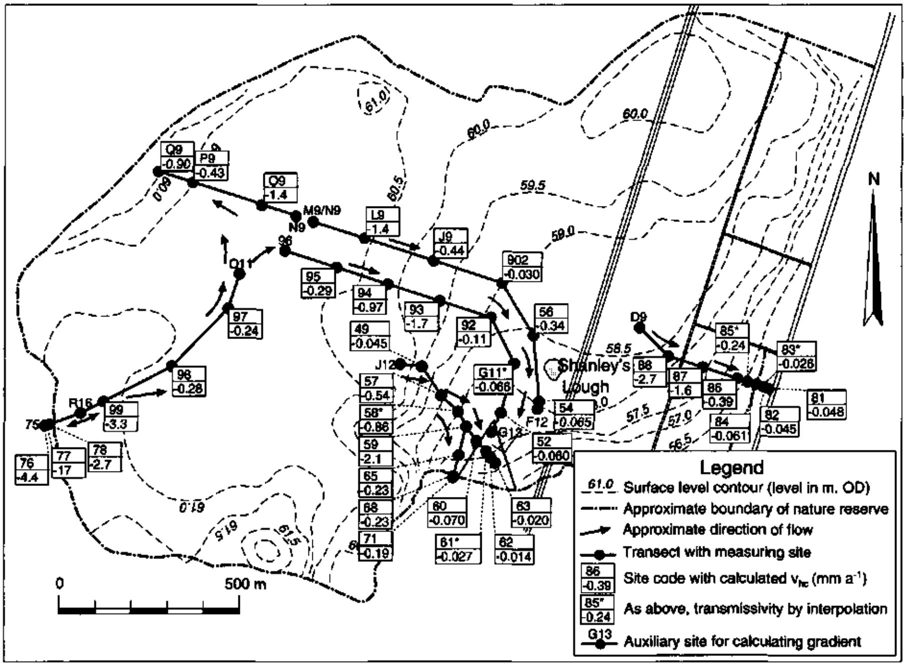

Fig. 5.16. Positions of the transects for specific horizontal discharge v_{hc} through the catotelm and calculated v_{hc}.

The trends in v_{hc} are rather consistent. This indicates that the results are reasonably reliable. Because the transects are not exactly in the direction of the flow, the values of v_{hc} may be slightly underestimated. The main features are:

- The largest values of v_{hc} occur in the central and western flat area, approximately coinciding with the largest values of T_c.
- Low values of v_{hc} occur W and SW of Shanley's Lough where subsidence is likely to have occurred (see also Chapter 7).
- In the area of Shanley's Lough the flow converges from a large part of the bog expanse into a relatively narrow "corridor" towards the south.

- In the S and E, v_{hc} decreases towards the margin and the Clara-Rahan road, but in the W and SW no such decrease occurs. The large values of v_{hc} in the SW (sites 76-78) are remarkable. There is no indication of overestimated T_c and thus no good explanation for the difference with other parts of Clara Bog.

Apart from a few exceptions, notably the face bank in the SW, v_{hc} at the margins is around 1 mm a^{-1} or less. A safe assumption would probably be 0.5-1.0 mm a^{-1} for the bog as a whole. This is almost the same as found for Raheenmore Bog. Clara Bog West has more than twice the size of Raheenmore Bog. Both Eq. (2.10) and Eq. (5.49a) indicate that v_{hc} is inversely proportional to R^2 and thus to the bog area (assuming equal hydraulic conductivities and heights above the surroundings). Although v_{hc} of Clara Bog seems slightly smaller than v_{hc} of Raheenmore Bog, the uncertainty of the values is too large for a conclusion.

The low values of T_c close to the margin reduce the outflow in the S and E. This confirms Aue 's conclusion (1991, 1992) on the effect of low hydraulic conductivities along secondary bog margins. However, considering the small values of v_{hc}, his term *Hydrologische Schutzfunktion* (hydrological protection function) is hardly appropriate in the case of Clara and Raheenmore Bog.

To the NW of Shanley's Lough, a rather sudden transition in the value of v_{hc} occurs from an order of magnitude of 1 mm a^{-1} to 0.1 mm a^{-1} or less. It coincides with the convergence of the flow to the relatively narrow "corridor" of Shanley's Lough (see also Fig. 5.15). Thus v_{hc} in the corridor may be overestimated.

Such a decrease in v_{hc} must be compensated for by a change in the vertical flow component U_{vc} (principle of continuity). Where the exfiltration U_e is small enough, this could result in an upward flow in the upper part of the catotelm. Although no evidence was found in any of the piezometer sets, such a flow might exist locally and perhaps temporarily. As the groundwater in the fen peat has concentrations of Ca^{2+} well above 1 meq/l (Van den Boogaard, 1993), a local upward flow could cause a slight enrichment with calcium of the water in the upper (bog) peat. This could explain why in the surroundings of Shanley's Lough and some other parts of Clara Bog the vegetation contains indicators of more minerotrophic conditions, such as *Menyanthes trifoliata, Myrica Gale* and local birch groves. The upward seepage need not even occur exactly on the spot, because acrotelm flow provides a means of horizontal transport of dissolved components, even though this is accompanied by a considerable dilution.

Conclusions

- The flow pattern of Clara West differs from the "classic" raised bog in that it is not a divergent radial pattern, but a mixture of divergent, parallel and convergent flow. Therefore, the GMT is not applicable on Clara Bog West in any form discussed.

- The value of the catotelm transmissivity T_c in the central part of the bog is in the range of 0.2-1 $m^2 d^{-1}$, except in a small area in the centre of the flat area in the W around site 96, where it is 1-3 $m^2 d^{-1}$ and the in area N and W of Shanley's Lough where it is considerably below 1 $m^2 d^{-1}$. The decrease of T_c towards the margin is strong: by at least two orders of magnitude.
- The specific catotelm discharge as calculated for the different sites varies over some orders of magnitude. A safe estimate for the entire bog would be $v_{hc} \approx 0.5\text{-}1$ mm a^{-1}.
- There is a considerable spatial variation in the lateral flow through the catotelm; towards the margin the horizontal flux often shows a tendency to decrease. This could possibly result in small local areas of a small net upward seepage from the catotelm into the acrotelm. The existence of places with a vegetation that indicates influences of minerotrophic water might depend on such local phenomena. In view of the low flow rates, the amounts must be small, if such upward flow exists at all.

In view of the small lateral outflow, the reduced T_c along the bog's margin have no function in protecting the bog from drying out, even though their relative effect on the outflow is large.

5.5. Exfiltration

5.5.1. Introduction

Exfiltration from bogs often is estimated from the water balance. A requirement is that all other terms of the balance must be known with sufficient accuracy. Because in the field work period on Raheenmore and Clara Bog measurements of acrotelm discharge Q_a could only be made of parts of the bogs, the size of these parts must be known to obtain a water balance. As the exact sizes cannot be determined directly from the available data, exfiltration estimated by another method is needed in checking the estimated size of catchments on the bogs.

The exfiltration is calculated basically from the vertical resistance of the catotelm C_c and from differences between piezometric levels at different depths. As concluded in 5.3.4, C_c is far less reliable than T_c, whether derived from directly measured k or from estimates based on ϕ_b. This means that differences between values of the estimated exfiltration from neighbouring sites do not necessarily reflect a real variability in conditions. However, from the total set of values one may probably derive a realistic value of the exfiltration at the scale of the bog.

The basic results are presented in Appendix C. Fig. C.1. shows the positions of individual sites and the way, their values of C_c were estimated. Table C.1 shows results for Raheenmore Bog, Table C.2. for Clara Bog West. The results from both bogs will be discussed simultaneously, because their differences have no bearings on the estimating technique of C_c. The estimating technique will first be discussed briefly.

5.5.2. The estimating method

Over any depth interval in the catotelm, the vertical component of the flow rate may be defined as

$$U_{vc} = -k_v \frac{\Delta h}{\Delta z} \approx \frac{(h_1 - h_2)}{C_c(z_1, z_2)} \tag{5.53}$$

where

U_{vc} = 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 definition of U_{vc} implies that its value is negative in the event of downward flow of water in the catotelm. Consequently, a positive value of U_{vc} implies upward seepage.

At the bottom of the catotelm, U_{vc} is identical with the exfiltration U_e. Above that level, U_{vc} is a quantity in its own right, because of a possible exchange of water between horizontal and vertical fluxes. As long as U_{vc} is several times as large as U_{hc}, the error in U_{vc} that is caused by neglecting the exchange may be assumed negligible compared to errors in U_{vc}, resulting from uncertainties in C_c, if averaged over an area in the order of magnitude of several hectares; smaller in the centre and larger towards the margin. Whenever U_e is estimated from differences in h over arbitrary depth intervals, the postulate $U_e \approx U_{vc}$ is essential.

5.5.3. Results

In Appendix C.1, estimates of U_e have been calculated in two ways:

- for depth intervals from the surface to the filter depth of the piezometer involved and
- for depth intervals between piezometers at adjacent depths.

The second method seems less accurate at first sight, because it is based on a part of the peat profile instead of on the entire depth. However, it turns out to be the preferred method, as is shown below.

For many sites, Tables C.1 and C.2 show a considerable decrease of $|U_{vc}|$ with increasing depth. The values calculated for small depths often are too large to be credible and their downward decrease usually is too large to be explained by assuming local variations in the vertical component of groundwater movement. A more likely explanation is a decreasing anisotropy of the hydraulic conductivity k. Values of k on which C_c is based, are either direct or indirect results of the piezometer method and thus are horizontal k-values. In the event of anisotropy in the vertical plane caused by approximately horizontal layering over smaller depth intervals then the length of the piezometer filters (20 cm), this will result in overestimating vertical flow.

Where anisotropy exists in peat, it is related to alternating looser and more compacted peat layers. As shown in the statistical analysis of k versus ϕ_0 (section 4.3.3), compaction has a strong effect on k. Consequently, the presence of alternating layers of small and larger ϕ_0 means alternating layers of large and smaller k. In the continuing process of decay and compaction in the catotelm, compaction is likely to have its strongest effect on layers with the loosest structure. Thus a stronger decrease of k_h than of k_v with increasing depth may be expected, because k_h mostly depends on layers with a large k and k_v on those with a small k. The phenomenon was indeed found in laboratory tests as reported by Hobbs (1986).

Assuming the above conclusion to be correct, the best way to estimate U_e is between the deepest pair of piezometers at a site. Appendix C shows that this usually yields the smallest exfiltration rates. A complication is that a considerable number of deep piezometers turned out to have been installed below the peat in the mineral subsoil. They were installed at an early stage of the project when the peat depth was unknown and it was believed that piezometers could not be pressed down manually into the subjacent mineral deposits. On Clara Bog, this occurred several times, on Raheenmore Bog only at two sites (209 and 211) with certainty. Because C_c was always calculated for the peat only, such situations may result in overestimating the exfiltration rate, especially when small d_f (d_f<0.5 as an indication) are involved.

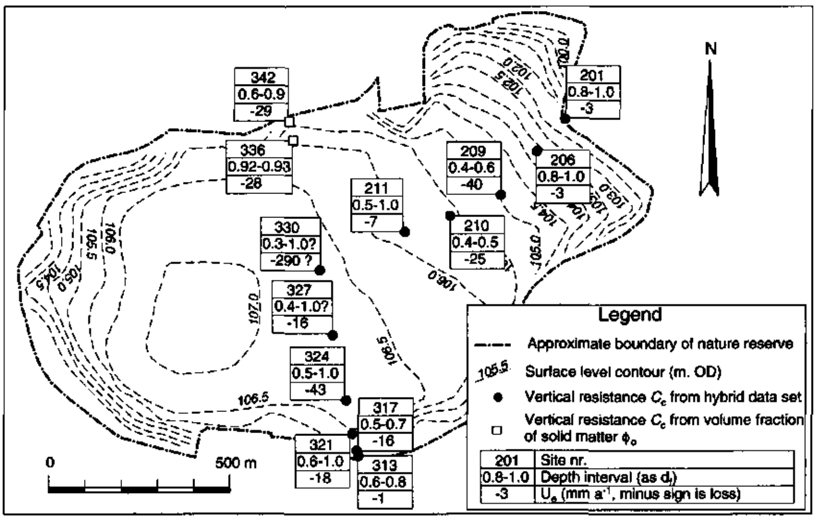

Fig. 5.17. Exfiltration rates U_e and depth intervals (expressed as fractional depth d_f) over which they were calculated for *Raheenmore Bog*.

Therefore the values of U_e in Fig. 5.17 (Raheenmore Bog) and Fig. 5.18 (Clara Bog) are given with the levels of d_f between which the exfiltration was estimated.

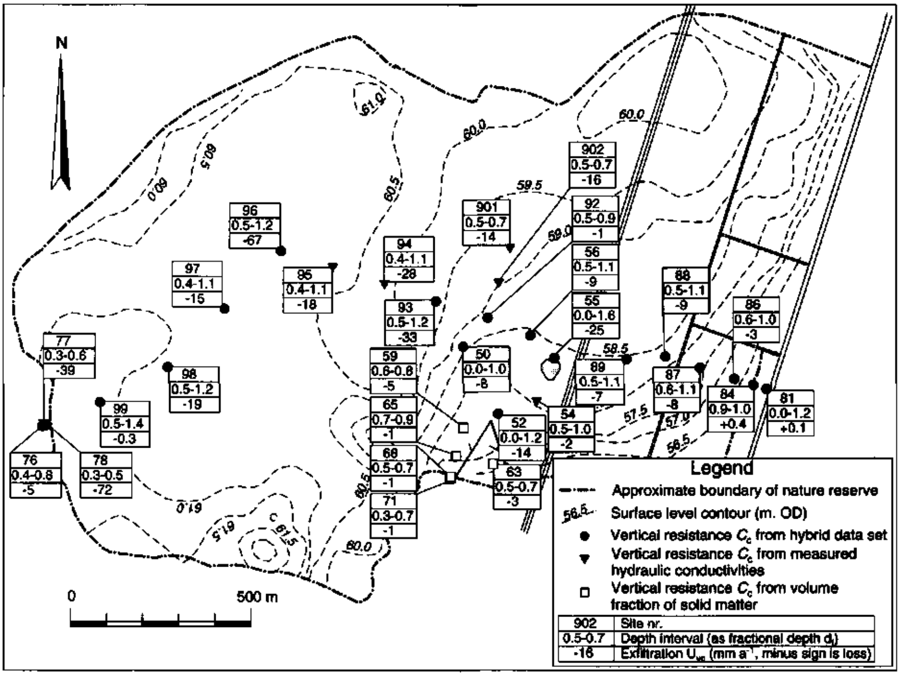

Fig. 5.18. Exfiltration rates U_e and depth intervals (expressed as fractional depths d_f) over which they were calculated for *Clara Bog West*.

The arithmetic mean is simple to calculate, but large outliers have a relatively strong influence on the results. This effect is smaller for the geometric mean. A third option, the harmonic mean, is relatively strongly affected by small outliers in a set and is therefore likely to give an underestimated v_e.

The estimated U_e is inversely proportional to C_c, which itself is inversely proportional to k_v and k was assumed to be approximately lognormally distributed. This is a (weak) indication in favour of applying the geometric mean in estimating the total exfiltration. The general tendency of overestimating U_e in the methods applied is yet another indication for not applying the arithmetic mean.

Table 5.7 gives the three different means for both bogs. As some outliers occur (site 330 on Raheenmore Bog and 78 and 96 on Clara Bog), columns with and without outliers are given. For Clara Bog, the two sites with upward seepage (81 and 84) near the Clara-Rahan road are not included, because they represent entirely different flow conditions.

Table 5.7. Arithmetic, geometric and harmonic means of the exfiltration rates U_e of Raheenmore Bog and Clara Bog West, with and without outliers. Values in mm a^{-1}. Minus signs as shown in Fig. 5.17 and Fig. 5.18 have been omitted.

	Raheenmore Bog		Clara Bog West	
	all data	w/o outlier 330	all data	w/o outliers 96 and 78
n	13	12	28	26
Arithmetic mean	39.9	19.0	15.1	10.9
Geometric mean	14.6	11.3	6.8	5.7
Harmonic mean	4.2	3.9	2.4	2.2

As the harmonic mean is likely to give too low and the arithmetic mean too high estimates of the specific vertical discharge v_e, the geometric mean probably gives the best approach of the three. It implicitly assumes a lognormal distribution of the data. The two outliers have little effect on the geometric mean. Thus v_e for Raheenmore Bog may be estimated safely at 10-15 mm a^{-1} and for Clara Bog West at 5-10 mm a^{-1}.

Clara Bog has two specific features:

- The relatively low values of U_e in the area around Shanley's Lough. They reflect the larger C_c in that area and account for a large part of the difference between the v_e of Clara Bog West and Raheenmore Bog. The western half of Clara Bog West shows values, not much lower than those of Raheenmore Bog.
- The positive U_e in a narrow zone along the Clara Rahan Road. Because the surface levels along the road lie up to 5-6 metres below the highest parts of both Clara West and East, the piezometric level of the till aquifer below the glacio-lacustrine clay lies about 1.50 m above the road level in the centre Clara Bog (Flynn, 1993). The small values of U_e are correlated to the large C_c of the compressed peat and the subjacent lacustrine clay in that area.

5.5.4. Discussion

In both bogs, the largest exfiltration rates U_e tend to occur in the central parts and the smallest along margins where the vertical resistance C_c tends to have its largest values. This result shows that, contrary to a common belief among nature conservationists, the direct effect of drains along margins on the quantitative hydrology of the bogs is small. The only exception seems to be the southwestern margin of Clara Bog. The U_e in that part was calculated for relatively shallow depth intervals where anisotropy probably still occurs. The transition from 5 mm a^{-1} at the margin to 72 mm a^{-1} some 8 m inside the bog coincides with a decrease of d_f (Fig. 5.18). Thus U_e was probably overestimated. It seems likely that the compact peat along natural margins and surface subsidence and related compaction of the peat along man-made margins provides a sealing that prevents the bog from being drained by low(ered) piezometric levels in a subjacent aquifer.

A remarkable feature of Raheenmore Bog is the large difference between piezometric levels *h* in the upper and middle part of the catotelm on one hand and the deepest part at or (just) below the bottom of the peat on the other. The differences are 2.5-3 metres at sites 327 and 330 (Table C.1 in Appendix C). A similar difference (about 3 metres) was found in a borehole drilled into the mineral subsoil between sites 211 and 330 by the GSI[1]. This indicates that a layer with an extremely small *k* exists at the base of the peat in the central part of Raheenmore Bog. This conclusion is supported by the sudden sharp increase of ϕ_b found at the base of the peat in some profiles, for example 210, 211 and 324 (Appendix A, Figs. A.12 and A.13). If such a layer is thinner than 0.50 m, it may not be sampled when the sampling depth interval is 0.50 m. It is missed easily when piezometers at even larger depth intervals are used for measuring *k*. This may explain the extremely large estimated exfiltration at site 330, where the probable peat depth is about 14 m and the deepest 1-2 metres of the peat could not be sampled. The piezometer for the measurement of *k* was installed at 13 m below the surface and still gave a relatively large *k* (Appendix B, Fig. B.2).

On Clara Bog, this kind of "sealing" was never found. Probably the subjacent glacio-lacustrine clay acts as a sealing agent. Values of *k* were found to vary between 27 and 37 mm a^{-1} (Rodgers, 1993). Even smaller values, about 15 mm d^{-1} were measured during the field work in 1993 in two samples taken by the Soil Mechanics Laboratory of University College Galway at piezometer site 97. This means a *C* of the clay in the order of 10000-20000 days per metre thickness. Locally, the clay is up to 7 metres thick (Flynn, 1993).

On Raheenmore Bog, the subjacent mineral material was not sampled for laboratory tests but examined at a few occasions when it was brought up in the peat sampler. It mostly was a gritty loam and definitely coarser in texture than the glacio-lacustrine clay of Clara Bog. Bennett and Johnston (1996) reported the composition of the mineral subsoil of Clara Bog to vary from blue/grey "lacustrine" clay to clayey gravel. Hence, the subjacent material of Raheenmore Bog is likely to have a (considerably) larger *k* than the material of Clara Bog. This may indicate a possible self-sealing property of peat which is activated when subsurface discharge through subjacent layers induces a relatively low pore pressure at the base of the catotelm. The weight of the overburden that is not compensated for by pore pressure may then cause compression of the base peat and a related decrease of its hydraulic conductivity. Thus a sealing layer at the base of the peat may be formed (Van der Schaaf, 1998b). This hypothesis is supported by the fact that the scarce studies on exfiltration seem to give fairly similar results. Eggelsmann

[1]Geological Survey of Ireland

(1960) found 36 mm a^{-1} for Königsmoor in Germany. In a later publication (Eggelsmann, 1990a) the same author mentioned <30 mm a^{-1} as an average for raised bogs in northwestern Germany. Roshdeztvenskaya (1973, cit. Ivanov, 1981) found 27 mm a^{-1} as a 6 year average in a water balance study of a bog catchment of 2.9 km^2 in Russia. Streefkerk and Casparie (1989) mentioned 26 mm a^{-1} for the Dutch bog remnant Bargerveen. Ingram (1982) reported the same value for Dun Moss in Scotland. Siegel (1992) found >10 mm a^{-1} for the Red Lake Peatlands in Minnesota. The values found for Clara and Raheenmore Bog thus lie at the lower end of the range, found in literature.

The existence of a self-sealing mechanism might be important in the conservation of bogs lying in drained surroundings. However, if the bog is also drained internally, the protective function of the peat at the base may be destroyed by the forming of cracks over the depth of the remaining peat. This may explain the dependence on surrounding groundwater levels of the hydrological conditions in some partly cutover raised bogs. Schouwenaars *et al.* (1992) found 80-100 mm a^{-1} for the partly cutover bog Engbertsdijksvenen in the Netherlands, which lies on a sandy subsoil and where the groundwater levels in the surroundings have been lowered for agricultural purposes. Later, Schouwenaars (1993) mentioned 80-200 mm a^{-1} for the same area. Van Walsum and Veldhuizen (1995) found 132 mm a^{-1} over 1982-1985 in a model study of the partly cutover raised bog Fochteloërveen in the Netherlands.

5.5.5. Conclusions

- The specific exfiltration discharge v_e of Raheenmore Bog lies between 10 and 15 mm a^{-1}; in Clara Bog West between 5 and 10 mm a^{-1}. These values are small compared with exfiltrations reported from raised bogs in other parts of the world.
- The lower v_e of Clara Bog West is in part caused by low values in the subsided area of Shanley's Lough; in the western part the values are closer to, but still below those of Raheenmore Bog.
- The upper peat is anisotropic in the sense that horizontal k-values are (considerably) larger than vertical ones. The anisotropy decreases with depth. Because k was measured with the piezometer method which yields horizontal k, the most reliable estimate of U_e is from k in and differences in h over the deepest part of the catotelm.
- Where peat is underlain by relatively permeable mineral material, probably a natural sealing process occurs by compaction of peat caused by the combination of the weight of the overburden and (relatively) low pore pressure. The process seems to have occurred at the base of the catotelm of Raheenmore bog, not in Clara Bog, where exfiltration is limited by the presence of a glacio-lacustrine clay with a very low k in the order of 0.05-0.1 mm d^{-1}.
- The margin zones of both bogs tend to yield the smallest values of U_e. The high values found for the southwestern margin of Clara Bog probably are overestimated as a

result of too shallow depth intervals for the estimation of U_e. This means that lowered groundwater levels resulting from drainage in the surrounding area and even at the bog margin have a limited effect on water losses by exfiltration, as long as the bog has no effective artificial internal drainage.

6. ACROTELM HYDROLOGY

6.1. Introduction

The hydrological properties of the acrotelm of Clara Bog and Raheenmore Bog and their relationship with the hydrological system of both bogs are discussed in this chapter. Compared to the rather static processes in the catotelm, those in the acrotelm are much more dynamic. In a living raised bog system, conversion of precipitation to discharge, changes in water storage and alternating aerobic and anaerobic conditions occur in the acrotelm.

The description of the acrotelm by Ingram (1978) and Ingram and Bragg (1984) is not a definition in the sense that it unambiguously describes the properties of the substance involved. It rather is a (useful) concept that needs a more exact definition to serve as a basis for quantitative assessments where repeatability is indispensable. As mentioned in 2.8, Verry (1984) proposed the addition: "the top layer of the peat with a degree of humification of 4 or less on the Von Post scale". Although this addition may not have the same meaning for any raised bog regardless of its geographical position, it gives an unambiguous definition of the concept "acrotelm" for the situation of Raheenmore Bog and Clara Bog. It was applied by Van 't Hullenaar and Ten Kate (1991) in the acrotelm survey of Raheenmore Bog. During this survey it was found that material with a degree of humification of 4 contributed little to the transmissivity of the acrotelm aquifer. Therefore the limit was adjusted to "a degree of humification of 3 or less" in the survey of Clara Bog (Van der Cruysen *et al.*, 1993). This change, although justified from a hydrophysical point of view, meant a loss of comparability between the results from both bogs. Therefore the data of Van 't Hullenaar and Ten Kate used in this chapter were adjusted using the original field data.

The acrotelm is the result of the annual cycle of production of dead plant material by a living vegetation, followed by a process of decay that slows down as the material is buried by newly formed plant remains. As the thickness of overlying material increases, conditions gradually become more and more anaerobic, the peat material more compressed and the fibres more interspersed with finer and sometimes even colloid-like particles. This process of compression and decay affects both the hydraulic conductivity and the storage coefficient μ (as discussed in 2.5). The physical mechanism is the reduction of the fraction of coarse pores. In a healthy acrotelm this is a natural process. Bragg (1995) found that in a *Sphagnum magellanicum* lawn the fraction of pores with a diameter larger than 100 μm decreased from about 0.9 at 1 cm below the surface to 0.45 at a depth of 15 cm. Disturbance, usually by drainage in any form, speeds up the process of decay and the formation of new material ceases. This may lead to a breakdown of the acrotelm.

This chapter focuses on

- The relationship of μ with depth rather than "the" value of μ in the acrotelm;
- The effect on μ of microtopography when hollows become filled with water and/or pools expand (see also Fig. 2.2);
- The relationship of depth and hydraulic conductivity k and hence the relationship of the phreatic level h and acrotelm transmissivity T_a;
- The relationship of locally measured T_a and discharge Q_a of water from the bog;
- T_a as related to surface slope and flow pattern;
- Effects of disturbance on T_a;
- Acrotelm depth D_a as an indicator of flow conditions and relationships with μ and T_a;
- h and its fluctuation as conditions for acrotelm growth.

6.2. The storage coefficient

6.2.1. Introduction

In a living bog, the storage coefficient is a property of the acrotelm, because the latter is the zone in which the phreatic surface usually fluctuates. A storage coefficient of a soil never has a single value, because it depends on the potential and actual storage of water above the fluctuating phreatic level. Because in a living raised bog the phreatic level is always close to the surface, the storage coefficient μ depends less on conditions in the unsaturated zone than in most mineral soils.

Two properties contribute to the large values of μ in living bogs:

- The proportion of large pores, especially in the upper part of the acrotelm;
- The microtopograpy (hummock-hollow and/or ridge-pool complexes), where the presence of open water in the lower parts may cause large values of μ.

The effect of the former mechanism can be derived from the lysimeters that were used on both Clara and Raheenmore Bog. The effect of the latter may be inferred by combining results of recording rain gauges and groundwater level recorders. Both analyses are discussed.

6.2.2. Storage coefficients from lysimeters

The applied technique was similar to the one, described by Schouwenaars and Vink (1992). The specific storage of the lysimeter S_{wL} can be derived directly from its mass by

$$S_{wL} = \frac{m_L - m_{Lref}}{A_L \rho_W} \tag{6.1}$$

where

S_{wL} = Specific storage in the lysimeter [L]

m_L = Mass of the lysimeter [M]

m_{Lref} = Reference mass of the lysimeter (may be any, if related to some phreatic level in the lysimeter) [M]

A_L = Area of the lysimeter [L^2]

ρ_W = Mass density of water [ML^{-3}]

The relationship between specific storage S_w, the storage coefficient μ [1] and the phreatic level h [L] is

$$\mu(h) = \frac{dS_w}{dh} \tag{6.2}$$

A relationship

$$S_w = f(h) \tag{6.3}$$

had to be derived from the lysimeter observations. Second degree polynomials gave a good fit for all lysimeters (*cf.* Fig. 6.1), hence

$$S_w \approx a + bh + ch^2 \tag{6.4}$$

where

a, b, c = regression parameters; [L], [1] and [L^{-1}], respectively

Hence the relationship

$$\mu(h) \approx b + 2ch \tag{6.5}$$

yields a storage coefficient that depends linearly on the depth of the phreatic level. It results in μ<0 or μ>1 at sufficiently large depths, depending on the sign of c. Thus relationship (6.5) only has an approximate validity over a limited range of h. A safe estimate may be the acrotelm's upper 15 cm. If the surface level is taken as the reference level for h (i.e. h=0 at the surface), b equals the storage coefficient when the water table reaches the surface. The value of c gives the change of μ with depth.

The lysimeters had different vegetation covers (*cf.* 3.11). For Raheenmore Bog, the data from lysimeters with a deep acrotelm and from those with a shallower one were processed separately. For Clara Bog, such a differentiation was not applied for reasons mentioned in 3.11.

Fig. 6.1 shows the graph of S_w versus h for a representative lysimeter of three vegetation elements.

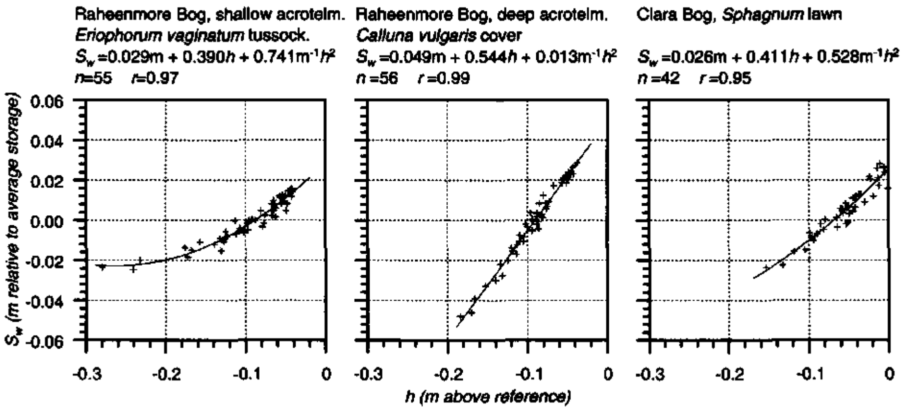

Fig. 6.1. Specific storage S_w versus phreatic level h for three representative lysimeters (data in Table 6.1 and Table 6.2).

Table 6.1 shows the results of Raheenmore Bog for all vegetation elements, Table 6.2 shows them for Clara Bog.

Table 6.1. Results of parameter fitting for specific storage S_w versus phreatic level h (relative to surface and negative downwards) using Eq. (6.4) for *Raheenmore Bog*. Shaded rows mark lysimeters of which a full graph is shown in Fig. 6.1.

Vegetation dominated by	*Poor* acrotelm					*Deep* acrotelm				
	n	b (-)	c (m^{-1})	r	lowest h (m)	n	b (-)	c (m^{-1})	r	lowest h (m)
Calluna	56	0.234	-0.174	0.97	-0.25	56	0.391	-0.244	0.97	-0.19
	54	0.842	2.28	0.96	-0.22	56	0.544	0.013	0.99	-0.19
Narthecium	56	0.225	-0.114	0.97	-0.21	56	0.489	0.580	0.98	-0.22
& Sphagnum	56	0.248	0.341	0.96	-0.24	56	0.268	-0.577	0.98	-0.20
Eriophorum	55	0.390	0.741	0.97	-0.28	56	0.517	0.425	0.97	-0.18
vaginatum	55	0.328	-0.107	0.97	-0.18	55	0.632	1.01	0.98	-0.27
Sphagnum	56	0.649	1.29	0.98	-0.19	56	0.127	-0.806	0.98	-0.24
	56	0.652	1.15	0.97	-0.24	56	0.137	-1.16	0.96	-0.15

Table 6.2. Results of parameter fitting for specific storage S_w versus phreatic level h (h relative to surface and negative downwards) using Eq. (6.4) for *Clara Bog*. The shaded row marks the lysimeter of which a full graph is shown in Fig. 6.1.

Vegetation dominated by	*n*	*b* (-)	*c* (m^{-1})	*r*	lowest *h* (m)
Calluna, burnt	42	0.314	0.436	0.94	-0.18
	41	0.295	0.602	0.95	-0.32
	41	0.475	1.02	0.97	-0.21
Calluna, "undisturbed"	39	0.251	0.637	0.94	-0.35
	48	0.455	0.514	0.99	-0.41
	33	0.362	0.400	0.96	-0.13
Sphagnum	48	0.134	0.064	0.96	-0.27
	48	0.537	1.03	0.97	-0.19
	42	0.411	0.528	0.95	-0.15
Eriophorum vaginatum	48	0.204	0.184	0.95	-0.22
	43	0.666	1.53	0.97	-0.12
	43	0.136	0.025	0.94	-0.23
Molinia	45	0.476	0.598	0.96	-0.44
	30	0.373	0.458	0.99	-0.43
	38	0.555	0.842	0.97	-0.38

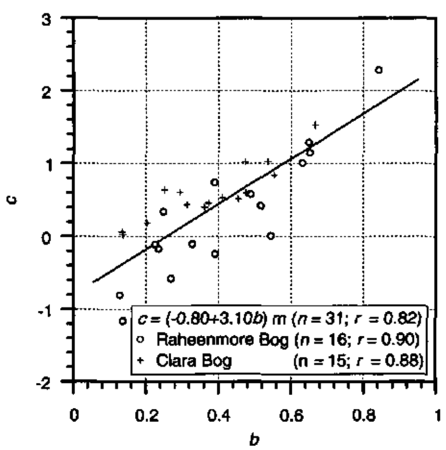

Fig. 6.2. Parameters *b* versus *c* of Eq. (6.4).

The values of *b* vary rather strongly from one lysimeter to another. No correlation was found of the parameters *b* and *c* with vegetation type. However, the values of *b* and *c* themselves are positively correlated as demonstrated by the regression test in Fig. 6.2. Although small differences between the results of Raheenmore and Clara Bog cause a lower overall correlation than for individual bogs, the result is convincing (α<0.001). Its physical meaning is that differences between storage coefficients at different places decrease with increasing depth of the phreatic level. Fig. 6.3 indeed indicates such a relationship, with a minimum bandwidth at a depth of 13-15 cm. Increases at deeper phreatic levels are probably due to limitations of the linear approximation of μ versus h rather than to physical causes.

Except for the deep acrotelms with approximately constant μ, μ decreases from approximately 0.4 at the surface to 0.17-0.19 at a depth of 15 cm. The average storage coefficients in the upper 15 cm generally vary around an average of 0.3, but around 0.4 in deep acrotelms.

The latter result differs little from those of Lammin Suo presented by Vorobiev (1963) and reproduced in Fig. 2.3. However, storage coefficients at depths of 5 cm and less are considerably larger for Lammin Suo. This should probably be attributed to storage in open water that was avoided in the lysimeters. The data from Raheenmore and Clara Bog tend to be larger than those of the lysimeter experiment in the Engbertsdijksvenen in The Netherlands, reported by Schouwenaars and Vink (1992). They found a range of $0.20 \leq \mu \leq 0.33$ for the depth range of 0-10 cm. A μ of 0.16 at a depth of 20 cm can be derived from their data. The difference may be due to the fact that Engbertsdijksvenen is a cutover raised bog with only a small (12 ha) uncut but damaged core.

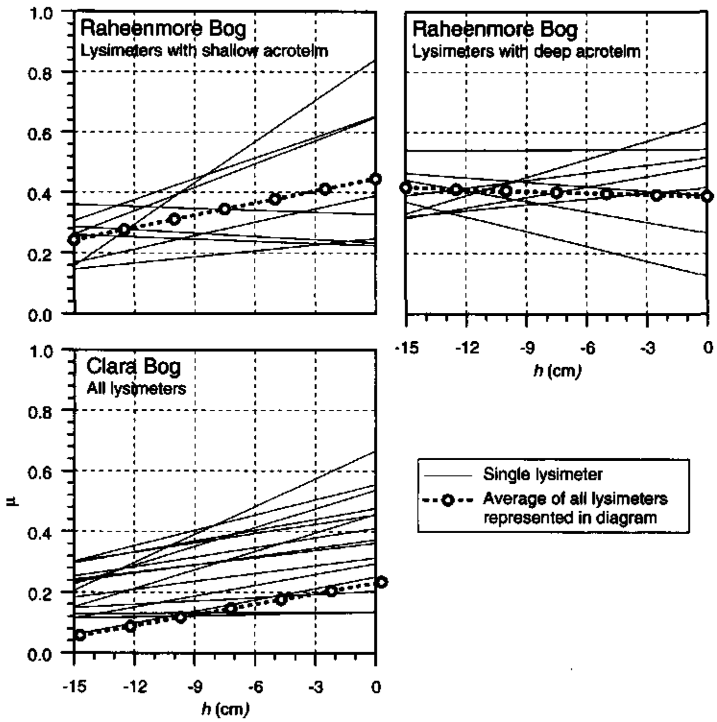

Fig. 6.3. Storage coefficient μ derived from the fitted Eq. (6.5), versus phreatic level h for all lysimeters.

6.2.3. Storage coefficients from rain gauge and phreatic level recordings

Introduction

Areal storage coefficients can be calculated from the water balance of short periods with large precipitation sums. If water losses are neglected, the storage coefficient μ can be estimated from

$$\mu \approx \frac{P^*}{\Delta h} \tag{6.6}$$

where

P^* = precipitation sum over the observed time interval [L]

Δh = the change in phreatic level over the same time interval [L]

There are three sources of error when Eq. (6.6) is applied:

- Water losses during precipitation that are not negligibly small compared to P^*;
- Instrumental errors;
- Storage in the unsaturated zone.

If water losses during the observed period are not negligibly small, μ is overestimated. During periods of large precipitation, covering a short period of time such as a day, lateral discharge through the acrotelm or by open water on the bog surface constitutes the main loss. The loss increases with increasing h, as a result of increasing T_a (*cf.* 6.3.3). In the summer, evapotranspiration and storage in the shallow unsaturated zone may also cause an overestimation of μ. To limit overestimation to an acceptable level, Eq. (6.6) should only be applied on periods of up to 24 hours with more than 10 mm of rainfall, if the level recorder(s) show(s) a clear reaction.

Instrumental errors may cause random errors of μ. Rain gauges usually do not cause large errors, unless the electrical or mechanical system has developed a failure. Such failures are detected easily when the results of the recording gauge are compared with those of one or more nearby storage gauges with manual readout. Because all data have been checked with those from two hand gauges installed within 50 m of each recording gauge, this kind of error in the checked data may be ruled out. Level recorders cause more serious errors. The types applied had a float and counterweight system, in which hysteresis, caused by the starting torque on the pulley may have caused recording errors of some mm (Van der Schaaf, 1984). Although allowable in the vast majority of hydrological applications, such behaviour may result in relatively large errors when μ is as large as in raised bogs. This is another reason why only short periods with $P^*>10$ mm should be considered for estimating μ. In summer periods, storage in the shallow unsaturated zone may even necessitate considerably larger minimum values, such as 15-20 mm.

Because large lateral discharges and large μ usually occur simultaneously at high phreatic levels, special care must be taken in such situations. However, also in less extreme situations errors occur easily and a considerable number of measurements is needed to obtain a reasonably reliable relationship of h and μ.

Raheenmore Bog

The groundwater level recorder RHG1 on Raheenmore Bog was installed in the area of the system of old infilled drains shown in Fig. 3.4. The area has a degraded acrotelm in its lower parts, usually with humification H>4 at the surface (details are given by Van 't Hullenaar and Ten Kate, 1991). The microrelief is smaller than in the more intact parts of the bog. Hence, the local surface level at the recorder site (the average of the surface levels at the four corners of the 0.5m x 0.5m recorder table) is relatively well defined.

The calculation of μ from Eq. (6.6) usually gave values well above 1 when the phreatic level rose to less than about 2 cm below the surface, indicating the occurrence of sheet flow. This phenomenon was also observed visually on several occasions and at several places with degraded acrotelms on both Clara and Raheenmore Bog. When phreatic levels remained more than 3 cm below the surface, the phenomenon could rarely be found in the data of RHG1. Fig. 6.4 shows μ versus h.

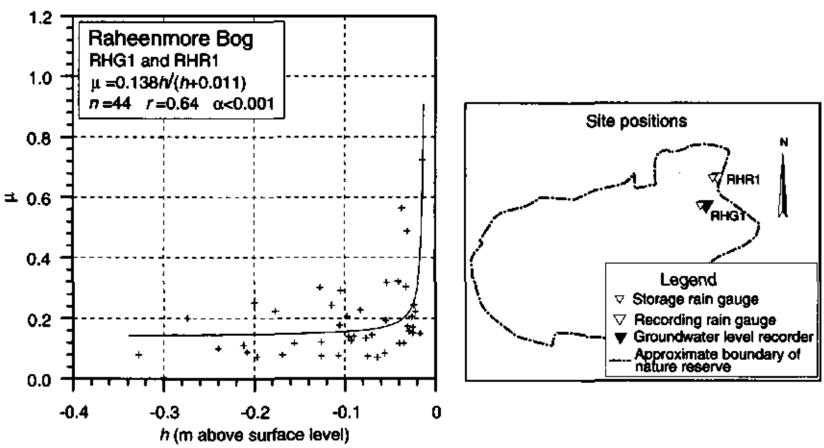

Fig. 6.4. Storage coefficient μ versus phreatic level h for groundwater level recorder site RHG1 and recording rain gauge RHR1 (*Raheenmore Bog*).

The fitted curve is of the type $y = \frac{ax}{x+b}$. It allows a better fit to the sudden transition at the surface than a 2nd or 3rd degree polynomial. The value of the correlation coefficient r (0.64) reflects the scatter of the data points. However, the statistical significance of the existence of a relationship (α<0.001) is strong. The diagram shows a rather constant level of $\mu \approx 0.15$-0.16 at depths below 0.1 m and a sharp increase at levels less than a few cm below the surface. The values at depths below 0.05 m are slightly smaller than those shown for depths of 0.15-0.20 m in Fig. 6.3, except for the lysimeters with a deep acrotelm. Thus Fig. 6.4 shows the behaviour of the relationship of μ versus h under degraded acrotelm conditions where the storage properties, normally present at depths of more than 15-20 cm, extend to the surface.

Clara Bog

Data from three recorder sites on Clara Bog, CWG1, CWG2 and CWG3 are available, each representing different conditions. Results and locations are shown in Fig. 6.5.

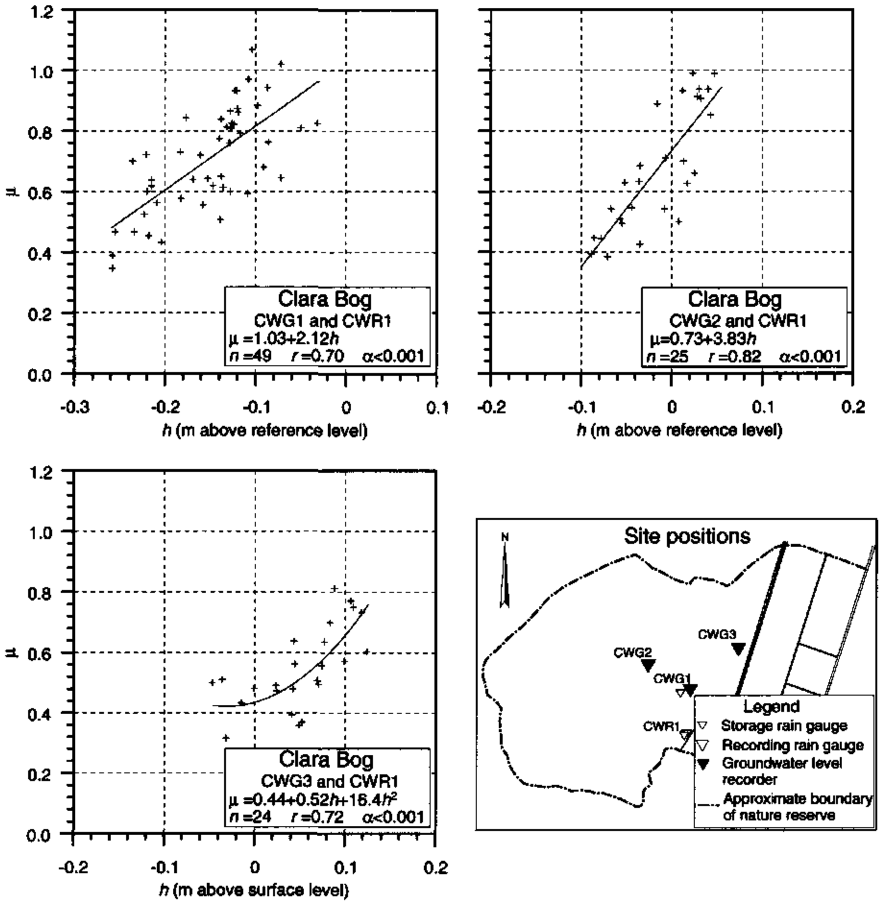

Fig. 6.5. Storage coefficient μ versus phreatic level h for groundwater level recorder sites CWG1, CWG2 and CWG3 and recording rain gauge CWR1 (*Clara Bog*).

Site CWG1 is located in the soak system of Shanley's Lough. It was in operation from September 1990 to July 1993. It was installed in a pool to monitor the fluctuation of the water level in the soak system and actually measured open water levels in a pool. The reference level is the surface at a piezometer site, positioned about 6 m south-west of the recorder on top of a hummock. Thus the value of h in the relationship $\mu(h)$ is relative to a rather arbitrary level. The large proportion of open water is reflected in the level of the fitted line, which approaches 1 at h=0, indicating complete inundation. Two data points with calculated μ>1 have not been removed, because their existence is a logical consequence of the scatter of the calculated μ, even though such values are physically impossible.

Site CWG2 was installed in an area with a rather uniform hummock and hollow microtopograpy. It was operational from May 1992 until the end of July 1993. Its reference level was the average of the levels right below the four corners of the square (50 x 50cm^2) recorder table.
The area had many pools that kept containing water during the summers of 1992 and 1993. This explains the high average μ. The relatively steep slope of the line compared to the one of CWG1 is probably caused by the much more uniform height and shape of the hummocks in the area compared to the more diverse conditions around Shanley's Lough.

Site CWG3 was installed in a transitional position between a hummock and hollow complex and a drier area. The reference level was determined in the same way as for CWG2. It was operational over the same period as CWG2. A second-degree polynomial gave a better correlation than a straight line (r=0.72 versus r=0.65). The near horizontal part of the curve, indicating the absence of water filled pools at corresponding phreatic levels, lies near the average value of μ, found in the lysimeter tests for depths of less than 3-4 cm. This result confirms the value of $\mu \approx 0.4$ in a well developed acrotelm where the phreatic level is not more than a few cm below the surface and in the absence of nearby open water.

6.2.4. Conclusions

- At the top of an acrotelm with a low degree of humification (H<4) and without open water, the storage coefficient μ has a value around 0.4;
- In more humified material (H>4) in degraded acrotelms and at the transition to the catotelm, the value of μ generally lies between 0.15 and 0.20;
- In the presence of open water, areal μ-values are considerably larger than 0.4. At the highest water levels, values of 0.8 and above may occur;
- No correlation between μ and vegetation was found;

- In areas with severely degraded acrotelms, sheet flow is common when high rainfall and near-surface phreatic levels occur simultaneously. When sheet flow occurs, μ is hard to measure, but under such circumstances it is a rather irrelevant quantity.

6.3. Acrotelm transmissivity

6.3.1. Introduction

The positions of the measuring pits on Raheenmore Bog and on Clara Bog West are shown in Figs. 3.22 and 3.23, respectively. The pits on Clara Bog East were restricted to the plots A, B and C (positions shown in Fig. 3.8). The test pits were made at a distance of about 5 m or less from the dip wells; one in a hummock and one in a hollow position near each of the three wells between the drains.

Because no established field method was available for measurements of acrotelm transmissivity T_a, three different methods were applied to elaborate the data from the acrotelm pits. In this section the results of the different methods are compared and a final selection of methods is made. Two models for the relationship of T_a and phreatic level h are examined to find to what extent h regulates T_a. The effect of T_a on discharge Q_a is also examined. This links h and Q_a, demonstrating the self-regulating mechanism that reduces discharge from a raised bog when the phreatic level falls. The section ends with a discussion on another self-regulating mechanism: acrotelm transmissivity as regulated by hydraulic gradient, flow pattern and climatic conditions.

6.3.2. Comparing methods.

Modifications to methods

The applied methods were the semi-steady state method, described in 3.14, the modified pit bailing method, also described in 3.14 and the piezometer method.

The usage of the latter was inspired by the similarity between Eqs. (3.4) and (3.26). The piezometer method was applied on the same data sets as the pit bailing method. To be applicable in this special situation, the equation for the piezometer method needs two modifications:

- The shape factor A_p has to be adjusted for "cavities" (pits) that extend upwards to the phreatic level;
- The piezometer method yields the saturated hydraulic conductivity k_a of the acrotelm instead of T_a. The obtained value of k_a must be multiplied by the wetted acrotelm depth (acrotelm depth below the phreatic level) in order to obtain an acrotelm transmissivity T_a.

For this special situation A_p can be derived from the tables of Youngs (1968) as follows.

The length of the cavity L_c (Fig. 3.18) is identical to the wetted length of the pit. If the capillary fringe above the phreatic level is neglected, the upper end of the cavity (pit) and the phreatic level coincide. Hence

$$L_w \approx 0 \qquad (6.7)$$

Because the measurements were made in pits with a depth of at least 40 cm and acrotelm depths D_a rarely exceeded 40 cm, the assumption of an impervious layer immediately below the pit is reasonable. Therefore d_{imp}= 0 was assumed.

Youngs' tables give ratios of $\frac{A_p}{r_c}$ for $\frac{L_w}{r_c} = 4, 8, 12, 16$ and 20. These values can be extrapolated for $L_w = 0$. Youngs' values of $\frac{A_p}{r_c}$ for d_{imp}= 0 show an almost perfect fit to the model

$$\frac{A_p}{r_c} = a + b\exp\left(c\frac{L_w}{r_c}\right) \qquad (6.8)$$

where *a*, *b* and *c* are dimensionless model parameters.

$\frac{A_p}{r_c}$ was extrapolated for $\frac{L_c}{r_c} = 1, 2, 4$ and 8, using Eq. (6.8). The range of $\frac{L_c}{r_c}$ in the pits was about 1.5-5, which is well within the range of 1 through 8. $\frac{A_p}{r_c}$ for intermediate values of $\frac{L_c}{r_c}$ was interpolated using a third degree curve, fitted through the four points.

The wetted acrotelm depth was assumed to be equal to L_c. Although this may seem arbitrary at first sight, the assumption is reasonable because errors are to a large extent compensated for by the estimated shape factor A_p, which itself is a function of the wetted length. Hence

$$T_a \approx k_a L_c \qquad (6.9)$$

where

k_a = the saturated hydraulic conductivity of the acrotelm (obtained from the piezometer method equation) [LT^{-1}]

During the first tests on Raheenmore Bog, the pit bailing method as modified in 3.14.3 was used only when the value of T_a was too small to reach "steady" state. Later it was also used as a recovery method in addition to the semi-steady state method. The equation of the piezometer method was applied to all data sets obtained from the pit bailing method, including the recoveries. This allows all three methods to be compared. Measuring intervals were 5-60 s, depending on the speed of recovery. No test took more than six minutes of pumping and recovery.

Although Eq. (3.20) implies that the sensitivity of T_a to the value of the storage coefficient μ is not very large, μ was made dependent on the phreatic level. For levels at the surface, a value of 0.3 was assumed, linearly decreasing to 0.1 for a depth of 30 cm. This is less than derived in 6.2, but lysimeter tests on Raheenmore Bog by Sijtsma and Veldhuizen (1992) showed that short-term changes (e.g. adding or removing water in lysimeters) yield such values of μ.

Results

The diagrams in Fig. 6.6 (Raheenmore Bog), Fig. 6.7 (Clara West) and Fig. 6.8 (Clara East) allow a comparison of the methods. Because of the large range of T_a, $\log_{10}T_a$ (formally $\log_{10}\frac{T_a}{\mathrm{m^2d^{-1}}}$) is shown. The regression lines were obtained by means of the MRA method, described in 5.3.2.

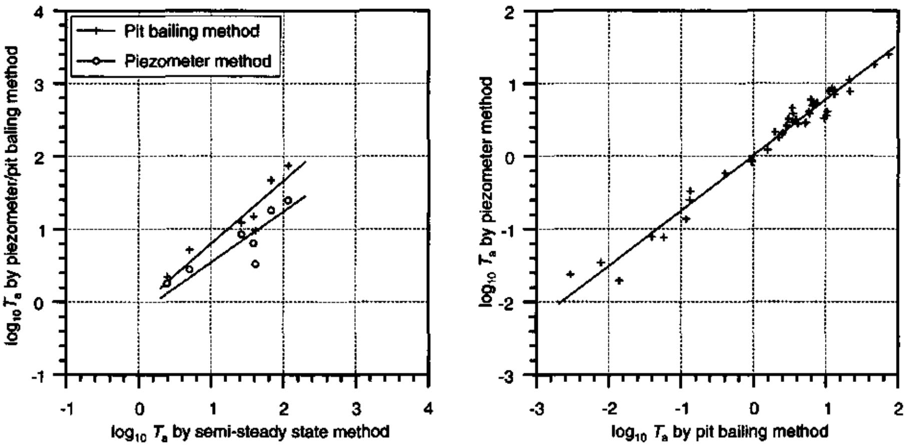

Fig. 6.6. Results of three methods for *Raheenmore Bog*: pit bailing and piezometer method versus semi-steady state method (left hand diagram) and piezometer method versus pit bailing method (right hand diagram).

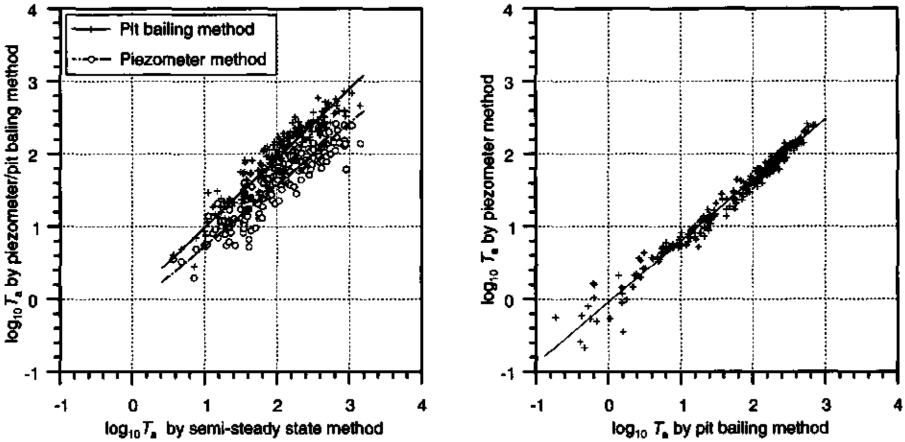

Fig. 6.7. Results of the three methods for *Clara Bog West*: pit bailing and piezometer method versus semi-steady state method (left hand diagram) and piezometer method versus pit bailing method (right hand diagram).

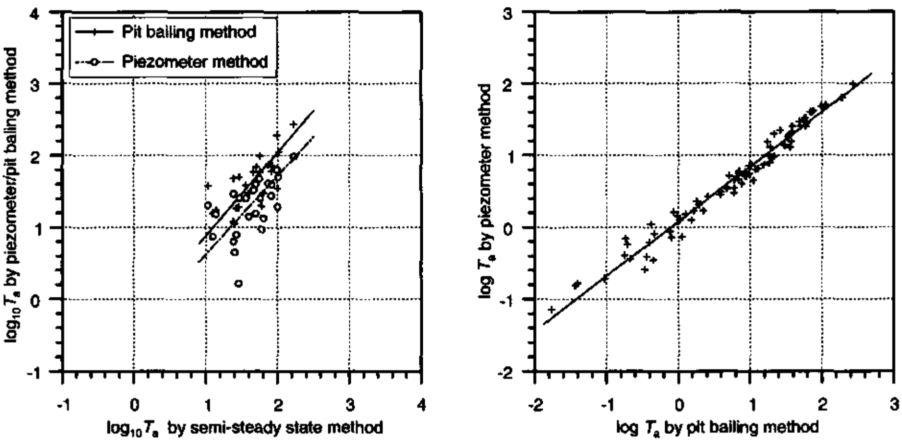

Fig. 6.8. Results of the three methods for *Clara Bog East*: pit bailing and piezometer method versus semi-steady state method (left hand diagram) and piezometer method versus pit bailing method (right hand diagram).

Results of the statistical analysis are given in Table 6.3.

Table 6.3. Results of significance tests for the diagrams of Fig. 6.6, Fig. 6.7 and Fig. 6.8 with model parameters and their 95% confidence bounds. $T_{a_{ss}}$ stands for acrotelm transmissivity based on the semi-steady state method, $T_{a_{pb}}$ for acrotelm transmissivity based on the pit bailing method and $T_{a_{pz}}$ for acrotelm transmissivity based on the piezometer method.

Model	$\log_{10}\frac{T_{a_y}}{\mathrm{m\,d^{-1}}} = a + b\log_{10}\frac{T_{a_x}}{\mathrm{m\,d^{-1}}}$									
Bog	*n*	*r*	*F*	*α*	95% lower	*a* estim.	95% upper	95% lower	*b* estim.	95% upper
Raheenmore; $T_{a_{pb}}$ vs. $T_{a_{ss}}$	7	0.931	32.3	0.002	-0.50	-0.07	0.36	0.58	0.87	1.15
Raheenmore; $T_{a_{pz}}$ vs. $T_{a_{ss}}$	7	0.868	15.2	0.011	-0.58	-0.12	0.33	0.38	0.68	0.99
Raheenmore; $T_{a_{pz}}$ vs. $T_{a_{pb}}$	42	0.973	713	<0.001	-0.05	0.02	0.06	0.75	0.81	0.86
Clara West; $T_{a_{pb}}$ vs. $T_{a_{ss}}$	171	0.941	1304	<0.001	-0.07	0.04	0.14	0.90	0.95	1.00
Clara West; $T_{a_{pz}}$ vs. $T_{a_{ss}}$	171	0.919	914	<0.001	-0.22	-0.12	0.01	0.79	0.85	0.90
Clara West; $T_{a_{pz}}$ vs. $T_{a_{pb}}$	225	0.986	5811	<0.001	-0.08	-0.04	-0.01	0.82	0.84	0.86
Clara East $T_{a_{pb}}$ vs. $T_{a_{ss}}$	25	0.715	24.1	<0.001	-0.83	-0.27	0.28	0.82	1.16	1.49
Clara East; $T_{a_{pz}}$ vs. $T_{a_{ss}}$	25	0.633	15.4	<0.001	-1.04	-0.46	0.12	0.74	1.09	1.43
Clara East; $T_{a_{pz}}$ vs. $T_{a_{pb}}$	81	0.986	2762	<0.001	0.05	0.08	0.11	0.73	0.76	0.79

Generally, the relationships show a good level of significance with the exception of those with the semi-steady state method on Raheenmore Bog, where only 7 data sets were available and where the level of significance is good to moderate and on Clara East, where the correlation coefficients are not very high.

Discussion

Transmissivities obtained from the pit bailing method and the semi-steady state method show a near 1:1 relationship over the analysed range. For high levels of T_a, the piezometer method yields smaller values of T_a than the pit bailing and the semi-steady state method. For the lowest levels, larger values of T_a are obtained from the piezometer method. A likely explanation is the following.

The equation for the piezometer method as modified for acrotelm tests reads

$$T_a(t) = \frac{\pi r_w^2 L_c}{A_p} \frac{\mathrm{d}}{\mathrm{d}t}\left(\ln\frac{y_{w0}}{y_w(t)}\right) \tag{6.10}$$

Eq. (3.26), developed for the pit bailing method when n_w may be assumed independent of t (but with unknown value), can be modified for possible non-linearities in the flow system during the test to:

$$T_a(t) = \frac{r_w^2 \ln n_w}{2} \frac{d}{dt}\left(\ln \frac{y_{w0}}{y_w(t)} \right) \tag{6.11}$$

Substitution of T_a yields an expression for A_p:

$$A_p = \frac{2\pi L_c}{\ln n_w} \tag{6.12}$$

which proves that a time independent shape factor A_p implies a time independent n_w. This assumption is reasonable for a medium where the storage coefficient around the cavity is negligibly small. In an acrotelm, a large storage coefficient occurs as was demonstrated in 6.2. Consequently, n_w is time dependent in acrotelm transmissivity tests, because such tests affect the shape of the phreatic surface.

The larger T_a, the wider and flatter is the depression cone around the pit. Consequently, n_w increases more rapidly in time with larger than with smaller T_a. If any time independent n_w is assumed in a test, T_a will be underestimated when the real n_w is larger and overestimated when it is smaller. Contrary to the piezometer method, the modified pit bailing method accounts for the change of n_w during the test. Hence the piezometer method may indeed be expected to underestimate large and overestimate small T_a in comparison with the modified pit bailing method.

The modified pit bailing method tends to give slightly smaller results than the semi-steady state method. The upper bound of the 5% confidence interval for the regression coefficient b for Clara Bog West, far and away the narrowest of the three, is 1.00 and is not contradicted by the other two. Considering the implicit assumption of instantaneous release of water from storage during the test and knowing that in reality some water will be released with a certain delay, this is a remarkable result. The effective storage coefficient may be expected to increase slightly during the test. This would cause an opposite effect: an underestimation of T_a during the first part of the test and/or an overestimation during the last part. Hence, the pit bailing method may be expected to yield slightly larger values of T_a than the semi-steady state method.

This unexpected behaviour is probably caused by the flexibility of the peat matrix. The suction induced by pumping from the pit may cause a temporary decrease in the apparent hydraulic conductivity k, similar to changes observed in piezometer tests. This effect was observed in a considerable part of the measurements. When a reduction of apparent k occurred, it rarely was instantaneous. It usually took between some tens of seconds and a few minutes to develop.

In some recovery tests, mostly with relatively small T_a, a sharp decline in the apparent T_a was calculated for time intervals during the recovery, some time after the pumping had been stopped. For such tests, only those intervals were used for which $\ln\frac{y_{w0}}{y_w(t)}$ versus t produced an approximately straight line (*cf.* Fig. 3.19) and before the decline in apparent T_a occurred. Sometimes an increase in apparent T_a followed when the gradient towards the pit had become small. In other tests, the apparent T_a increased during the entire recovery, indicating that a minimum of k had been reached during semi-steady state. This may explain why results of the semi-steady state method give a better correlation with results of the pit bailing method than with those of the piezometer method. Two examples from data collected on Clara West in November 1992 are shown in Fig. 6.9.

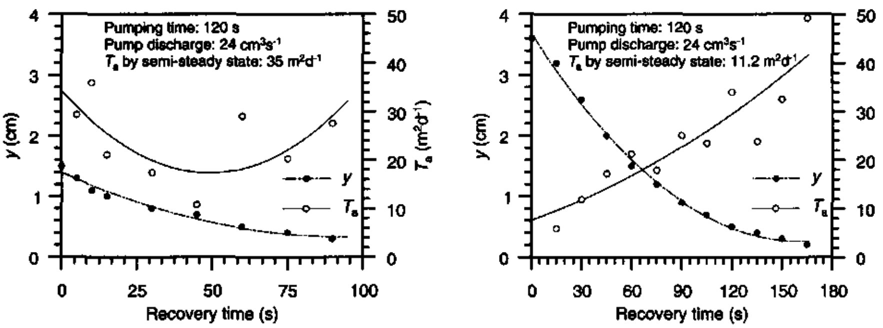

Fig. 6.9. The change of apparent T_a during recovery (modified pit bailing method). Data points and fitted 2nd degree polynomials. Left: minimum occurring during recovery, right: minimum during semi-steady state.

Because the effect, when it occurred always began some time after the beginning of the pumping, it is more likely to affect results of the recovery than of the preceding semi-steady state measurement, which usually took between about 15 and 180 seconds. The smaller pumping times coincided with large T_a because of the larger pumping rate applied. The decrease in apparent T_a was indeed observed more often during recovery with large than with small T_a.

Conclusions

- The piezometer method is likely to underestimate large T_a and to overestimate small T_a. A 1:1 ratio with the pit bailing method exists when T_a is in the order of magnitude of 1 $m^2 d^{-1}$;
- The pit bailing method and the semi-steady state method gave reasonably comparable results, with the pit bailing method tending to give slightly smaller values. When large differences between both occur during a single test, a temporary reduction in

apparent T_a as a result of the flexible peat matrix and the lowering of the water table in the pit is the likely cause;

- In view of the previous two points, the steady state method and the pit bailing method were adopted as approximately equivalent standard methods. Where both methods were applied during a test, the largest resulting value of T_a is likely to be the best choice.

6.3.3. Acrotelm transmissivity and phreatic level

Introduction

As pointed out by Russian authors in particular (Ivanov, 1953, 1957, *cit.* Romanov, 1968; Ivanov, 1981; Romanov, 1968), the hydraulic conductivity k in the acrotelm decreases strongly with increasing depth. In section 2.8, Ivanov's equation was integrated to obtain a relationship between the phreatic level h and T_a (Eqs. 2.5 and 2.6). T_a can be measured more easily than k, because the latter changes considerably over vertical distances of a few centimetres. T_a is also more relevant to flow processes at the scale levels of a microlandscape or a bog than k.

Measurements of T_a on the networks of Raheenmore Bog and Clara West were repeated several times with different phreatic levels. Thus it was possible to test whether Ivanov's equation, originally developed for continental bogs, is applicable under Irish raised bog conditions. The largest number of tests at a single site was 8 on Clara Bog West. Available time allowed only 5 tests at a limited number of sites on Raheenmore Bog.

Models

Because two degrees of freedom are involved in fitting Ivanov's equation, data from sites with at least 5 observed values were used in order to keep the number of degrees of freedom in the residual larger than the number involved in the model. Sometimes the fitting process yielded poor levels of significance, mostly coinciding with values of less than 2.5 for the model constant m_l. This value is rather small to satisfy the assumptions underlying the simplification from Eq. (2.5) to (2.6). Therefore, in addition to Ivanov's model, a logarithmic model was fitted of the form

$$\log_{10}\frac{T_a}{\mathrm{m^2d^{-1}}} = a_{lm} + b_{lm}\frac{h}{\mathrm{cm}} \qquad (6.13)$$

where

h = phreatic level relative to the surface (negative if below the surface) [T]

a_{lm} = regression intercept of the logarithmic model [1]

b_{lm} = regression coefficient of the logarithmic model [1]

For reasons of comparability of significance levels, the Ivanov parameters were fitted to

$$\log_{10}\frac{T_{\mathrm{a}}}{\mathrm{m^2d^{-1}}} = \log_{10}\left(\frac{8.64\dfrac{a_{\mathrm{I}}}{\mathrm{cm\ s^{-1}}}(1-\dfrac{h}{\mathrm{cm}})^{1-m_{\mathrm{I}}}}{m_{\mathrm{I}}-1}\right) \tag{6.14}$$

which is Eq. (2.6) in a logarithmic form. T_{a0} is the acrotelm transmissivity when h=0. From Eq. (6.13) follows:

$$\log_{10}\frac{T_{\mathrm{a0}}}{\mathrm{m^2d^{-1}}} = a_{\mathrm{lm}} \tag{6.15}$$

a_{I} is identical to the hydraulic conductivity of the acrotelm material at zero depth. In Ivanov's equation it is expressed in $\mathrm{cm\,s^{-1}}$. To maintain compatibility with values of the parameters a_{I} and m_{I} in other publications, this "convention" is kept.

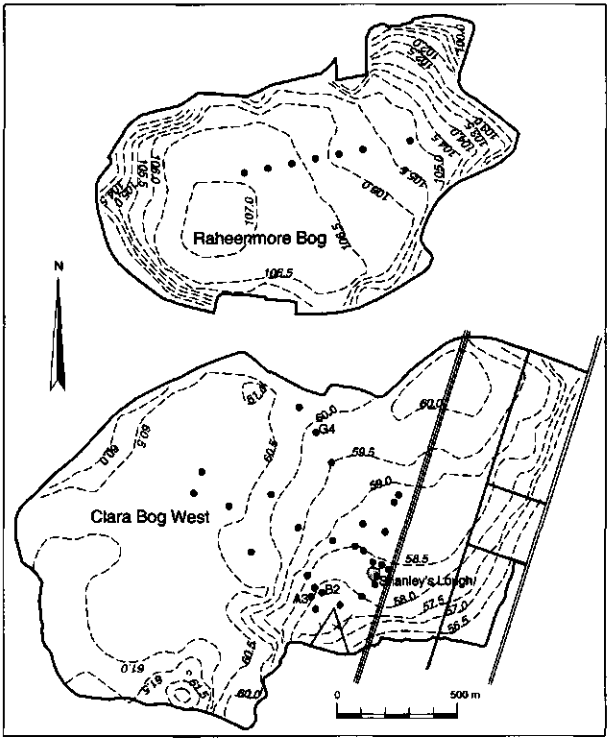

Fig. 6.10. Positions of acrotelm pits (black dots) with at least 5 measured values of the acrotelm transmissivity T_{a}. Fitted curves of the sites on *Clara West*, marked "A3", "B2" and "G4" are shown in Fig. 6.11.

Results

The positions of the sites are shown in Fig. 6.10.

Table 6.4 gives ranges of the phreatic level h at the tests and of measured T_{a}. T_{a} varies by 1-2 orders of magnitude when h fluctuates by about a dm and by 2-3 orders of magnitude between sites. Considering that no measurements were carried out at the highest phreatic levels because of overflow in too many pits, it is clear from Table 6.4 that values of T_{a} well above 1000 $\mathrm{m^2d^{-1}}$ are not unusual on days with high phreatic levels.

Table 6.4. Ranges of phreatic level h at measurements of acrotelm transmissivity T_a, ranges of T_a measured and average ratios of measured T_a at highest and lowest phreatic level.

Bog	Number of sites	Data per site (average)	h (cm above surface) range of max.	range of min.	T_a measured (m^2d^{-1}) range at max. h	range at min. h	$\frac{T_a \text{ at max } h}{T_a \text{ at min } h}$ average over sites
Raheenmore	7	5	0.0...-7.0	-6.3...-20.4	6.3...1350	0.13...22	50
Clara West	28	5.7	0.0...-7.7	-4.4...-17.7	23...4000	0.7...320	39

For a large majority of sites, the models developed in this section could be fitted with a reasonable level of statistical significance, even with the limited number of data per site. Table 6.5 gives results. It shows that the F-test yielded better levels for the logarithmic than for Ivanov's model.

Table 6.6 gives averages and standard deviations of fitted model parameters of both the Ivanov and the logarithmic model with a level of significance better than 0.1. For better comparability of a_I and a_{lm}, $\log_{10}a_I$ (formally: $\log_{10}\frac{a_I}{\text{cm}}$) instead of a_I is used.

Table 6.5. Median values and distribution of significance levels α based on the F-test in three classes for Ivanov's model (Eq. 6.14) and the logarithmic model (Eq. 6.13). 7 data sets are from Raheenmore Bog and 28 from Clara West.

Model	n	median of α	α>0.1	0.1<α<0.01	α<0.01
Ivanov	35	0.037	9	19	7
Logarithmic	35	0.015	5	17	13

Table 6.6. Averages and standard deviations of fitted parameters of the Ivanov model ($\log_{10} a_I$ and m_I) and the logarithmic model (a_{lm} and b_{lm}).

		Ivanov model		Logarithmic model	
Bog	Quantity	$\log_{10} a_I$	m_I	a_{lm}	b_{lm}
	average	2.73	3.40	2.24	0.138
Raheenmore	standard dev.	1.48	1.27	0.75	0.036
	n	5		7	
	average	3.02	2.94	3.14	0.161
Clara West	standard dev.	1.25	0.88	0.84	0.070
	n	21		23	

The mean of 500-1000 cm s^{-1} of a_I that can be derived from Table 6.6 is smaller than values of some bogs in the former Soviet Union presented by Romanov (1969) and two values of Dun Moss presented by Ingram and Bragg (1984), which have an average around 3000 cm s^{-1}. m_I is in good agreement with the values presented by these authors. Considering that a_I in Table 6.6 has been calculated as a geometric mean, which is more sensitive to small values than an arithmetic mean and that it includes data from sites with poor acrotelm conditions, the result must be judged as being in reasonable agreement with others.

a_I is sensitive to small errors in the surface level because of the curvature of the fitted curve between depths of approximately 0-2 cm. The logarithmic model is not sensitive to such effects as can be seen in Fig. 6.11, that shows three diagrams with fitted lines for both models.

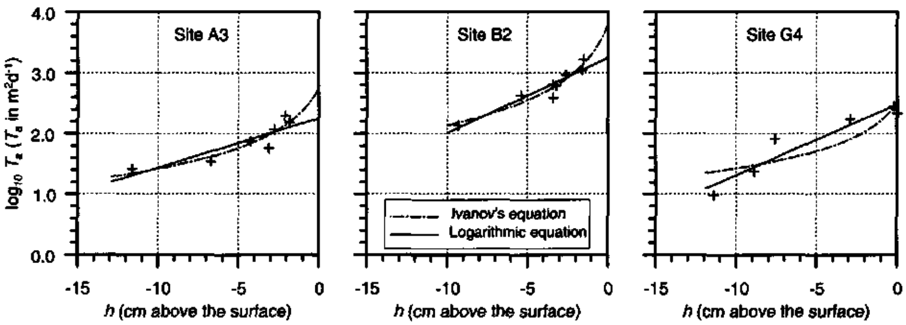

Fig. 6.11. Examples of relationships of $\log_{10} T_a$ versus h with fitted logarithmic and Ivanov models (Eqs. 6.13 and 6.14, respectively). The F-test gives a better fit of Ivanov's equation than for the logaritmic one for site A3, an equally good fit for B2 and a better fit of the logarithmic model for G4. Site positions are shown in Fig. 6.10.

Discussion

Fig. 6.11 demonstrates that Ivanov's equation probably is more suitable than the logarithmic model to fit extremely large hydraulic conductivities at the bog surface, assuming such values occur. Occasionally extremely high values for the parameter a_I were extrapolated that can hardly occur with subsurface flow. This is also indicated by the standard deviations of $\log_{10} a_I$ in Table 6.6. Values of 10^3 cm s^{-1} correspond to an effective pore radius of approximately 3 mm, as can be derived from Poiseuille's law[1]. Such a pore size must be close to the maximum possible value in freshly formed acrotelm

---

[1] For the flow rate Q at laminar flow through a circular pipe with radius R, Poiseuille's law states that $Q = -\frac{\pi R^4}{8\eta}\rho g \frac{dh}{dx}$, where η is the dynamic viscosity of the liquid [ML^{-1}T^{-1}]. Using Darcy's law, the "hydraulic conductivity" k of the pipe may be expressed as $k = \frac{R^2 \rho g}{8\eta}$ and hence $R = \sqrt{\frac{8k\eta}{\rho g}}$. For water of 10°C, $\eta \approx 1.3 * 10^{-3}$ Pa s. Consequently, for k=10 m s^{-1}, R≈3 mm.

material. Consequently, larger values of a_I than 10^3-10^4 cm s^{-1} are unlikely to be realistic. This means that the value of some extremely large extrapolated values of a_I may indeed be too high.

The logarithmic model does not give this "overshoot" at the surface, but it gives a stronger decrease of T_a with increasing depth than Ivanov's model. In 5.4 the conclusion was drawn that catotelm transmissivities lie at or -more often- below 1 m^2 d^{-1}. When T_a was calculated for a phreatic level of 1 m below the surface for the sites with a statistically significant result (α<0.1), the Ivanov model yielded a realistic (but not necessarily correct) geometric mean of 0.47 m^2 d^{-1} and the logarithmic model an unrealistic one of 2.4*10^{-13} m^2 d^{-1}. This means that the logarithmic model is restricted to the range of small depths it was fitted for.

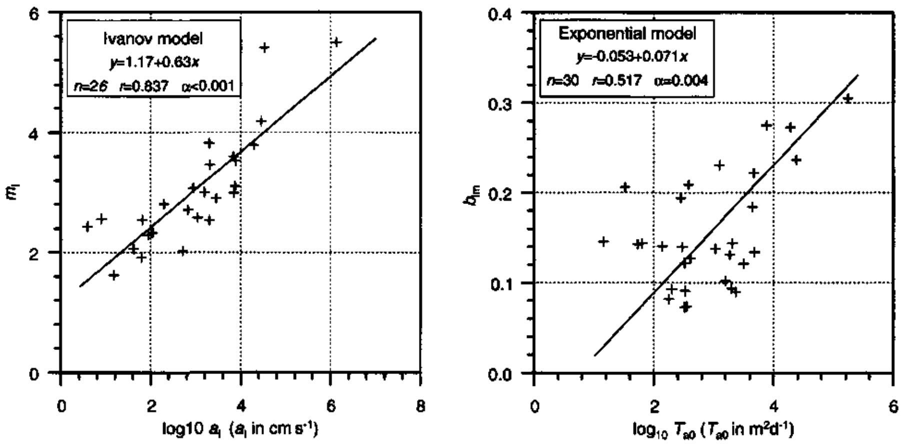

Fig. 6.12. Ivanov model parameter m_I versus $\log_{10}a_I$ and the logaritmic model parameters b_{lm} versus a_{lm} (as T_{a0}). Lines fitted by the RMA-method.

For Ivanov models, fitted by Sijtsma and Veldhuizen (1992) and Van der Cruysen *et al.* (1993) for sites on Raheenmore Bog and Clara West with similar vegetation, Van der Schaaf (1999) found that log a_I and m_I were positively correlated. The physical meaning is that in an acrotelm with a large k at and just below the surface, k declines faster with increasing depth than in an acrotelm with a small k at the surface. One may wonder whether such a relationship also exists for a_I and m_I derived for individual sites (as was done in this section) and for the parameters a_{lm} and b_{lm} of the logarithmic model. Fig. 6.12 shows diagrams for the sites where the models gave a statistically significant relationship (α<0.1). They show a statistically significant relationship for both models, with a considerably higher correlation for the Ivanov parameters than for those of the logarithmic model. The relationships also seem to be stronger for large than for small parameter values.

A practical test is a comparison of standard deviations around the mean of log T_a, obtained at different phreatic levels h for a number of sites. A complicating factor is the increasing difference between phreatic levels at different places when their average falls, caused by the decrease of the storage coefficient with falling h. Measured T_a of different days with a reasonable difference in average h and a reasonable number of measured sites were used. Table 6.7 gives results.

Table 6.7. Average phreatic levels $\bar{h}$ in acrotelm pits, their sample standard deviations s_h, the average value of the logarithm of measured acrotelm transmissivity $\overline{\log_{10} T_a}$ and its sample standard deviation $s_{\log_{10} T_a}$ for the two bogs.

Date	$\bar{h}$ (cm)	s_h (cm)	$\overline{\log_{10} T_a}$	$s_{\log_{10} T_a}$
		Raheenmore Bog (n=17)		
5th June 1991	-14.0	4.9	0.69	1.02
1st November 1991	-4.5	3.2	1.77	0.67
19th November 1991	-3.7	2.9	1.86	0.69
		Clara Bog (n=15)		
22nd March 1993	-11.4	3.0	1.47	0.67
4th November 1992	-7.5	2.2	2.32	0.44
16th November 1992	-5.4	2.2	2.54	0.46
8th December 1992	-3.2	1.9	2.67	0.53

The effect indeed seems to exist at depths of less than 10 cm. Whether the increase of the standard deviation of log T_a at deeper phreatic levels is caused by an increasing variation in h or the non-existence of the equalising effect described above is not clear.

Conclusions

- In both Raheenmore Bog and Clara Bog West, the acrotelm transmissivity T_a depends strongly on the phreatic level. A decrease in T_a by more than an order of magnitude may be expected when the phreatic level falls by 10 cm or even less from a few cm below the surface;
- The logarithmic model (log T_a depending linearly on the phreatic level) tends to give a better fit than Ivanov's equation within the range of phreatic levels at which values of T_a were measured. When extrapolated to catotelm levels, the logarithmic model yields unrealistic low values, the Ivanov model gives values in the range calculated in 5.4, which, however, are not necessarily correct. Estimated T_a from both models within the measured range show a highly significant near 1:1 relationship;
- Both models show a statistically significant positive correlation between their own parameters, the Ivanov model in particular. It implies that the spatial variation of T_a

decreases with a falling phreatic level. The effect could be observed, but only for phreatic levels of less than 10 cm below the surface.

6.3.4. Acrotelm transmissivity and discharge

Introduction

In a raised bog, temporal variations in areal discharge must reflect variations in T_a, because the hydraulic gradient in the acrotelm is nearly constant in time. Hourly discharge sums were available of all days on which T_a was measured on one or more sites. Because series of measurements of T_a usually took a full day to make, the results were compared with discharge sums over the period from 6:00 a.m. and 6:00 p.m. The discharge recording sites have been described in 3.15. To test the existence of spatial differences in the correlation, an analysis was made of the relationship of T_a and acrotelm discharge Q_a for individual measuring sites. It is followed by an analysis for the catchments of Raheenmore Bog and Clara West that discharge *via* the stations RHD1 (Raheenmore Bog, position shown in Fig. 3.13) and CWD1 and CWD2 (Clara Bog, positions shown in Fig. 3.14). Catchment sizes, needed to convert Q_a to specific discharge v_a, have been calculated from surface contours by Lensen (1991). He found a size of approximately 30 ha for the catchment on Raheenmore Bog that discharges *via* RHD1 and one of about 100 ha for the catchment on Clara Bog that discharges *via* CWD1 and CWD2. In Chapter 9 it will be shown that these sizes are approximately correct.

The spatial pattern of correlations

Correlation coefficients of T_a and Q_a were calculated for T_a-sites with a reasonable number of measurements. For Clara Bog, the minimum number of data pairs was set at 5, resulting in 28 available sites. For Raheenmore Bog a minimum of 5 would yield only 7 sites. Therefore, also sites with only 4 observed values were included. Consequently, the result for Raheenmore Bog has less significance than the one for Clara Bog. Fig. 6.13 shows the pattern of Raheenmore Bog.

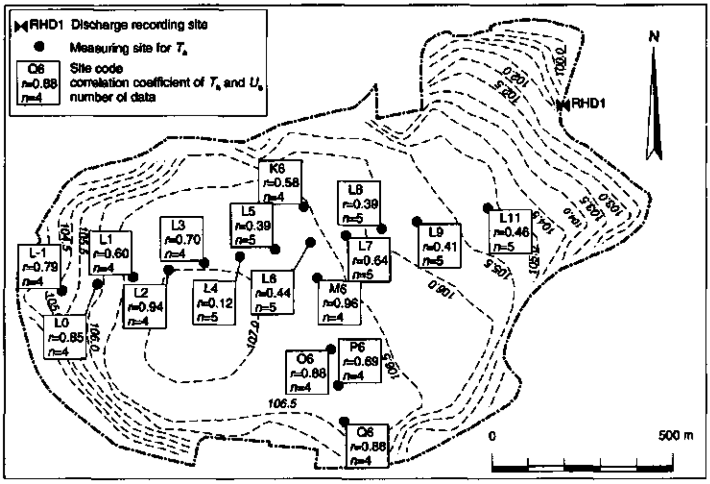

Fig. 6.13. Correlation coefficients of acrotelm transmissivity T_a and acrotelm discharge Q_a on *Raheenmore Bog.*

The correlation coefficients in the central part of the bog are remarkably low, whereas the majority of sites closer to the margin shows relatively high levels of correlation. This was probably caused by a combination of the position of the discharge recording site RHD1 at about 1.5 km from the highest point of the bog and a discharge peak of 7.6 mm d^{-1} on 12th April 1991, falling to 1.5 mm d^{-1} on 16th April when T_a was measured. The central area with a large proportion of well-developed acrotelms (*cf.* 6.4) apparently had not yet released all its excess water, whereas a wide zone along the margin was already back to more average conditions. If the discharge of 16th April is replaced by the one of 13th April (3.8 mm d^{-1}), the pattern of correlation coefficients is almost reversed: the highest correlations occur in the central part and the lower ones closer to the margin (Fig. 6.14).

This demonstrates that the discharge behaviour of the central area of Raheenmore Bog differs from a wide zone along the margin and that correlations of T_a and Q_a should have been based on measurements on days preceded by a few days with little change in discharge. All other measurements of T_a on Raheenmore Bog were indeed made on days with a discharge that had remained rather steady over the preceding days.

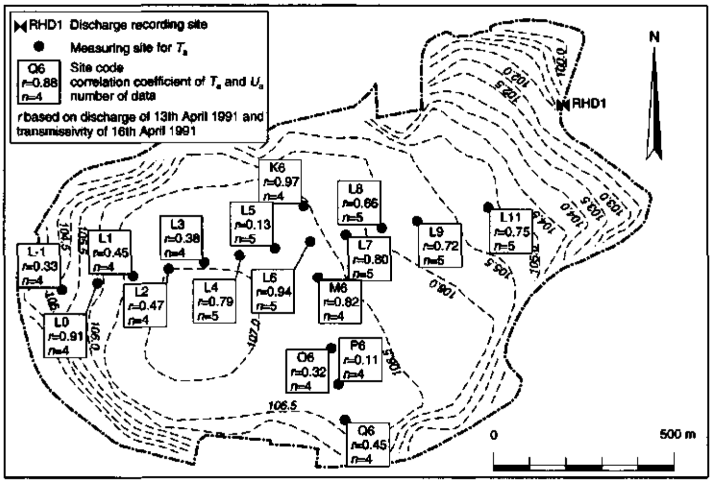

Fig. 6.14. Correlation coefficients of acrotelm transmissivity T_a and acrotelm discharge Q_a for *Raheenmore Bog*; discharge of 16[th] April 1991 replaced by the value of 13[th] April 1991.

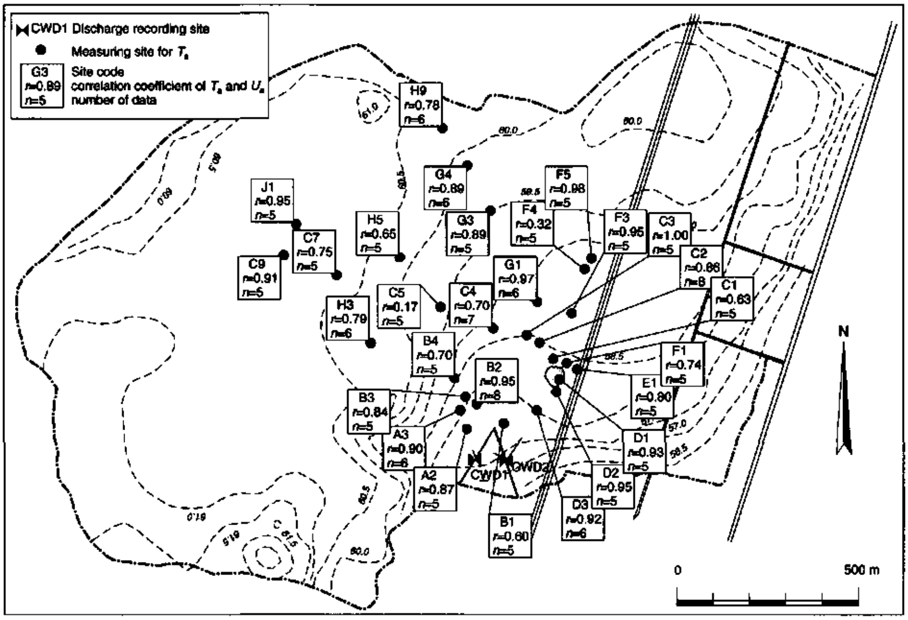

Fig. 6.15. Correlation coefficients of acrotelm transmissivity T_a and acrotelm discharge Q_a for Clara Bog West.

Fig. 6.15 gives the values for Clara Bog West. Contrary to Raheenmore Bog, there is no clear spatial pattern of correlations. With a few exceptions, the correlations are moderate to high. A delay effect as described for Raheenmore Bog was not found. Neither is it indicated by a decreasing r with increasing distance to the outlets at CWD1 and CWD2. This is no evidence it does not exist, but because the discharge at CWD1-2 was generally more steady than at RHD1, the effect on Clara West may be less important than on Raheenmore Bog.

Analysis by catchment

Specific acrotelm discharge v_a is used instead of discharge Q_a. This facilitates comparisons between Raheenmore and Clara Bog. v_a is calculated from Q_a by

$$v_a = \frac{Q_a}{A_c} \tag{6.16}$$

where

A_c = catchment area [L^2]

In Eq. (6.16) the horizontal catotelm outflow Q_{hc} is neglected because of its small value (*cf.* 5.4). A period of time for which v_a is calculated, must preferably not be preceded by large fluctuations of Q_a, as was found for 16th April 1991 on Raheenmore Bog.

Because of the differences in T_a between measuring sites, the values have to be made mutually compatible. An obvious procedure would be dividing each T_a by the average T_a of the site it was measured on. Because measurements could not be made at all sites on all dates, this would yield either incompatible results or a very small number of sites. Therefore T_a measured on the date with the largest number of measurements was used as a reference. This leads to the equation

$$T_a' = \frac{T_a}{T_{ref}} \tag{6.17}$$

where

T_a' = "normalised" acrotelm transmissivity [1]

T_{ref} = reference T_a [L^2T^{-1}] (measured on the date with the largest number of measurements).

A disadvantage of this procedure is that the set of T_{ref} is likely to contain a few large errors. Any error in T_{ref} affects all T_a' for the site considered. Therefore the normalised series of all sites were compared to those of neighbouring sites. Series in which differences of at least an order of magnitude with surrounding sites were found in most T_a' were discarded. This was done with 1 out of 21 series of Raheenmore Bog and with 4 out of 47 of Clara West. For Clara West, the series of 4th and 5th November 1992, was used as T_{ref}. The data of both dates were used as a single set because the discharges on both dates differed only marginally (219 and 222 m^3 in 12 hours). The reference of Raheenmore Bog was the series of 19th November 1991.

Per measuring date, all available T_a' were averaged to obtain a single value. Results and fitted curves are shown in Fig. 6.16.

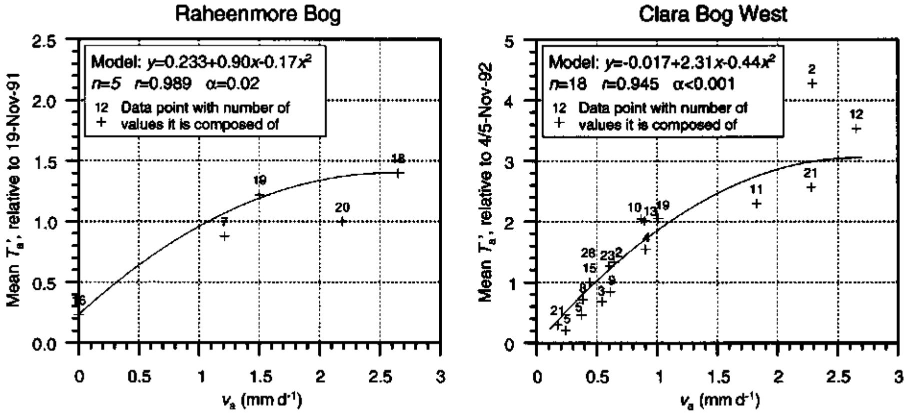

Fig. 6.16. Mean normalised acrotelm transmissivity T_a' (*cf.* Eq. 6.17) versus specific acrotelm discharge v_a.

The diagram for Clara Bog suggests a smaller increase of T_a' when v_a exceeds 1.5 mm d^{-1}. Therefore a 2nd degree polynomial was fitted. For the sake of comparability between the diagrams, the same was done for Raheenmore Bog, although the number of only five available data points does not entirely justify this. Nonetheless, the statistical significance improved from α=0.025 to α=0.020. The fitted curves indeed suggest a smaller increase of T_a' for v_a>1.5 mm d^{-1}.

The physical explanation of the curvature is that hollows get filled and pools and hollows become interconnected with rising phreatic levels. As a result of this process, an increasing proportion of the discharge flow paths is *via* open water and thus v_a is no longer proportional to T_a.

The curve for Clara Bog has no significant intercept (as may be expected, v_a=0 when T_a'=0), but the one for Raheenmore Bog has a distinct one. Two explanations are possible.

a. The measurement of the smallest T_a on Raheenmore Bog was done in June, when evapotranspiration may have prevented discharge from the central part of the bog from reaching the margin (all other measurements were done in November through March when evapotranspiration is small);

b. The gauging site RHD1 is situated downstream of an area with a degraded acrotelm where transmissivities tend to be smaller than in other parts of the bog. This may have little effect on discharge during the winter when phreatic levels are close to the surface, but there may be a noticeable effect in the summer.

The discharge at RHD1 indeed stopped usually during part of the summer, whilst it always continued on the gauging sites of Clara West, albeit at a low rate.

The analysis proves that indeed the mechanism behind the limitation of the discharge from a raised bog is the regulation of T_a by the phreatic level h and that consequently the acrotelm is an aquifer with a transmissivity controlled flux. The analysis also shows that in times of increased discharge additional discharge capacity is created by interconnections of hollows and/or pools.

Conclusions

- The recession of the phreatic level in the central area of Raheenmore Bog after a period of time with high precipitation may lag a few days behind the same process in the margin zone; for Clara West such an effect was not found. This does not mean it does not exist, but it is likely to be smaller than on Raheenmore Bog. Consequently, specific discharge as calculated from the discharge at the gauge of Raheenmore Bog is only representative for the bog when the day it was calculated for is preceded by days with an almost equal discharge;
- The correlation of T_a and discharge Q_a is generally high for individual sites, especially on Clara West. On Raheenmore Bog, the relationship is less clear, possibly as a result of delayed discharge from the centre compared with the margin;
- There is an almost linear relationship between the average acrotelm transmissivity T_a and Q_a if the specific discharge v_a does not exceed 1.5 mm d^{-1};
- For values of v_a in excess of 1.5 mm d^{-1}, measured T_a keeps increasing with v_a, but less than proportional. This indicates creation of discharge capacity by the forming of interconnections between pools and/or hollows. T_a then no longer is the only regulator of discharge from the bog;
- An acrotelm is an aquifer with a transmissivity-controlled flux; transmissivity is controlled by the phreatic level.

6.3.5. Spatial patterns of acrotelm transmissivity

The acrotelm transmissivity T_a in both bogs was found to have a distinct spatial pattern. Fig. 6.17 shows transmissivities for Raheenmore Bog of 16th April 1991. The date was chosen in spite of the discrepancies between central area and margin zone discussed in 6.3.4, because T_a of some margin sites had been measured on that date only. Fig. 6.17 also shows the pattern of surface gradients as presented in 5.4.2 (Fig. 5.8).

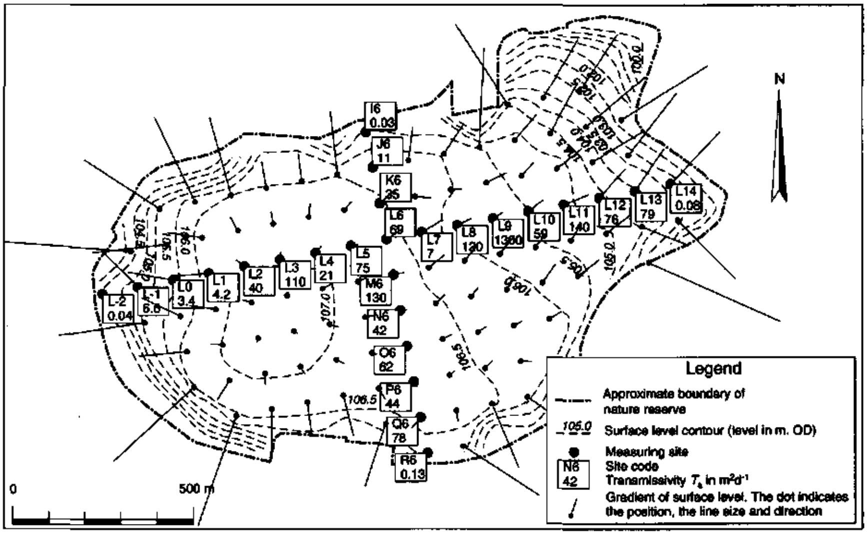

Fig. 6.17. Acrotelm transmissivities T_a on Raheenmore Bog, measured on 16th April 1991.

T_a along the margins is 2-4 orders of magnitude smaller than T_a in more central parts of the bog. The zone with T_a<1 $m^2 d^{-1}$ coincides with the proximity of the bog margin. The increase of T_a towards the centre is far from monotonous. The value tends to vary with the surface slope (e.g. the small value at L7, the large value at L9). A second factor that affects T_a is the size of the upstream catchment area. The values of L-2 to L1 to the east of the highest point of the transect L-2 to L14 are considerably smaller than those at L11 to L13, where the surface slope is about the same, but the distance to the highest point of the bog is considerably larger.

Most data used for the map of Clara Bog West (Fig. 6.18) were measured on 4th and 5th November 1992, when the specific discharge v_a was 0.44 mm d^{-1}. Data of sites where no measurements were made on these days were estimated from values of other days assuming a linear dependence of T_a on v_a. The values for the sites I1-I3 and J1-J3 were thus derived from values measured on 30th November 1992 when v_a had a value of 1.6 mm d^{-1}. Hence the resulting values of T_a may have been slightly underestimated. For C10 and C11, values could be derived from measurements of 22nd February 1993, when v_a was 0.38 mm d^{-1}, small enough for a linear relationship.

The pattern in Fig. 6.18 confirms the conclusions on Raheenmore Bog. In spite of relatively large surface level gradients in the area to the southwest of Shanley's Lough to which the flow from the large catchment converges, extremely large transmissivities occur in this area. In the western part of the bog the values of T_a are generally smaller. Small values, comparable to those of Raheenmore Bog, occur in the western part of the bog (for a realistic comparison the values of Clara Bog must be multiplied by the ratio of the v_a on the respective measuring dates, in this case 1.5/0.44 ≈3.5).

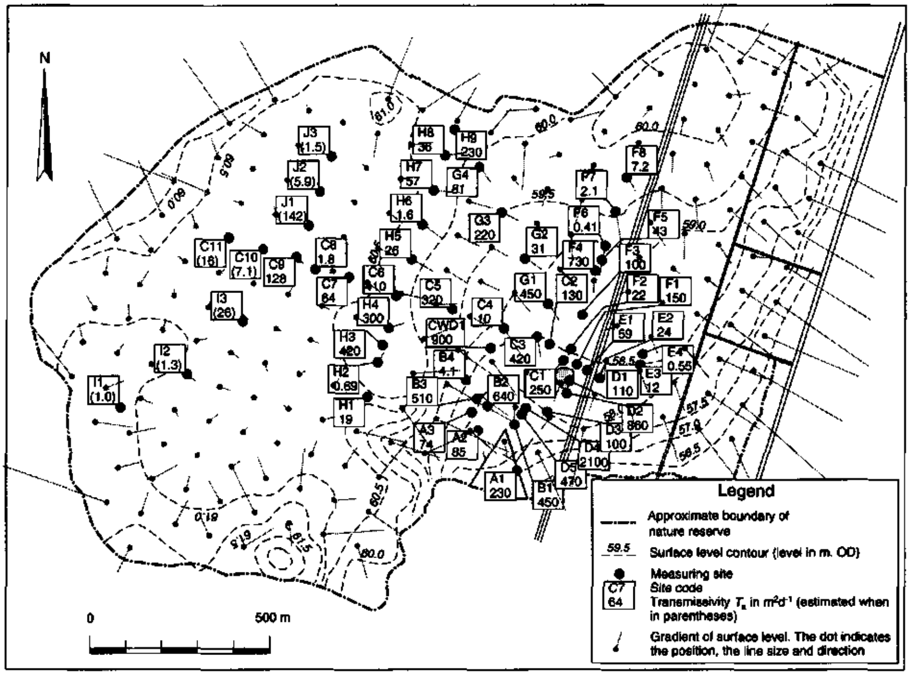

Fig. 6.18. Acrotelm transmissivities T_a on Clara Bog West, measured on 4th and 5th November 1992. Values in parentheses have been estimated from measurements of 30th November 1992 (sites I1-I3 and J1-J3) and of 22nd February 1993 (sites C10 and C11).

This means that the general level of T_a of Clara Bog for comparable discharge conditions is considerably higher than for Raheenmore Bog. This may be caused partly by the difference in size between the bogs, but the difference in flow pattern (mainly diverging on Raheenmore Bog and for a large part converging on Clara Bog) is probably more important. The pattern of decreasing T_a towards the margin also occurs on Clara West (sites I1-I3, J1-J3, E1-E4), with the exception of the converging flow system towards the area of Shanley's Lough. Another exception is the large transmissivity at H9 in the north. It probably is not due to a measuring error, because the acrotelm remains relatively well developed until close to the margin (*cf.* Fig. 6.24). The area is also marked as having frequent pools on the ecotope map by Kelly and Schouten (1999).

It can be concluded that the spatial pattern of T_a is closely related to the surface slope, the length of the flow path and the flow pattern (diverging, parallel or converging)

Two remarks should be made.

a. A bog surface often is not uniform within an area of 1000 or even 100 m^2. This should result in differences in T_a over short distances. The measured T_a were all point measurements, made at positions that were not inundated during measurements, which implies that sites could not be selected randomly. From data collected by Van der Cruysen *et al.* (1993), differences in T_a up to an order of magnitude over distances of 10 m can be derived;

b. The structure of a microlandscape may affect the dependence of its effective areal T_a on h. For example, the mechanism that causes the effective T_a to increase with h in a *Sphagnum* lawn is not the same as in a hummock-hollow complex. In a lawn, the flow is through the *Sphagnum* cover (until it becomes inundated); in a hummock-hollow complex the hollows become interconnected at high phreatic levels. In the latter situation, part of the value of areal T_a is due to the presence of connections *via* surface water. Such effects could not be measured with the methods available but as mentioned, but the curves in Fig. 6.16 reflect their presence.

6.3.6. Acrotelm transmissivity as a function of slope and flow pattern

The concept of acrotelm transmissivity as a function of surface slope and flow pattern is not new, but it is barely mentioned in other publications than those by Ivanov who developed it (Ivanov, 1965, 1972, 1981). It is implicitly based on the assumption of a self-regulating process that is controlled by the speed of production and decay of fresh organic material. It can be summarised as follows.

- Acrotelm material above the water table is aerated whereas in the material below anaerobic conditions prevail. Consequently, the decay of acrotelm material above the water table is faster than below it;
- A lowering of the water table, if prolonged for a sufficiently long time, will result in an acceleration of the speed of decay of the overlying material and eventually in a change in vegetation and even cessation of the peat forming process;
- A rise of the phreatic level will reduce the speed of decay, but if prolonged sufficiently, will also cause changes in the vegetation that may eventually result in a reduction of the production of fresh organic matter and thus in a reduced (or even an end to) peat growth;
- Hence, optimum peat forming conditions must be characterised by fluctuations of the phreatic level that are sufficiently large and around a sufficiently low mean to sustain the growth of a peat producing vegetation and at the same time sufficiently small and around a sufficiently high mean to reduce the speed of decay to a minimum;
- The above conditions are usually ensured by the relationship of acrotelm transmissivity T_a and the phreatic level h described in 6.3.3 and the effect on discharge described in 6.3.4: the strong increase of T_a when h rises into the upper 0-2 cm of the acrotelm, allowing a fast discharge of excess water and a strong reduction of T_a when the phreatic level falls again, causing a reduction or even cessation of acrotelm discharge.

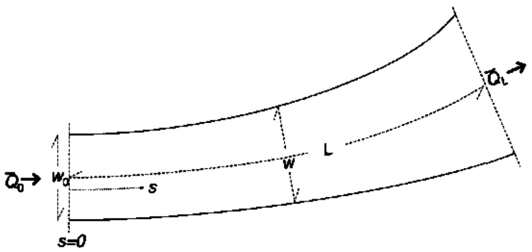

Fig. 6.19. Flow path section.

For a flow path between two streamlines (Fig. 6.19) on a bog, a steady state equation can be derived that describes the increase of the flux Q_a through the acrotelm at a cross-section perpendicular to the direction of flow:

$$\frac{d\overline{Q}_a}{ds} \approx \overline{U}_v w(s) \qquad (6.18)$$

where

$\overline{Q}_a$ = long term mean of the flux through the acrotelm along the flow path [L^3T^{-1}]

s = distance along the middle of the path [L]

w = width of the path at the cross section [L]

and

$\overline{U}_v = \overline{P}_e + \overline{U}_c$

where

$\overline{U}_v$ = long term mean of the net supply rate to the acrotelm [LT^{-1}]

$\overline{P}_e$ = long term mean of the excess precipitation flow rate [LT^{-1}]

$\overline{U}_c$ = long term mean of the flow rate of the exchange of water between acrotelm and catotelm

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 $\overline{Q}_a$ using $\overline{Q}_a \approx -\overline{T}_a w(s)\frac{dh}{ds}$, expressing $\overline{Q}_{a0}$ in flux per width q using $\overline{Q}_{a0} = w_0\overline{q}_{a0}$ and integration, Eq. (6.18) yields

$$\frac{dh}{ds} \approx -\frac{w_0\overline{q}_{a0} + \int_0^L \overline{U}_v w(s)ds}{w_L\overline{T}_a} \qquad (6.19)$$

where

h = phreatic level [L]

$\overline{q}_{a0}$ = long term mean of the flux per width at the upstream end of the flow path [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]

$\overline{T}_a$ = long term mean of acrotelm transmissivity [L^2T^{-1}]

The hydraulic gradient $\frac{dh}{ds}$ is almost identical with the surface slope I. Substitution and placing T_a explicit yields:

$$\overline{T}_a \approx -\frac{w_0 \overline{q}_{a0} + \int_0^L \overline{U}_v w(s) ds}{I w_L} \tag{6.19a}$$

where

I = surface slope, expressed as change in vertical position per horizontal distance [1]

Eq. (6.19a) is likely to give its most reliable results in the more downstream part of a flow path. Close to the water divide, the value of I, the result of the integral and q_0 are small. Consequently, small local variations in I and surface level may have a relatively large effect on $\overline{T}_a$ which thus may vary strongly over short distances.

As was demonstrated in 6.3.3, T_a is a function of the phreatic level, or, in other words, a function of the position of the boundary between the saturated and the unsaturated part of the acrotelm:

$$T_a = f(D_a - D_{a_{unsat}}) \tag{6.20}$$

where

$D_{a_{unsat}}$ = the depth of the unsaturated zone of the acrotelm.

$D_{a_{unsat}}$ increases as T_a decreases and vice versa.

Eqs. (6.19a) and (6.20) are nearly similar to the equations presented by Ivanov in his theory of self regulation of acrotelm transmissivity in a raised bog, although the symbols differ. The equations describe T_a as a function of climatic conditions (precipitation and evapotranspiration) and internal conditions of the bog (surface slope and length and shape of the flow path). If one or more of these conditions change, the acrotelm will eventually adjust itself to the changed conditions. If, for example, the surface slope increases as a result of peat cutting and subsequent subsidence at the bog margin, the average $D_{a_{unsat}}$ will increase at the expense of the saturated part of the acrotelm and the resulting increased speed of decay will not only reduce the entire acrotelm depth, but also the structure of the material, leading to a lower hydraulic conductivity. Thus the process also ensures the automatic adjustment of the hydraulic properties of the acrotelm to prevailing local conditions. Ivanov stated that each type of microtope has its typical range of $\overline{T}_a$. Edom and Golubcov (1996) even applied Ivanov's equations to predict the development of ecotope zones in a bog restoration project, using the surface topography and local climatic conditions as input. It is questionable, however, to what extent the development of a living bog is comparable with the development that may be expected on a substrate consisting of a formerly drained and/or cutover bog.

The same process occurs as a result of superficial drainage. On a bog surface with drains, L in Eq. (6.19) becomes very small (on average one quarter of the drain distance), because new flow paths start between each pair of drains. At the same time the first term in the numerator of Eq. (6.19a) becomes virtually zero.

6.3.7. Testing the theory of self-regulating acrotelm transmissivity

Introduction

The theory developed in 6.3.6 was tested using the results from Raheenmore and Clara Bog. Flow paths were estimated from the surface gradient maps of Fig. 5.8 (Raheenmore Bog) and 5.15 (Clara West). An additional map was made for Clara East. Calculations of surface slope values were based on the 100*100 m surface level grid of OPW.

The paths were based on an assumed distance w perpendicular to the direction of flow at a point where T_a was measured. T_a at a particular point in time depends on $\overline{T}_a$ and v_a. 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, T_a may replace $\overline{T}_a$ in Eq. (6.19a). 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, $v_a = \frac{1}{A_u}\int_0^L \overline{U}_v w(s)\mathrm{d}s$ and the flow path begins at a watershed, Eq. (19a) reduces to

$$T_a \approx \frac{A_u v_a}{Iw} \tag{6.21}$$

The approaches for Raheenmore Bog, Clara West and Clara East differed. On Raheenmore Bog, flow paths for a number of individual T_a-sites could be constructed. This was facilitated by the relatively simple flow pattern. However, only one site per flow path was available which made it impossible to account for local variations in T_a. For Clara East, a similar approach was followed, but the presence of clusters of several measuring sites allowed average values of T_a of a small area (about 300-400 m^2) to be used. The data set of Clara West with its concentration of sites in the area of Shanley's Lough and the converging flow from a large catchment area, allowed a catchment-based approach where local variations could be ruled out.

Raheenmore Bog

The selection of sites was based on the following considerations:

- Test sites should not be in the central flat part of the bog where flow areas cannot be defined with a reasonable accuracy and where T_a is too sensitive to small local differences in surface slope and -level;
- The distance to the bog margin should be large enough to ensure that it does not influence the estimated value of the surface slope.

Fig. 6.20 shows the selected sites and part of the estimated flow path areas. Each flow path was given a width of 100 m at the test site.

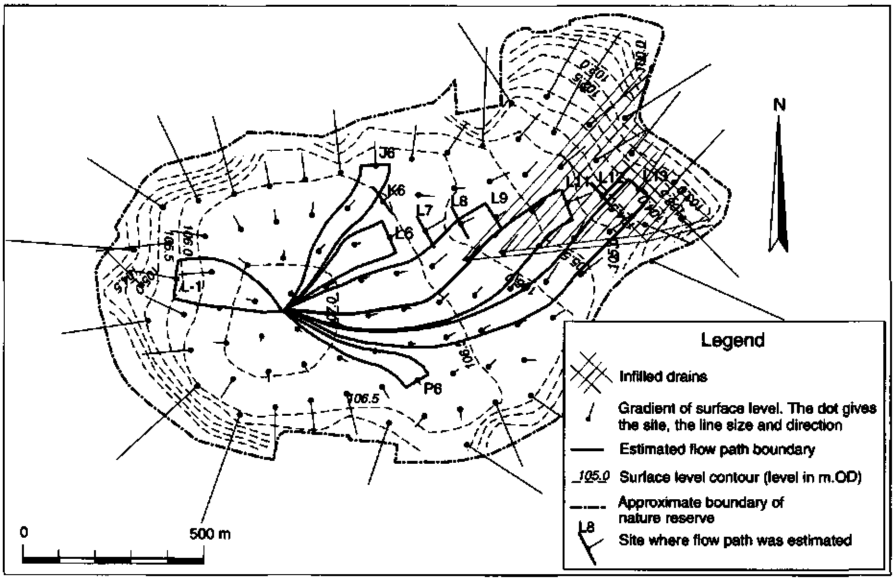

Fig. 6.20. Measuring sites for acrotelm transmissivity T_a, partly with estimated upstream flow path areas for which T_a was predicted using Eq. (6.21).

Table 6.8 gives estimated A_u and I. Calculation of surface slope values were based on the 100*100 m surface level grid of OPW. Sites L11-L13 are situated in the area with infilled drains (Fig. 6.20).

Table 6.8. Upstream flow path areas A_u and surface slopes I of the sites in Fig. 6.20.

Site	A_u (ha)	I	Site	A_u (ha)	I
J6	2.5	0.0043	L9	6	0.0020
K6	2	0.0039	L11	6	0.0046
L-1	2.5	0.0093	L12	7	0.0067
L6	2	0.0027	L13	6	0.0089
L7	3	0.0043	P6	2	0.00088
L8	4.5	0.0026			

Table 6.9 gives predicted and measured T_a. The data set of 5th June 1991 was not used because almost no discharge occurred (leftmost data point in the Raheenmore Bog diagram in Fig. 6.16).

Table 6.9. Predicted (Eq. 6.21) and measured acrotelm transmissivities T_a on *Raheenmore Bog*.

Date	16-04-91		01-11-91		19-11-91		25-03-92		
v_a	1.5 mm d^{-1}		2.7 mm d^{-1}		2.2 mm d^{-1}		1.2 mm d^{-1}		Ratio of
Site	T_a pred.	T_a meas.	T_a pred.	T_a meas.	T_a pred.	T_a meas.	T_a pred.	T_a meas.	$\frac{\overline{T}_a \text{ predicted}}{\overline{T}_a \text{ measured}}$
J6	87	11	160	20	130	5.9	-	-	**10**
K6	77	35	140	25	110	14	-	-	**4.5**
L-1	40	6.6	73	44	59	13	-	-	**2.7**
L6	110	69	200	35	160	29	89	26	**3.5**
L7	100	6.3	190	3.9	150	5.4	84	5.2	**26**
L8	260	120	470	67	380	67	210	120	**3.6**
L9	450	1300	810	550	660	920	360	1100	**0.6**
L11	200	140	350	36	290	140	160	39	**2.8**
L12	160	76	-	-	230	67	130	41	**2.8**
L13	100	79	-	-	150	77	-		**1.6**
P6	340	44	610	110	500	65	-		**6.6**

A ratio of about 1 of average predicted and measured T_a was expected. However, most measured values in Table 6.9 are considerably smaller than the predicted ones. Although the values of v_a were at such a high level that measured T_a was likely to underestimate effective areal T_a, most ratios are too large to be explained by this effect. Only sites L9 and L13 get reasonably close to a value of 1. The result means that surface flow is a normal phenomenon on Raheenmore Bog, both in areas with and without a good-looking acrotelm. The conclusion is that that either the model of Eqs. (6.19a) and (6.21) is not applicable to raised bogs in the Irish Midlands or the acrotelm of Raheenmore Bog has suffered overall damage. The matter will be discussed further after the results of Clara Bog (West and East) have been presented.

Clara Bog West

The position of the estimated catchment area, the T_a-sites and the cross section for which the calculation on Clara Bog was done, are shown in Fig. 6.21.

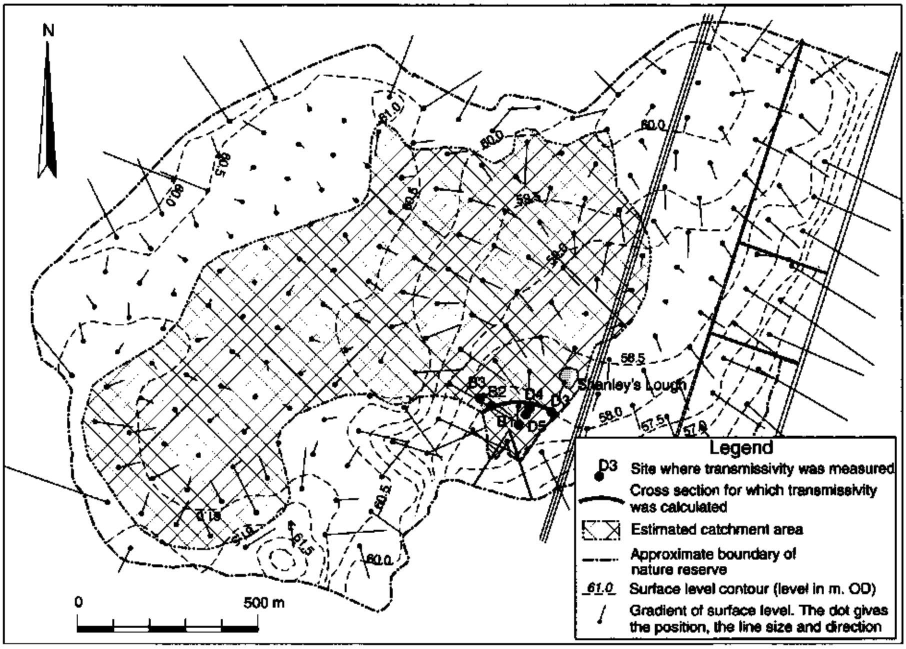

Fig. 6.21. Catchment area and measuring cross-section for Clara Bog West.

The size of the catchment shown in Fig. 6.21 is 95 ha. The cross section is about 230 m long. The area of the catchment downstream of the cross section is 2 ha, leaving 93 ha for the upstream part. The average surface slope at the cross section, estimated from the OPW-contour map, is 0.0033. The sites near the cross section had complete data sets of four measuring dates except for only one missing value. Table 6.10 gives predicted and measured values.

The average measured and predicted T_a are in almost perfect agreement. The differences between T_a of individual sites may be explained by differences in surface level and -slope, causing flow to be concentrated along flow paths at scale levels of a few tens of metres or even less. The local vegetation may also reflect different conditions. Site B1 was located in a deep hollow filled with *Sphagnum cuspidatum*. B2 and B3 were located in a hollow with *Sphagnum cuspidatum*, surrounded by low *S. magellanicum* hummocks. D3 (by far the smallest T_a) was located in a *S.* magellanicum lawn. D4 with its extremely large T_a was installed in a soak vegetation with *S. recurvum* and *Eriophorum vaginatum* and D5 in a soak vegetation with *Molinia caerulea* and *Sphagnum magellanicum*.

Table 6.10. Measured and predicted acrotelm transmissivities T_a (Eq. 6.21) at the cross-section shown in Fig. 6.21. Estimated average surface slope at sites: 0.0033. Value in parentheses: missing value, estimated from previously measured data.

Day	v_a (mm d^{-1})	Measured T_a (m^{2}d^{-1}) at site						Average T_a measured	T_a predicted	Ratio $\frac{\overline{T}_a \text{ predicted}}{\overline{T}_a \text{ measured}}$
		B1	B2	B3	D3	D4	D5	(m^{2}d^{-1})	(m^{2}d^{-1})	
04-11-92	0.46	450	640	510	100	2100	470	710	580	**0.8**
16-11-92	1.01	870	1100	680	140	3000	590	1100	1200	**1.1**
06-01-93	0.63	380	610	380	95	2500	320	710	760	**1.1**
07-03-93	0.25	60	140	(250)	33	1600	190	380	300	**0.8**

Clara Bog East

Clara East was drained in 1983-84 by open drains parallel to the Clara-Rahan road, 50-60 cm deep and 18-20 m apart. In 1989 an attempt was made to block the drains. Judging from visual observations, the operation had only yielded reasonable results in the central flat parts of the bog. The acrotelm was shallow or absent in most places (Van der Cruysen *et al.*, 1993).

Measurements of T_a were done on the plots A, B and C (positions shown in Fig. 3.8). At two out of the three clusters of dip wells of each plot, six pits were made, three in hollows and three in hummocks, to allow possible differences between these positions to be assessed. T_a was measured on three different dates in 1992/93. It was not always possible to measure T_a at all pits, either because the pits were flooded or because they were nearly dry. A flow path, 100 m wide at each cluster was estimated as it had probably existed before the drains were cut. The paths were based on the flow pattern derived from the data of the OPW 100x100 m grid and the OPW contour map. The flow pattern, the positions of the clusters and the flow paths are shown in Fig. 6.22.

No reliable discharge data of Clara East were available. Measured data would be of little use, however, because a reconstruction of the situation without drains requires data from an undrained Clara East. The discharge of Clara West probably is not a good estimate of the discharge of Clara East, because the flow paths on Clara West are longer and the soak area around Shanley's Lough at the end of the flow system might also affect the temporal pattern of the outflow from Clara West. The spatial pattern of Clara East is more radial and thus resembles Raheenmore Bog rather than Clara West.

Because Raheenmore Bog is only about half the size of Clara East, the discharge of Clara East was estimated as the average of Raheenmore Bog and Clara West.

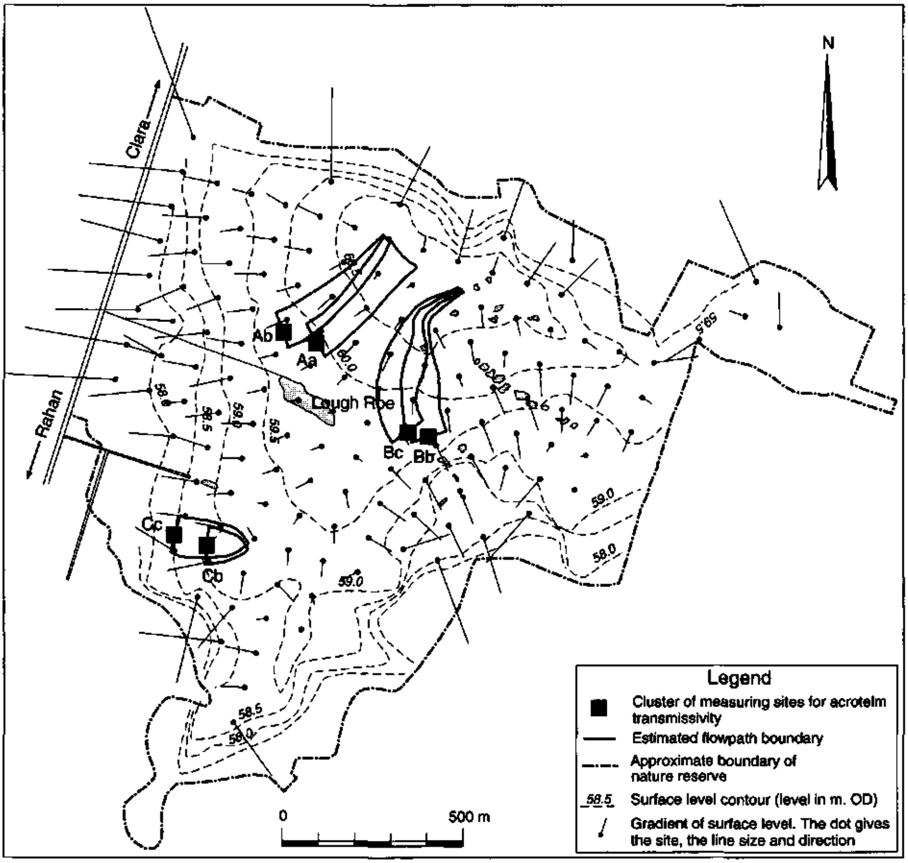

Fig. 6.22. Flow pattern, flow paths and positions of clusters of acrotelm transmissivity pits, Clara East.

Table 6.11 gives the surface slope and the flow path size at the clusters. Information as to the effectiveness of the drain blocking, derived from data presented by Huisman (1991) has been added. Table 6.12 gives the results of estimates and measurements for all clusters.

Table 6.11. Data of the cluster sites (positions shown in Fig. 6.22). "Effective" means that in wet periods the water level in the drains rises to the bog surface and stays at that level for at least some days.

Cluster	Upstream flow path area A_u (ha)	Surface slope I (-)	Drain blocking
Aa	3.5	0.0018	Effective on both sides of plot
Ab	2.5	0.0031	Effective on both sides of plot
Bb	3	0.0030	Effective at one side of plot
Bc	3.5	0.0020	Effective over 50% of drain depth
Cb	0.6	0.0055	Effective over 50% of drain depth
Cc	1.5	0.0061	Effective over 60% of drain depth

Table 6.12. Predicted (Eq. 6.21) and average measured acrotelm transmissivities at different specific discharge v_a. Predicted values are for an undrained situation on Clara East. Cluster positions are shown in Fig. 6.22. CE = Clara East, CW = Clara West, RHM = Raheenmore Bog. Absence of data because of flooding or too low water level in the pits is indicated by a "-".

		v_a (mm d^{-1})			T_a pred.	T_a measured in hummocks		T_a measured in hollows		Ratio $\overline{T_a}$ predicted / $\overline{T_a}$ measured
Cluster	Date	RHM	CW	CE	(m^2 d^{-1})	(m^2 d^{-1})	n	(m^2 d^{-1})	n	
Aa	25-11-92	4.1	3.0	3.6	700	140	2	-	0	**5.0**
	9-12-92	2.5	2.1	2.3	450	75	3	-	0	**6.0**
	10-02-93	0.57	0.59	0.58	110	42	3	25	3	**3.3**
Ab	24-11-92	3.8	2.8	3.3	270	48	3	47	2	**5.7**
	9-12-92	2.5	2.1	2.3	190	25	3	-	0	**7.6**
	10-02-93	0.57	0.59	0.58	47	8	3	10	3	**5.2**
Bb	25-11-92	4.1	3.0	3.6	360	95	3	48	1	**4.3**
	9-12-92	2.5	2.1	2.3	230	21	3	49	1	**8.2**
	12-02-93	0.50	0.55	0.53	53	7	3	21	3	**3.8**
Bc	25-11-92	4.1	3.0	3.6	630	64	3	73	3	**9.2**
	9-12-92	2.5	2.1	2.3	400	28	3	53	3	**9.9**
	10-02-93	0.57	0.59	0.58	100	6	2	8	2	**14**
Cb	24-11-92	3.8	2.8	3.3	36	3.9	3	10	3	**5.2**
	9-12-92	2.5	2.1	2.3	25	1.4	3	12	3	**3.7**
	13-02-93	0.48	0.52	0.50	5.5	-	-	1.0	2	**5.5**
Cc	24-11-92	3.8	2.8	3.3	87	0.4	3	22	3	**7.8**
	9-12-92	2.5	2.1	2.3	60	0.5	3	19	3	**6.2**
	13-02-93	0.48	0.52	0.50	13	Pits dry or nearly dry				**>10**

Although two thirds of the values of T_a in Table 6.12 have been measured at such levels of v_a that calculated T_a should exceed measured values, the differences with estimated T_a are too large to have been caused by the non-linearity of the relationship, shown in Fig.

6.16. The large ratio of $\frac{\overline{T}_a \text{ predicted}}{\overline{\overline{T}}_a \text{ measured}}$ of February 1993, when v_a was well below 1 mm d^{-1} is sufficient evidence. The clusters Aa, Ab and Ba indeed show the smallest ratio in February, the other -more intensively drained- sites rather show an opposite effect, probably as a result of the drainage. At Cc, pits were too dry to yield a measurable T_a. This implies an actual value that probably was below 1 $m^2 d^{-1}$. If the outlier L7 of Raheenmore Bog is ignored, the average level of the ratio $\frac{\overline{T}_a \text{ predicted}}{\overline{\overline{T}}_a \text{ measured}}$ at the wettest sites (Aa, Ab and Bb) is even larger than for Raheenmore Bog. If these ratios are caused by a decay of the acrotelm of Clara East, they indicate that most damage to the acrotelm of Clara East was probably done between 1983 and 1989 and that the process has slowed down in later years when the first drain blockings took effect. An additional indication is that in the plots where the blocking was most effective (A and Bb), the difference between hummock and hollow pits is small; in the drier plots (Bc and C) the acrotelm seems to have been preserved best in the hollows. The small difference in surface level of 10-15 cm, seems to have been enough to prevent the material in the hollows from drying out too often and too strongly.

The short flow path upstream of plot C probably is an indirect effect of peat cutting along the south-eastern and south-western margin of Clara East. The flow pattern in Fig. 6.22 suggests that the flow has been diverted to these margins as a result of subsidence subsequent to cutting .

Discussion

The results of the test of the theory of self-regulation of acrotelm transmissivity as a resultant of surface slope and flow pattern give rise to the question whether the results obtained for Raheenmore Bog and Clara East should be attributed entirely to a damaged acrotelm. The result for the catchment area of Clara West gave an almost 1:1 relationship between predicted and measured T_a, albeit with a considerable variation between sites.

The acrotelms of Raheenmore Bog and of Clara East clearly are in a worse condition than predicted by the model. The explanation for Clara East is obvious: the drainage system must have done considerable damage by cutting off flow paths. The question what the condition of the acrotelm of Clara East was before the drains were cut cannot be answered because of lack of information. Judging by the description of the vegetation by Kelly and Schouten (1999), the situation must have deteriorated considerably since 1983. These authors classify the vegetation on 78% of the area of Clara East as being associated with a moribund acrotelm, whereas the assessments for Clara West and Raheenmore Bog are 57% and 53%, respectively. The higher percentage for Clara West is for a large part due to the zone along the Clara-Rahan road.

A likely cause is burning. In Ireland, burning of raised bogs has often occurred in the past and it still occurs (Clara West had a fire in 1994). Kelly and Schouten (1999) reported the occurrence of vegetation variants with signs of burning in the form of species that tend to colonise bare disturbed peat -such as *Campylopus introflexus* and *C. paradoxus*- in large parts of both Clara and Raheenmore Bog. Burning has its strongest effect in dry summers and on the drier parts of a bog. This may explain both the low values of T_a compared with theoretical values on Raheenmore Bog and those near the theoretical ones found on Clara West. Contrary to other parts of Clara Bog and Raheenmore Bog, the outlet of the large catchment of Clara West remains wet nearly all year round and thus is unlikely to have been damaged by burning. Also from information on the age of the birch wood at Shanley's Lough presented by Hill (1992), one can infer that no fire can have occurred there during at least the last 100-120 years.

On Clara East, the acrotelm has obviously deteriorated as a result of the drainage system. An answer to the question whether the process of decay was already in progress before the drains were cut, cannot be given without additional information. As to Raheenmore Bog, the situation is more difficult. The relatively large percentage of vegetation types related with a healthy acrotelm shown as a large central area on the map presented by Kelly and Schouten, suggests a positive development. This is also suggested by the occurrence of such a vegetation type inside the area of the infilled drains. Although this is only the westernmost part where the outer drains join, it indicates the development of an acrotelm because it must have been destroyed in the decades after the drains were cut. The ratios of predicted and measured T_a in the drain area (sites L11, L12 and L13) are much smaller than those found on Clara East. This probably indicates a recovering rather than a dying acrotelm. More about this will be said in the conclusions of section 6.4.

The statement by Kelly and Schouten that Raheenmore Bog is drying out because of the presence of a deep marginal drain must be dismissed in view of the extremely small vertical losses of water of 10-15 mm a^{-1} from the bog, assessed in 5.5.

Conclusions

- Ivanov's theory of self-regulation of acrotelm transmissivity T_a, based on surface slope, specific discharge and flow pattern is applicable to the transmissivities in the outlet area of the large catchment of Clara West;
- Considerable spatial variations of T_a of approximately an order of magnitude around a mean predicted by the model worked out in this section occur. They are probably due to local differences in surface slope and –level;
- On Clara East, the acrotelm has been destroyed following drainage. The model of Eq. (6.21) predicts values of T_a about 4-10 times as large as the measured values.

Whether the entire difference is due to the effect of the drains is uncertain, but not very likely in view of results found for Raheenmore Bog;

- The measured values of T_a for Raheenmore Bog are smaller than predicted by the model. Although the specific discharge values during the measurements were relatively high, they are unlikely to be due to the entire difference. Burning in the past is a likely cause. If this is correct, the acrotelm of Raheenmore Bog is recovering rather than decaying. The latter conclusion is supported by the vegetation type in the highest part of the area with infilled drains and the (relatively) large values of T_a measured inside the area of infilled drains;
- Ivanov's model of self-regulation may be a useful tool to predict the long term development of raised bogs that have been damaged by burning, internal drainage or other causes and where the cause of the damage has been removed by either natural or human induced processes. Whether the predictive power of the model also extends to severely damaged or even cutover bogs is unclear. Although the model may predict a future situation, it does not tell how far ahead such a future is.

6.4. Acrotelm depth

6.4.1. Introduction

Conditions for peat forming processes are not only likely to be reflected in acrotelm transmissivity, but also in acrotelm depth. The process described in 6.3.6 and 6.3.7 that governs acrotelm transmissivity T_a is based on the difference in speed of decay above and below the water table. This means that it also causes deep acrotelms to occur where conditions for peat growth are optimal and shallow ones (or none at all) where they are not. Hence acrotelm depth D_a and acrotelm transmissivity have a common cause and should show a relationship, both in locally occurring values and in spatial pattern. Haplotelmic (parts of) bogs indicate adverse conditions for peat formation, unless they are the result of one or even a series of temporary calamities such as bog fires or internal drainage. If the cause is structural, a bog (area) is in a state of permanent decay.

The spatial pattern of acrotelm depths must therefore coincide roughly with the pattern of acrotelm transmissivity as shown in Fig. 6.17 and Fig. 6.18 and a statistical relationship should exist between D_a and T_a. In 6.2 it was already shown that a relationship with the storage coefficient μ exists in that in deep acrotelms μ decreases relatively less with depth than in shallow acrotelms and that degraded acrotelms coincide with smaller storage coefficients than healthy ones.

The results of acrotelm surveys, carried out in 1991-1993 will be presented as D_a maps of Raheenmore Bog and of both Clara West and Clara East, followed by a statistical analysis of the relationship with T_a. Next, effects of local drainage conditions reflected in the surface slope and size of the upstream catchment area are investigated. This section ends with the development of a simple model for acrotelm (or peat) growth.

6.4.2. The spatial pattern

Raheenmore Bog

Fig. 6.23 shows a map of acrotelm depths of Raheenmore Bog, defined as the depth of the surface layer with a degree of humification $H \leq 3$. It is based on an interpretation of the field data of Van 't Hullenaar and Ten Kate (1991). Their data consist of information on the acrotelm pits, a full survey of acrotelm depths on the 100 x 100 m grid of OPW and an additional survey at a selection of grid points where the acrotelm depth in the hollows was examined.

The flow pattern in the form of gradients of the surface level, shown earlier in Fig. 5.8, is added. Well-developed acrotelms -judged by depth- only occur in the central part of the bog, not in the margin zone. The infilled drains in the north-east do not seem to have a strong influence on acrotelm development anymore. This is yet another indication that the bog is recovering from damage undoubtedly incurred by the cutting of the drains. The pattern coincides rather well with the map with transmissivities T_a shown in Fig. 6.17. Small T_a (<15 $m^2 d^{-1}$) entirely coincide with two lowest classes of acrotelm depth, larger values do not occur in areas with the depth class of 0 cm. The two areas of haplotelmic bog in the centre are remarkable. They might be a remnant of larger damage in the past.

Clara Bog West

Fig. 6.24 shows the acrotelm depth map of Clara West. Because of a better field mapping technique (the mapping was not done on a grid, but was based on a systematic observation of the acrotelm in the field with checks where necessary), the map is more accurate with more detail than the one of Raheenmore Bog.

Similar to Raheenmore Bog, no well developed acrotelms occur along the margins, although the margin zone without a top layer with $H \leq 3$ is locally much narrower, notably in the Northwest and to the South of Shanley's Lough. Very deep acrotelms (≥45 cm) occur where the flow converges. Noteworthy areas are in the Southwest and to the west and north of Shanley's Lough.

The triple infilled drain parallel with the Clara-Rahan road has a remarkable effect in that it seems to enhance growth conditions for acrotelm development along part of its course, probably after having been blocked to some extent by a natural process of infilling further downstream.

Deep acrotelms coincide with large values of T_a (Fig. 6.18), particularly in the area of Shanley's Lough. Small values of T_a, closer to the margin, coincide with haplotelmic areas or areas with a shallow acrotelm. Noteworthy is the haplotelmic area in the centre where indeed some of the smaller values of T_a were measured.

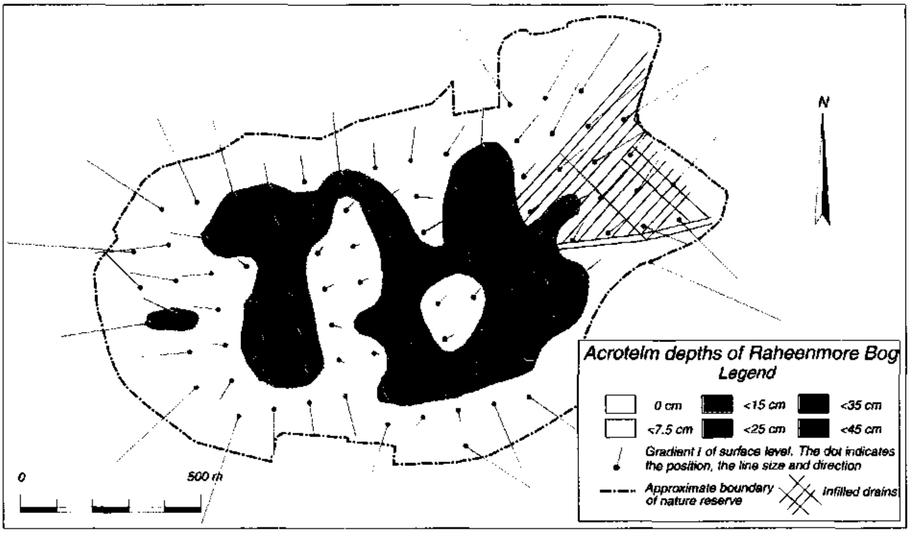

Fig. 6.23. Acrotelm depths D_a and gradients I of the surface level on Raheenmore Bog.

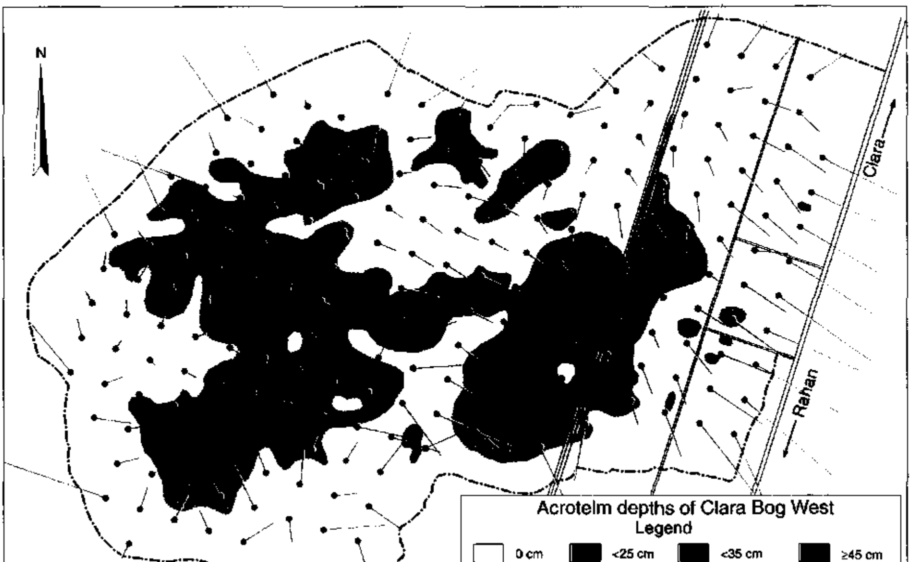

Fig. 6.24. Acrotelm depths D_a and gradients I of the surface level on Clara Bog West (after Van der Cruysen *et al.*, 1993).

Clara Bog East

The map of Clara East in Fig. 6.25 shows a larger proportion of areas without or with shallow acrotelms than Raheenmore Bog and Clara West. Deep acrotelms do occur, but in a patchy pattern. The deepest ones are infilling pools or infilling bog lakes (Lough Roe) and show little relationship with the flow pattern, except for a small area of about 5 ha with a deeper acrotelm in the east, where some converging flow may still occur. The difference with Clara West probably is caused in part by the difference in flow system.

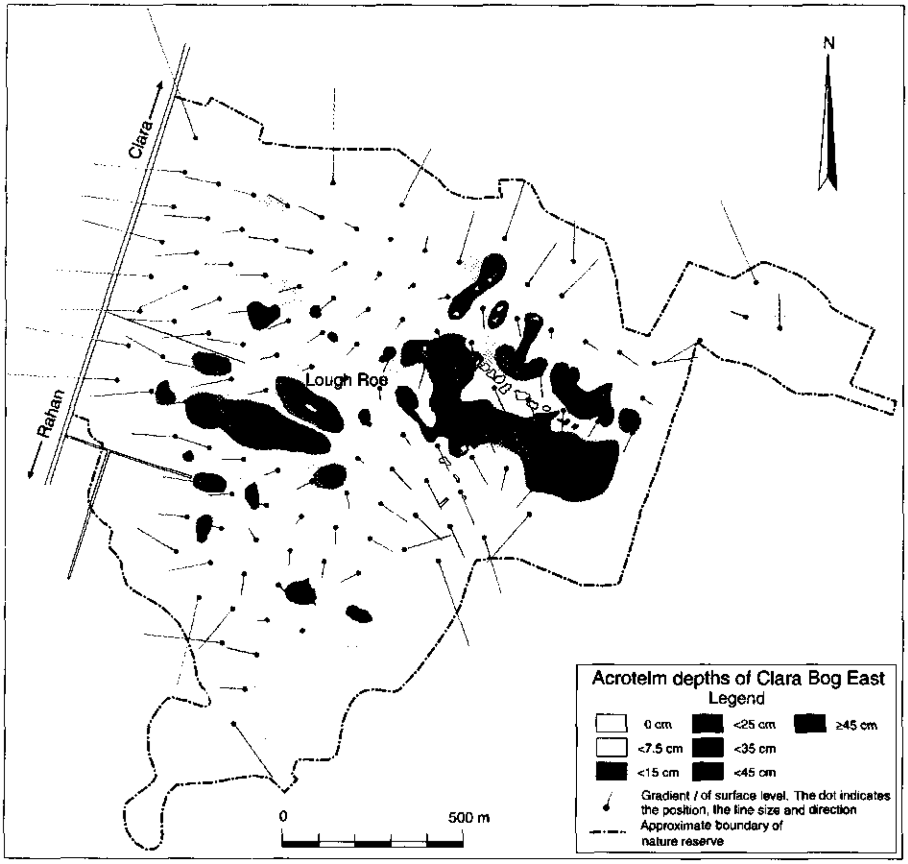

Fig. 6.25. Acrotelm depths D_a and gradients I of the surface level on Clara Bog East (after Van der Cruysen *et al.*, 1993).

Apart from the small area in the east that was mentioned above, the flow pattern is radial or parallel, comparable with Raheenmore Bog rather than Clara West. Although Raheenmore Bog is smaller than Clara East, its acrotelm is in a better overall shape. The difference has almost certainly been caused by the drainage system of Clara East. Because T_a was measured at only six places, a comparison with the spatial pattern of transmissivity is not possible.

6.4.3. Acrotelm depth and -transmissivity

The conclusion in 6.3.3 that relative differences between T_a may decrease when phreatic levels fall, could imply that a possible relationship between acrotelm depth D_a and T_a is more significant for shallow than for deep acrotelms. During the field work, D_a was estimated in increments of 10 cm from peat sampler cores (the unit of 5 cm was only used for acrotelms with less than 10 cm depth and in case of doubt at deeper ones). Hence a test of the above hypothesis, based on curve fitting, might not yield a more meaningful results than one based on classes. Therefore 6 classes were distinguished, starting with D_a<10 cm and ending with $D_a \geq 50$ cm, for which means of $\log_{10} T_a$ and their 95% confidence intervals were calculated, the latter using Eq. (4.2).

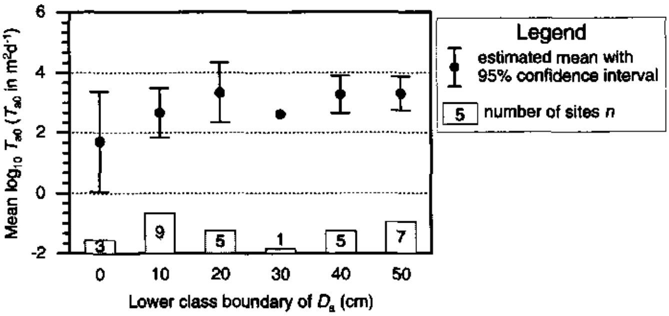

Fig. 6.26. Estimated acrotelm transmissivity T_{a0} (phreatic level equal to local surface level) versus acrotelm depth D_a. T_{a0} as mean of $\log_{10} T_{a0}$ (T_{a0} in $m^2 d^{-1}$). The 95% confidence interval is shown if number of sites n in class greater than 2. n is shown in the histogram along the horizontal axis.

Because measurements on Raheenmore Bog and Clara Bog were done during different periods and hence under different conditions, they were worked out separately. The only common data of the two bogs were extrapolated transmissivities T_{a0} (for phreatic level h=0) from the logarithmic model developed in 6.3.3. A diagram composed of results of relationships with a level of significance better than 0.1 is presented in Fig. 6.26. It indeed suggests that T_{a0} depends on D_a only if D_a<20 cm.

Fig. 6.27 shows a result for Raheenmore Bog derived from measurements of 16th April 1991, being the date with the largest number of measurements available. Although two classes have no values at all, the diagram suggests that indeed the largest increase in T_a with D_a occurs in the two classes with the smallest D_a.

he above conclusion is confirmed by the data from Clara West, where measurements were done at more sites.

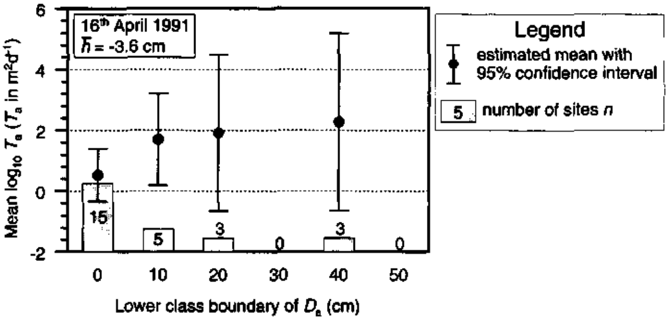

Fig. 6.27. Acrotelm transmissivity T_a versus acrotelm depth D_a on *Raheenmore Bog* on 16th April 1991. Transmissivity as mean of $\log_{10}T_a$ (T_a in m^2d^{-1}). 95% confidence intervalshown where $n>2$. Numbers of sites n per class in histogram along the horizontal axis. $\bar{h}$ is the arithmetic mean of the phreatic levels relative to the surface immediately around the measuring pits.

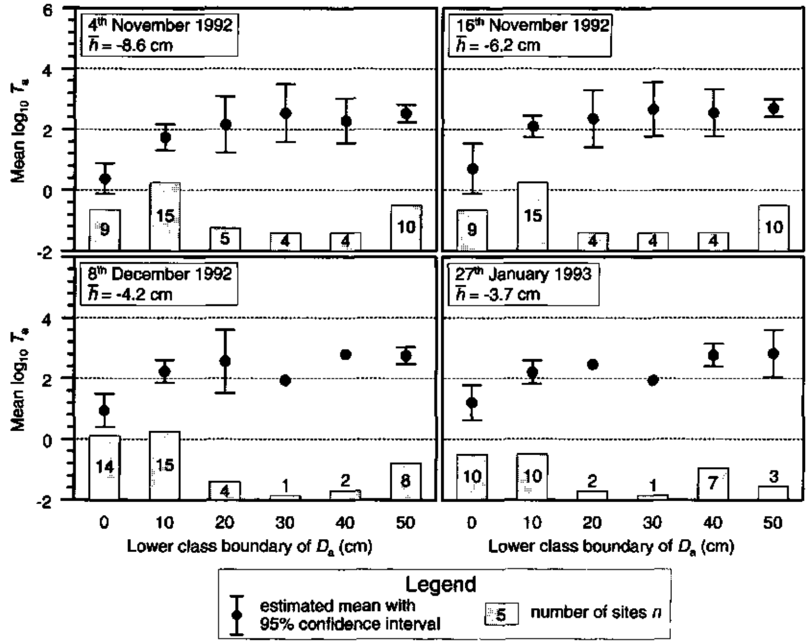

Fig. 6.28. Acrotelm transmissivity T_a versus acrotelm depth D_a on *Clara Bog West* for four dates. Acrotelm transmissivity T_a as means of $\log_{10}T_a$ (T_a in m^2d^{-1}) and 95% confidence interval given when $n>2$. Numbers of sites n per class in histogram along horizontal axis. $\bar{h}$ is the average water level relative to the surface during the measurements.

Fig. 6.28 shows values of four measuring dates with different mean phreatic levels.

The increase of $\overline{\log_{10} T_a}$ from the lowest class of D_a<10 cm to the one of 10 cm ≤D_a< 20 cm is large and statistically significant, the difference between the class 10 cm ≤D_a< 20 cm and the two classes D_a≥ 40 cm is small (although still significant) on all four dates. Whether a significant difference exists between the class of 10 cm ≤D_a< 20 cm and its next higher neighbour is not entirely clear from the diagrams, because the latter class contains too few observations. However, the diagrams of November 1992 suggest that indeed most of the remaining increase of $\overline{\log_{10} T_a}$ beyond the depth class of 10 cm ≤D_a< 20 cm occurs between this class and the next deeper one. A safe conclusion is that for both bogs a relationship between T_a and acrotelm depth is strong for acrotelm depths of less than 20 cm and that T_a increases little with larger depths.

Fig. 6.28 also suggests that T_a in profiles with D_a < 20 cm is not only smaller, but also more sensitive to changes in h than in profiles with larger D_a. This may be related to the larger change in the wetted proportion of D_a with changing h when D_a is small.

6.4.4. Acrotelm depth as a function of surface slope and flow path length

The conclusion that the relationship between acrotelm depth D_a and transmissivity T_a as developed above only shows a clear dependence for the smaller values of D_a, does not mean that acrotelm depth is an indicator of peat forming conditions for smaller depths only. Deep acrotelms can only develop when the rate of decay is small, i.e. when hydrological conditions ensure a quick conservation of newly formed organic litter below the water table.

The acrotelm depth maps in Fig. 6.23, Fig. 6.24 and Fig. 6.25 do not suggest otherwise. The surveys of Raheenmore Bog by Van 't Hullenaar and Ten Kate (1991) and Clara Bog by Van der Cruysen *et al.* (1993) show that indeed the wetter locations have the deepest acrotelms. Theoretically, they should also have the largest T_a. In the previous sections it was shown that both length of flow path and surface slope are important determining factors for acrotelm transmissivity.

Van der Schaaf (1996) developed statistical relationships between acrotelm depth D_a and surface slope I for Clara West, Clara East and Raheenmore Bog and concluded that the acrotelm depth on Clara East had been reduced by the drainage. Another conclusion was that well developed acrotelms are unlikely to occur where the surface slope is steeper than 0.01 and that at surface slopes of 0.02 and above, only haplotelmic bog occurred.

Fig. 6.29 illustrates the relationship for each bog. The data of Clara Bog were derived from the maps by Van der Cruysen *et al.* and those for Raheenmore Bog from the field data of Van 't Hullenaar and Ten Kate. The logarithm of the surface slope I was used instead of the slope value itself, because it gives a statistical relationship with a better level of significance than I itself (Van der Schaaf, 1996).

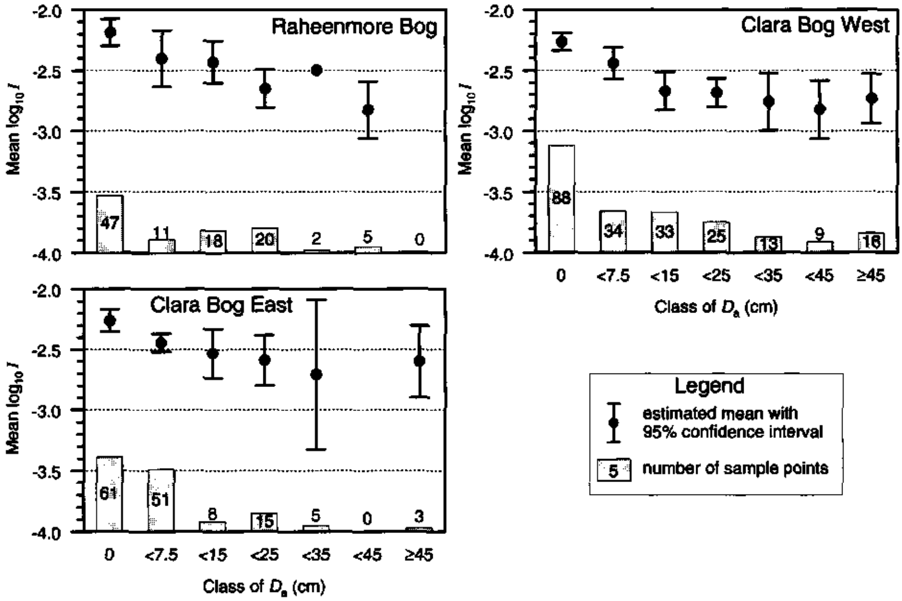

Fig. 6.29. *Logarithm of surface slope I versus acrotelm depth D_a, divided in seven classes. Bar graphs give number of sample points per class. At the data points, the 0.05 confidence interval of the mean of $\log_{10} I$ is shown.*

The decay of the acrotelm of Clara East shows up in the large proportion of sites with $D_a < 7.5$ cm. An interesting feature of the diagram of Clara West is the slight upward tendency of the relationship for the deepest acrotelms. This is largely caused by the situation in the area of Shanley's Lough. The average surface slopes in the area are not particularly small compared to the rest of Clara Bog. Nonetheless, deep acrotelms occur frequently, maintained by the converging flow system that ensures an almost continuous supply of water from other parts of the bog. This is a good reason to test whether besides the surface slope the position in the flow system has an effect on D_a. Theoretically, this could be done by evaluating the right hand member of Eq. (6.21) for each grid point. However, the procedure would be tedious and the result would probably contain a number of large errors, given the relative coarseness of a 100 x 100 m grid. For these reasons only the length of the flow path L_F [L] of each grid point was estimated as a rough indication of the value of the ratio $\frac{A_u}{w}$ in Eq. (6.21). Hence

$$L_F \approx \frac{A_u}{w} \tag{6.22}$$

For converging flow paths, $\frac{A_u}{w}$ is underestimated when L_F is measured on a flow map and overestimated for diverging flow paths. The tested variable was $\log_{10}\left(I\frac{\text{m}}{L_F}\right)$ to remain consistent with Fig. 6.29. Results are shown in Fig. 6.30.

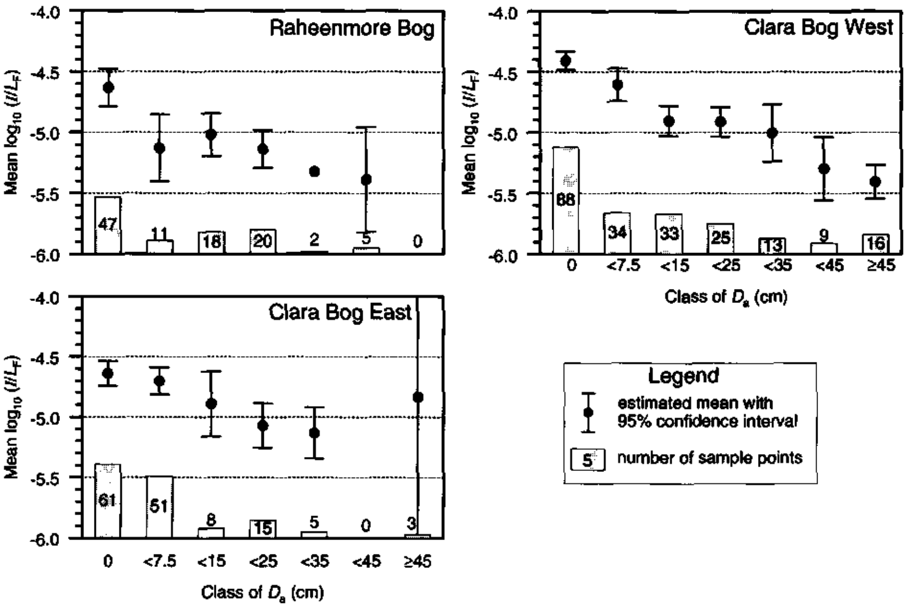

Fig. 6.30. Logarithm of the ratio of surface slope I and flow path length L_F versus acrotelm depth D_a, divided in seven classes. Bar graphs give number of sample points per class. At the data points, the 0.05 confidence interval of the mean of $\log_{10} I$ is shown.

Although the relationship for both Raheenmore Bog and Clara West has become steeper than in Fig. 6.29, there is no notable overall increase of the confidence interval of the means (but no decrease either). For Clara West in particular, adding the flow path in the relationship gives a better explanation of the existence and position of deep acrotelms than the surface slope alone.

For Raheenmore Bog, the position of the point for the class 0 cm< D_a< 7.5 cm, compared to Clara Bog (East and West) is remarkable. It is yet another indication that on Raheenmore Bog shallow acrotelms occur in areas that should have deeper ones in an entirely undisturbed situation. The low position of the point of the class of D_a=0 compared to Clara West is a similar indication.

The relationship for Clara Bog East has steepened less than the other two as a result of the addition of L_F. This indicates that D_a on Clara East is less dependent on flow path length as determined from surface levels than on the other two bogs. Because natural flow paths have been broken by the drains, drainage is the likely culprit. Another indication is the anomalous position of the point that represents the three sites in the class of largest D_a. As mentioned, they represent infilling pools and bog lakes rather than areas of converging flow.

6.4.5. Conclusions on acrotelm depth

- Acrotelm transmissivity T_a and acrotelm depth D_a are well correlated for D_a<20-25 cm. For larger D_a no correlation was found. This is in agreement with the conclusions as to the correlation of parameters inferred for the two empirical models of the relationship of acrotelm transmissivity T_a and phreatic level h in 6.3.3;
- Well developed acrotelms are generally absent along bog margins and other places where under current circumstances the surface slope is too steep or where other circumstances do not favour conditions of sufficiently prolonged wetness ensuring acrotelm development;
- Apart from a small surface slope, a long upstream flow path and convergent flow are favourable conditions for acrotelm development;
- A superficial drainage system like the one on Clara East causes a degradation of the acrotelm, measurable by both its transmissivity and its depth. It develops within a decade and probably in the first 1-5 years. In fact this process confirms the rule of self-regulation of a raised bog: unused discharge capacity is destroyed by decay;
- Drains eventually fill up by growth of fresh peat. A comparison of the situation in the area of the old infilled drains on Raheenmore Bog with the impact of the recent drainage of Clara East suggests a natural process of self-healing of a bog. However, such a process may take more than one or perhaps two centuries to complete;

6.5. A model of acrotelm growth based on hydrological conditions

The conclusions drawn above preferably need some support on the causality of the relationships they are based on. Therefore a simple model of acrotelm (or peat) growth depending on hydrological conditions was developed by the author.

An acrotelm grows at its upper boundary by the production of fresh organic litter. In every growing season, a certain amount is added. The production is estimated at different levels by different authors. A rate of of 2-10 tonnes of dry matter per ha is mentioned by Grosse Brauckmann (1990) and Clymo (1992). There is an annual loss by decay. As long as the material is aerated and *Sphagnum* is the main component, the loss of mass can be estimated at a level of 0.15 kg kg^{-1} a^{-1} (Clymo, 1997). Once it is permanently below the phreatic level, the speed of decay decreases to a negligible level in the order of $7*10^{-5}$ to $5*10^{-4}$ a^{-1} (Clymo, 1992).

The thickness D_0 [L] of a surface layer produced in a certain year may be expressed by

$$D_0 = \frac{M_{o0}}{\phi_{o0}\rho_o} \tag{6.23}$$

where

M_{o0} = Dry mass per area of produced organic matter during the considered year

ϕ_{o0} = Volume fraction [1] of the organic matter at the end of the season considered

ρ_o = Mass density [ML^{-3}]of organic matter. In Chapter 4 a value of 1400 kg m^{-3} was inferred from literature.

After a year, M_o is reduced by decay:

$$M_{o1} = M_{o0}(1-\delta_{o1}) \tag{6.24}$$

where

M_{o1} = Mass per area [ML^{-2}] of the layer, 1 year after it was formed

δ_{o1} = Mass fraction [1] of organic matter lost by decay during the first year after the layer was formed.

A second process is compaction. From the top of the acrotelm to the bottom of the catotelm, the total compaction may be 5- to 10-fold (*cf.* Chapter 4); within the acrotelm it is less, but not negligible. In a year, ϕ_0 has increased by compaction according to

$$\phi_{o1} = \frac{\phi_{o0}}{1-\zeta_{o1}} \tag{6.25}$$

where

ϕ_{o1} = Volume fraction [1] of organic matter, one year after the layer was formed

ζ_{o1} = Fraction of volume [1] lost by compaction during the first year after the layer was formed

The thickness of the layer D_1, one year after it was formed, is now expressed as:

$$D_1 = \frac{M_{o1}}{\rho_o\phi_{o1}} = \frac{M_{o0}(1-\delta_{od})(1-\zeta_{o1})}{\rho_o\phi_{o0}} \tag{6.26}$$

The thickness D_n after n years is

$$D_n = M_{o0}\frac{\prod_{i=1}^{n}\{(1-\delta_{oi})(1-\zeta_{oi})\}}{\rho_o\phi_{o0}} \tag{6.27}$$

The total depth of the acrotelm D_a is the sum of all D that may be considered part of the acrotelm:

$$D_a = \sum_{j=0}^{n} D_j = \sum_{j=0}^{n} \left[\frac{M_{oj}}{\rho_o \phi_{oj}} \prod_{i=1}^{n} \{(1-\delta_{oi})(1-\zeta_{oi})\} \right] \tag{6.28}$$

Eq. (6.28) describes the asymptotic growth of an acrotelm as a function of annual production, decay and compaction of organic debris. The growth described is asymptotic, because the annual loss from the total peat mass is assumed proportional to the total amount of organic matter stored. The concept of the asymptotic nature of peat growth was described earlier by Clymo (1984). To apply Eq. (6.28), values of M_o, ϕ_{o0}, δ_o and ζ_o are needed. The model does not include a notion as to the transition from acrotelm to catotelm in terms of degree of humification. A consequent definition would be the depth where the degree of humification H exceeds a value of 3. However, literature allowing a sensible relationship of H to be developed with compaction and/or the fraction of material lost after a certain time, was not found.

The model may give some additional inference as to whether the hypothesis of burning as a cause of long lasting damage to the acrotelm mentioned in the previous section on acrotelm transmissivity is realistic. Because no measured data of either Clara or Raheenmore Bog are available, some assumptions as to these values have to be made:

M_o: Is kept constant at a rate of 3.5 t ha^{-1} (the geometric mean of the range indicated above). In reality M_{o0} may be smaller at permanently deep phreatic levels and larger under more favourable hydrological conditions.

ϕ_{o0}: 0.015 for freshly formed material, based on a range of 0.01 to 0.02 (Clymo, 1992) and the smallest values of ϕ_o measured in the upper catotelm (*cf.* Chapter 4).

δ_o: Depending on phreatic level and its range of fluctuation: linearly decreasing from 0.15 (Clymo, 1997) for depths permanently above the phreatic level to 0.0001 for depths permanently below it. This introduces a dependence on the phreatic level and its fluctuation. Because of the dependence of the storage coefficient on the phreatic level, the highest level is assumed as one third of the fluctuation range above and the lowest level two thirds below the mean.

ζ_o: No information seems to be available in literature. Assuming that the transition to catotelm material in a healthy acrotelm lies at a depth where ϕ_o has an average value of around 0.025, reached after 50 years, a value of 0.01 seems reasonable (Eq. 6.25), assuming the assumption of ϕ_{o0}=0.015 is correct. Under natural bog conditions, however, a causal relationship between ζ_o and δ_o is likely to exist.

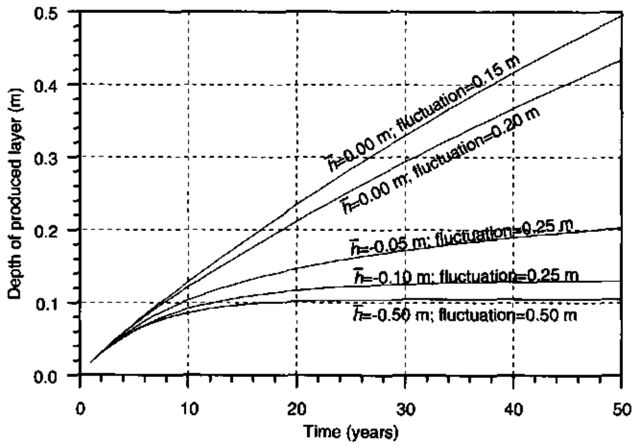

Fig. 6.31. Development of the depth of a peat layer, produced under different hydrological conditions, described by mean and fluctuation of the phreatic level *h* as predicted by the model of Eq. (6.28) with the assumptions as to values of model variables described in the text.

To obtain a rough idea as to the effect of phreatic level and its fluctuation, some graphs derived from the model are presented for different situations. Fluctuations of the phreatic level are related to its depth (*cf.* Ch. 8 and Van der Schaaf, 1995, 1999). Larger mean depths are related to larger fluctuations. Some realistic combinations of values based on this work have been used in Fig. 6.31.

The different curves allow the following conclusions:

- Mean at -50 cm, fluctuation of 50 cm. Produced material remains too long in the aerated zone to allow peat growth: the equilibrium of production and decay is reached at a layer thickness of 10.5 cm. In reality this level may not even be reached because the dry matter production may lie below the assumed level of 3.5 t ha^{-1}.
- Mean at -10 cm, fluctuation of 25 cm. The situation is similar to the previous one with a difference in layer thickness of only 2.5 cm.
- Mean at -5 cm, fluctuation of 25 cm. The small difference in mean phreatic level of 5 cm with the previous situation is sufficient to create a transition between the equilibrium of the previous two curves and peat growth in the next two. The sudden change, imposed by the difference in rate of decay between aerated (oxic) and non-aerated (anoxic) conditions is more important than the exact level of mean and fluctuation of *h* it is associated with.
- Mean at 0 cm, fluctuation of 20 cm. These hydrological conditions are those of an acrotelm in good shape. Peat is formed at a high speed: a top layer of 20 cm is formed in about 20 years (on a bog, this does not mean an increase in surface level of 20 cm, because the underlying catotelm keeps shrinking)

– Mean at 0 cm, fluctuation of 15 cm. The difference with the previous situation is an even more rapid development of the acrotelm. It shows that not only the mean phreatic level but also its fluctuation has an effect on acrotelm growth.

A recovery process of a damaged bog need not necessarily occur along one and the same curve. As conditions for accumulation change as a result of acrotelm building, a shift from e.g. the middle curve to the next higher one is possible. Consequently, the development of an acrotelm may speed up in the course of time after a slow start. However, in situations described by the two lower curves, such a development seems quite unlikely, unless the local hydrological regime changes following a change in the water supply from upstream parts that may have become more continuous, maybe as a result of acrotelm development in those parts. If the basic assumptions of the model are approximately correct, *the difference between rapid development (within 30 years) and slow development (50 years or more) may depend on differences of not more than a few cm in the phreatic level and its fluctuations.* Data from elsewhere indicate that recovery occurs, even after severe burning. A striking example is given by Averdieck and Schneider (1977), who discovered a layer of 60 cm of *Sphagnum* peat in the Große Moor near Barnstorf, overlying a bog surface that had been burnt for growing buckwheat crops.

6.6. Conclusions on acrotelm hydrology

6.6.1. The storage coefficient

In degraded acrotelms the storage coefficient μ lies below 0.20. In well developed acrotelms, $\bar{\mu}$ is around 0.4 when the phreatic level is in the upper 1-2 cm of the acrotelm. When the acrotelm is shallow (< 20 cm of peat with a degree of humification $H \leq 3$ at the surface), μ decreases to an average of 0.2 at depths of 15-20 cm. In deeper acrotelms the decrease of μ with depth is smaller and may not even be measurable in the upper 15 cm. Large values of μ at the surface tend to coincide with a larger decline with depth, resulting in more homogeneous values when the phreatic level is at a depth of 12-15 cm. At larger depths the storage coefficients have about the same values as in degraded acrotelms.

Areal values of μ may be considerably larger than 0.4. Values of 0.8 are not uncommon. These large values are related to storage in open water. This type of storage occurs in areas with pools or when hollows become filled with water. In well developed acrotelms with a hummock-hollow microtopography, the transition to these high values is gradual over a phreatic level range of 10-20 cm and sudden (within 1-3 cm) on degraded acrotelms where the surface is approximately flat.

6.6.2. Transmissivity

Measurements of acrotelm transmissivity T_a showed that T_a decreases by 1-2 orders of magnitude when the phreatic level is lowered from the surface to 10 cm below it. Ivanov's model of hydraulic conductivity k versus depth gave an acceptable approximation in the majority of cases, but tended to produce unlikely large values of the hydraulic conductivity k at the surface. The most extreme values required too large pore sizes to be explained by laminar flow through a "porous" medium and are almost certainly overestimated. An alternative model, assuming a logarithmic relationship of T_a and phreatic level h, yielded relationships with a better statistical significance and without "overshoot" when extrapolated to the surface. For depths larger than about 20 cm, the logarithmic model is likely to produce too low values of T_a, whereas Ivanov's model keeps producing realistic, but not necessarily correct values.

The positive correlation within the parameter pairs of both models indicates a decrease of relative differences of T_a over the bog when the phreatic level falls. Weak evidence for the effect was indeed found from measurements of T_a at different h. Some additional evidence was found in the analysis of T_a versus acrotelm depth D_a, which showed a relationship for acrotelms shallower than 20-25 cm, but none for larger D_a.

A clear relationship exists between measured T_a and acrotelm discharge Q_a. The relationship was linear for specific acrotelm discharges v_a of up to 1 and perhaps 1.5 mm d^{-1}. Above these values, the relationship became non-linear, indicating substantial flow through interconnected hollows an pools.

Because the hydraulic gradient in the acrotelm aquifer is determined by the shape of the catotelm and thus is approximately constant in time, acrotelm flow is not directly controlled by a varying hydraulic gradient, but by transmissivity, which in turn is controlled by the phreatic level. This relationship demonstrates the self-regulating process of discharge through the acrotelm: the discharge virtually ceases at low phreatic levels, thus preventing further losses of water and has a large values at high phreatic levels, thus ensuring a quick discharge of excess water.

There also is a long term relationship in that surface slope and size of the upstream area eventually determine acrotelm transmissivity by another self-regulating process. The average T_a in the outlet of the large catchment area of Clara West gave values that were in good agreement with this theory; Raheenmore Bog and Clara East gave lower values.

In the two latter bogs, the measured values were generally below those estimated from the theory, particularly in Clara East. In Raheenmore Bog, this may have been caused by burning. The model developed in 6.5 (Eq. 6.28) supports the view that recovery from a destroyed acrotelm may take several decades, especially when the burning has led to a deterioration of hydrological conditions and even if the change is no more than some 5 cm in the mean depth of the phreatic level. The lower values for Clara East are almost certainly caused by the system of drains that cuts off former flow paths. When a bog is drained, the process of decay is speeded up by faster oxidation whilst the production of new material decreases or maybe even ceases. This results in an acrotelm that becomes shallower and may disappear eventually. The effect is evident when acrotelm depths and -transmissivities of the drained Clara Bog East are compared with those of Raheenmore Bog and Clara Bog West. When conditions become wetter, the opposite process may be expected, resulting in a slowdown of decay and eventually, following the continuing production of fresh material, a deeper acrotelm. In fact, this is an aspect of the theory of self-regulation of acrotelm transmissivity.

6.6.3. Acrotelm depth

The spatial pattern of acrotelm depth D_a largely coincides with the spatial pattern of acrotelm transmissivity T_a. Acrotelms with D_a up to 20-25 cm show a clear relationship with T_a in two ways: shallower acrotelms tend to coincide with smaller T_a and with a larger sensitivity of T_a to the phreatic level h. This means that discharge depends more strongly on h in shallow acrotelms than in deep ones. Thus shallow acrotelms may be seen as transitional between a haplotelmic situation where the effective T_a suddenly increases to extreme values when the phreatic level reaches the surface causing sheet flow and the deep acrotelm where the change is more gradual. The growth model of Eq. (6.28) also suggests that deep acrotelms coincide with smaller fluctuations of h. This is supported by the presence of the deepest acrotelms in areas with converging flow and a small surface slope or long flow paths on Clara West. In these areas either the lateral losses are small as a result of the small slope or the supply of water is secure because of the large upstream catchment.

7. VOLUME FRACTION OF ORGANIC MATTER AND SUBSIDENCE

7.1. Introduction

General causes of subsidence of peatlands have been discussed in 2.7. Man-induced subsidence has altered hydrological conditions in large parts of Raheenmore and Clara Bog. On Clara Bog, subsidence has occurred visibly along face banks, the Clara-Rahan road in a zone of 300-500 m wide and in the area of Shanley's Lough as is suggested by the relatively steep upward slope of the bog surface, a few hundred m to the west of the little lake. On Raheenmore Bog, most visible subsidence effects are restricted to zones along face banks at the margin that have originated from turf cutting in the past, i.e. before the bog became a nature reserve in the early 1970's.

The main ecological problem caused by subsidence is related to the increase of the surface slope towards the subsided part. As was shown in the Chapter 6, the surface slope influences acrotelm conditions and thus the vegetation. Visible features on Clara and Raheenmore Bog are vegetations dominated by *Calluna vulgaris* that have replaced a vegetation with prevailing species like *Eriophorum vaginatum* and different *Sphagna*. This can usually be inferred from the composition of the upper peat. Where effects of subsidence on acrotelm conditions are not as visible, they may still be measurable as the acrotelm survey (Chapter 6) has shown.

Because subsidence of the bogs was known to have occurred, a research question posed in the Irish-Dutch project was to what extent it could be assessed by field methods and cheap laboratory procedures. For this purpose the method described in 3.10, based on drying undisturbed samples was developed. Its basic but questionable assumption is that peat profiles in the centre of a bog are comparable with profiles close to the margin in the sense that their original 'pre-subsidence' volume fractions of solid matter ϕ_o are approximately the same. The work was based on

- Evaluating the total amount of peat formed in relation to the position on the bog. The method can be refined by distinguishing between the main peat types FSP (Fresh *Sphagnum* Peat), HSP (Highly Humified *Sphagnum* Peat) and FP (Fen Peat). Relatively small amounts of FSP in a subsided profile may be an indication of losses by burning and/or turf cutting.
- Estimating 'original' surface levels by a comparison with one or more reference profiles and testing whether this results in a reasonable cross-sectional shape of the bog or parts of it.

Total amounts of peat in a profile are assessed by the partial peat depth D_{op} defined in 3.10, those in a peat layer, e.g. FSP, by the partial thickness D_o.

As pointed out in 2.7, drainage has had a much stronger effect on subsidence in Clara and Raheenmore Bog than oxidation or burning. This justifies neglecting effects of oxidation and burning in the estimating method of subsidence as described in 3.10.2, except in some exceptional situations. No fieldwork with regard to the subsidence survey was done on Clara Bog East. Hence the inferences in this chapter based on corings refer to Clara Bog West and Raheenmore Bog.

The chapter is concluded with an analysis of levelling data of 1948 (Raheenmore Bog) and 1982 (Clara Bog) of Bord na Móna, that became available recently. They allow an accurate assessment of subsidence in recent years.

7.2. Some remarks on the process of subsidence along disturbed margins

Most present day bog margins are face banks. Although the Clara-Rahan road lies across the central part of Clara Bog, probably the highest part of the former peat dome, it has caused effects on surface slope and vegetation similar to those of face banks. Effects of the subsidence on surface slopes have spread into the bogs over considerable distances from their source. The vegetation maps by Kelly and Schouten (1999) indicate severe to moderate effects (ecotopes named "facebank" and "marginal", respectively) in a zone of about 50 m wide along the margin of Raheenmore Bog and up to several hundreds of metres wide on Clara Bog (East and West).

These large widths are remarkable in view of the extremely small transmissivity T_c of the catotelm in subsided margins and the consequential small fluxes involved in lateral outflow through the catotelm as pointed out in 5.4. The width of the zone that is influenced directly by a face bank can be quantified by applying a model for the calculation of the width of hydrological buffer zones along bog margins devised by Van der Molen (1981). It was modified slightly by the present author to allow usage of catotelm transmissivity T_c instead of hydraulic conductivity. The modified equation reads

$$w_s = \frac{2.20\sqrt{T_c\left(t_s + \frac{\mu h_{fb}}{9P_{ew}}\right)}}{\sqrt{\mu}} \qquad (7.1)$$

where

w_s = width of the zone affected by drainage by the face bank [L]

t_s = length of a rainless summer period [T]

μ = storage coefficient [1]

h_{fb} = face bank height [L]

P_{ew} = excess precipitation rate in the winter [LT^{-1}]

The model deals with catotelm flow only. Consequently, it does not describe the entire flow system of a bog. For $T_c \leq 0.01$ m^2 d^{-1} (*cf.* 5.4), a storage coefficient $\mu \approx 0.15$ (*cf.* 6.2), $t_s \approx 100$ days, $h_{fb} \approx 2.5$ m and $P_{ew} \approx 2$ mm d^{-1}, it yields $w_s \leq 6$ m.

This result may explain how steep natural raised bog margins can exist without causing drying out of the bog. It also gives rise to the question, what causes the much wider zones of subsidence at face banks and the road. A likely answer is the following process. Once a margin begins to subside, the surface slope increases and causes an intensified drainage of a zone some metres more inward, which in turn begins to subside. Thus the effect spreads into the bog, causing a reduction of the depth and transmissivity of the acrotelm with its regulating effect on the hydrological system of the bog or even its disappearance. Such a process is an extreme form of the self-regulation t' at affects acrotelm transmissivity and -depth as described in 6.3 and 6.4.

7.3. Raheenmore Bog

7.3.1. Introduction

Three transects were sampled and analysed. They are marked C-E, NE-E and N-C-S and their positions are shown in Fig. 7.1 The main peat types FSP, HSP and FP were identified at each site to allow a reconstruction of the original bog surface level by a separate assessment of the shrinkage per peat type.

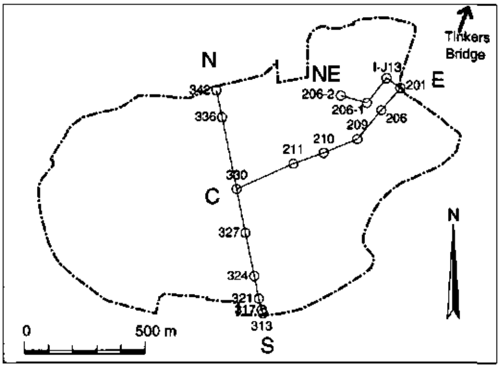

Fig. 7.1. Sampling transects and -sites on *Raheenmore Bog.*

The spatial patterns of volume fraction ϕ_o and partial thickness D_o of solid matter are discussed first. This is followed by a reconstruction of unsubsided surface levels based on the technique and its underlying assumptions worked out in 3.10.

7.3.2. Volume of solid matter per peat type: spatial patterns

Fig. 7.2, Fig. 7.3 and Fig. 7.4 show D_o of FSP, HSP and FP, the surface and bottom level of the peat and the average volume fraction of solid matter ϕ_o per peat type of the sites in the transects C-E, E-NE and N-C-S, respectively.

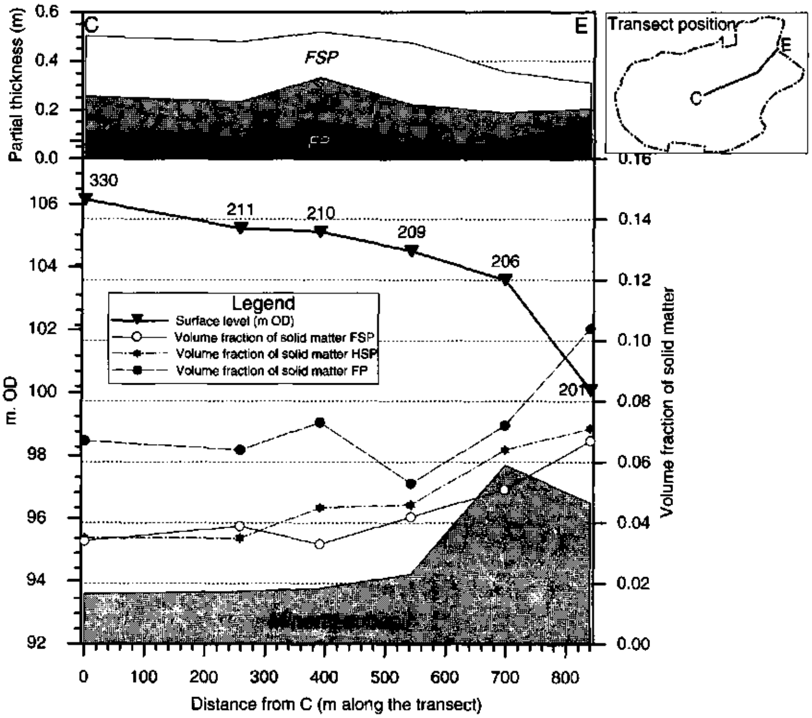

Fig. 7.2. Partial thickness D_0 and volume fraction of solid matter ϕ_0 of Fresh *Sphagnum* Peat (FSP), Strongly Humified *Sphagnum* Peat (HSP) and Fen Peat (FP) and levels of the peat surface and peat bottom along the transect C-E of *Raheenmore Bog*.

Fig. 7.2, Fig. 7.3 and Fig. 7.4 show that ϕ_0 increases from centre to margin along all transects and in all peat types as concluded earlier in 4.2.3. The largest values of ϕ_0 occur in the FP, the smallest in the FSP. In general, ϕ_0 in the HSP is closer to the value in the FSP than in the FP. Although this suggests a relatively strong compaction of the entire FP, the difference with FSP and HSP is mainly caused by a sudden increase of ϕ_0 at the base of the FP. This is demonstrated in the diagrams of Fig. A.12 and Fig. A.13 in Appendix A.

The share of the partial thickness of the FP increases towards the margins at the expense of the *Sphagnum* peat types (FSP and HSP). The increase may indicate that the influence of minerotrophic water from the surroundings has lasted longer along the margins than in the central part during the transition from fen to bog, allowing more time for the FP to form and less for the FSP and HSP. Evidence may be obtained from proper dating techniques, which were not available to the Irish-Dutch project.

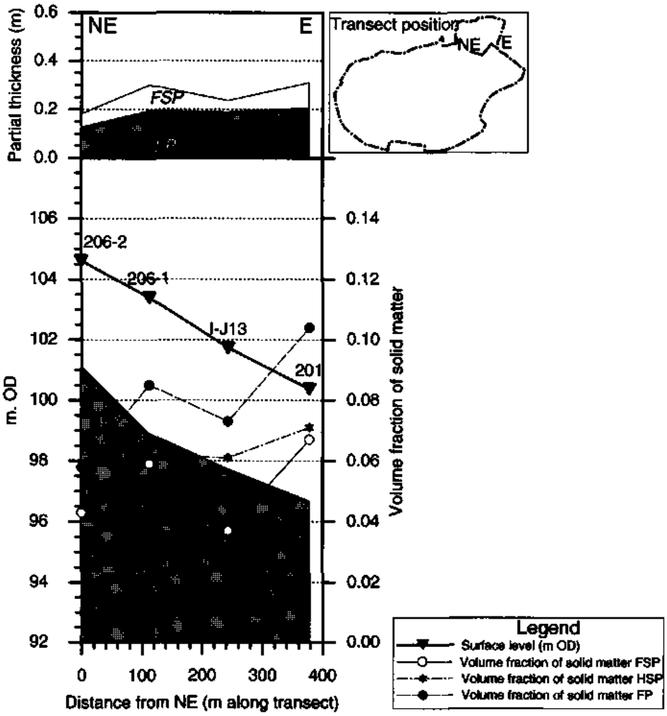

Fig. 7.3. Partial thickness D_0 and volume fraction of solid matter ϕ_0 of Fresh *Sphagnum* Peat (FSP), Strongly Humified *Sphagnum* Peat (HSP) and Fen Peat (FP) and levels of the peat surface and peat bottom along the transect NE-E of *Raheenmore Bog*.

At two out of three sampled margins, D_{0p} is about 0.30 m. At the third margin at 'S' of the N-C-S transect, D_{0p} is about 0.40 m. A difficulty in inferring a possible relationship with the margin position is that most of the present margins of Raheenmore Bog are artificial. However, the positions of the present day margins at the transect ends are not far from those of the bog in its undisturbed state. This may be inferred from the colour of the topsoil immediately outside the bog. At position "S", the mineral topsoil was found to change from near black to brown at about 60 m outside the present bog margin. It indicates a total width of 60 m of cutaway and former lagg. At position 'N' the transition occurred within 30 m, indicating an (almost) unchanged margin position. Along the margin near site 201, a 120 m wide and strongly disturbed lagg was distinguished by Kelly and Schouten (1999). Although the assumption that at least part of such a 'lagg' is actually an old cutaway seems equally reasonable, the large D_0 of the fen peat at site 201 indicates a close proximity to the position of the original margin and possibly a late transition from fen to bog. This means that the assumption that site 201 is close to the original margin position, is the more likely one.

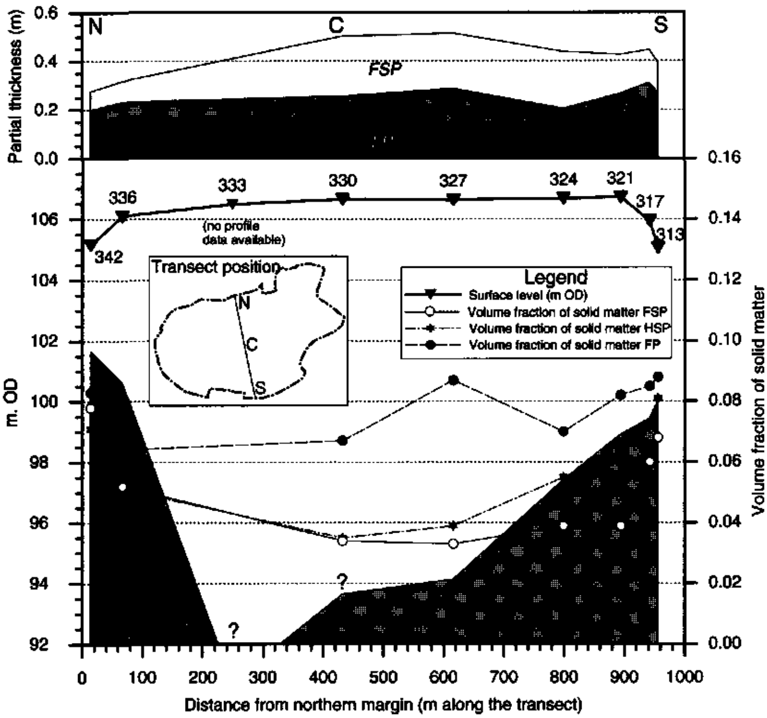

Fig. 7.4. Partial thickness D_0 and volume fraction of solid matter ϕ_0 of Fresh *Sphagnum* Peat (FSP), Strongly Humified *Sphagnum* Peat (HSP) and Fen Peat (FP) and levels of the peat surface and peat bottom along the transect N-C-S of *Raheenmore Bog*. Site 333 was included for its surface level and peat dept of over 14 m (value based on the length of a piezometer that was installed at this position). No data on the composition of the peat itself are available.

Burning may have reduced D_{0p} at margin sites, because margin zones usually are the driest places on a bog. However, since D_0 of the FSP is not disproportionally small compared with D_0 of the HSP at the margin sites, there is no reason to believe that the relatively small D_{0p} at the sampled parts of the margins of Raheenmore Bog reflects major effects of burning. For the same reason, there is no evidence of natural oxidation having played an important role.

High levels of the mineral subsoil in the bog are related to small D_{0p}. This is demonstrated in transect NE-E (Fig. 7.3), where the peat depth is obviously limited at the NE end of the transect because of the local high level of the peat bottom. D_0 of the FP is extremely small there, indicating a relatively short stage of minerotrophic peat forming conditions before the place was eventually overgrown by *Sphagnum* peat.

7.3.3. Reconstructing former bog surface levels

For the reconstruction, ϕ_o of FSP, HSP and FP was averaged over the sites 327, 330 and 211 (positions shown in Fig. 7.1) and the resulting averaged profile was used as a reference. The reconstruction was done separately for the three peat types. Reconstructed surface levels along the transects are shown in Fig. 7.5, together with the levels measured in 1991.

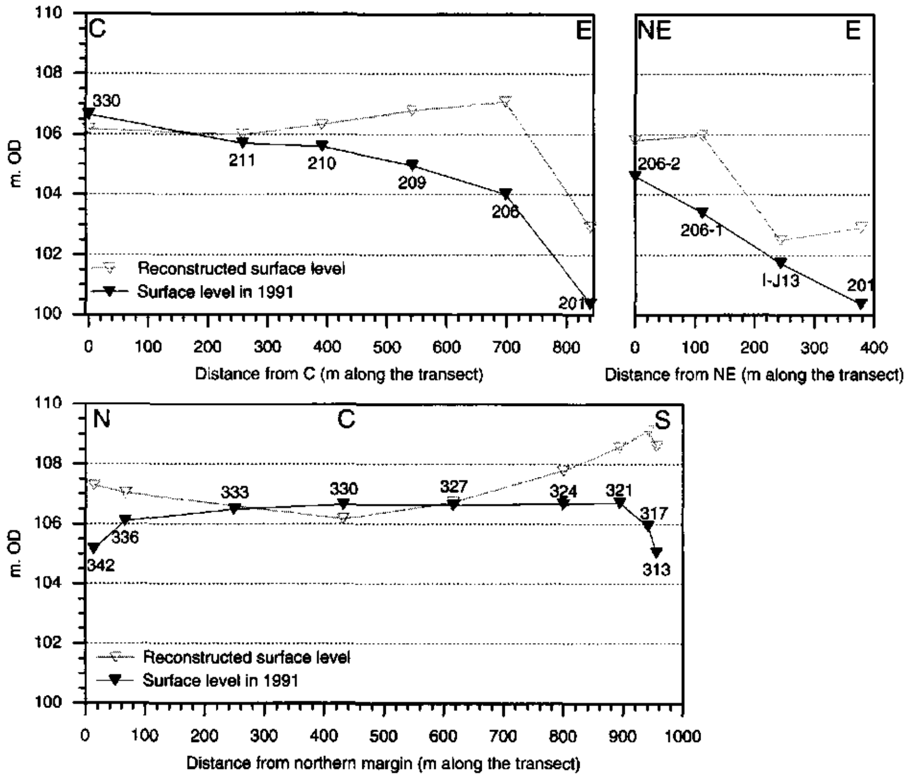

Fig. 7.5. Surface levels measured in 1991 and reconstructed original surface levels of *Raheenmore Bog.* The reconstruction is based on a reference profile averaged from sites 327, 330 and 211. The bottom level of the peat at site 330 was estimated from the depth of the deepest piezometer on the site.

Between the sites 206-2, 206 and 201 in the transects C-E and NE-E, the reconstructed surface level shows a sharp drop of several metres to the margin. The relatively high position of the mineral subsoil at 206 and 206-2 indicates the presence of a ridge that may have been overgrown by a bog forming vegetation at a relatively late stage of development of the Raheenmore Bog. It is visible in the field in the form of a slight local steepening of the NE facing surface slope. Because of the small differences in the field and the relatively coarse 100x100m levelling grid, it does not show up clearly on the surface level contour maps. Together with the relatively large D_o of the FP and the small D_0 of the HSP at 201 and 206-1, this supports the view expressed in 7.3.2, that this part is a lagg that has been overgrown by *Sphagnum* peat at a relatively late stage of the development of Raheenmore Bog, possibly when the ridge became overgrown by *Sphagnum* peat from its western side.

The reconstructed transect N-C-S shows a concave bog surface with the highest positions at or near the margins, 1-3 m above the centre. Such a cross sectional shape of an undisturbed raised bog seems unlikely, because it would effectively create a lake in the centre of the bog. The transect C-E gives a similar picture from the centre to site 206. The reconstructed surface level at site 206 is about 1 m higher than at 330. The sites 336 and 342 at the northern margin show a similar difference with the centre. Two hypotheses, explaining the apparently anomalous shape of the reconstructed surface are possible.

(h) Along margins, a denser peat has formed than in the central part.

(i) The central part of the bog has also subsided and the differences between the reconstructed levels in the centre and near the margins are related to differences between peat depths in the centre and along the margin.

Neither hypothesis excludes the other. However, the extent to which hypothesis (b) explains the phenomenon, determines the 'room' left for (a), and vice versa. An indication as to whether (a) is reasonably realistic in the case of Raheenmore Bog can be obtained by testing whether it would be realistic to attribute the entire effect to hypothesis (b).

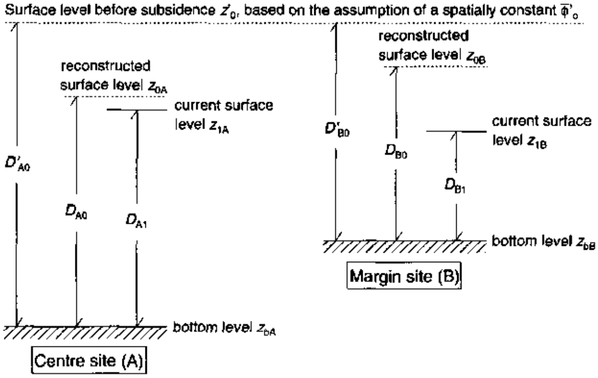

Fig. 7.6. Schematic representation of peat depths D, levels z and mean volume fractions of solid matter ϕ_0 used in deriving Eq. (7.3). Subscripts A and B refer to sites A and B, respectively. The subscripts 1 refer to the situation after subsidence, the subscripts 0 to the situation before subsidence. D' and z' refer to reconstructed situations that are entirely based on the hypothesis that differences in ϕ_0 are solely due to differences in peat depths before subsidence (hypothesis (b) only).

Let us consider a centre profile A and a margin profile B (Fig. 7.6) with respective bottom levels z_{bA} and z_{bB}, peat depths D_{A1} and D_{B1} and average volume fractions of solid matter $\bar{\phi}_{oA1}$ and $\bar{\phi}_{oB1}$. Comparison with a reference profile using Eq. (3.9) yields reconstructed surface levels and respective depths D_{A0} and D_{B0}, such that $\bar{\phi}_{oA0}$ and $\bar{\phi}_{oB0}$ of the respective reconstructed profiles equal $\bar{\phi}_{o0}$ of a reference profile.

A reconstruction that is entirely based on hypothesis (b) requires an additional assumption as to the original difference in surface levels between centre and margin sites. Because any such assumption would be a guess, the levels are assumed equal. This implies a mesa-shaped bog instead of a convex one and an underestimation of the subsidence in case only hypothesis (b) is true. Thus the same volume fraction of solid matter $\bar{\phi}'_{o0}$ before subsidence occurred is postulated at both sites ($\bar{\phi}'_{o0} = \bar{\phi}'_{oA0} = \bar{\phi}'_{oB0}$).

$\bar{\phi}'_o$ and $\bar{\phi}_o$ are related by

$$\frac{\bar{\phi}_o}{\bar{\phi}'_o} = \frac{D'_{A0}}{D_{A0}} = \frac{D'_{B0}}{D_{B0}} \tag{7.2}$$

Because $D'_{A0} = z'_0 - z_{bA}$ and $D'_{B0} = z'_0 - z_{bB}$,

$$\frac{z'_0 - z_{bA}}{D_{A0}} = \frac{z'_0 - z_{bB}}{D_{B0}} \qquad z_{bB} > z_{bA},\ z_{bB} + D_{B0} > z_{bA} + D_{A0} \tag{7.3}$$

or

$$z'_0 = \frac{D_{B0} z_{bA} - D_{A0} z_{bB}}{D_{B0} - D_{A0}} \qquad z_{0B} > z_{0A},\ z_{bB} + D_{B0} > z_{bA} + D_{A0} \tag{7.3a}$$

Applying Eq. (7.3a) to sites that meet the specified conditions yields the results shown in Table 7.1.

Table 7.1 shows that attributing the higher reconstructed surface levels near the margin entirely to hypothesis (b) yields unrealistic subsidence values of approximately the entire present peat depth at all sites on the southern end of the N-C-S transect. The results for the sites at the other ends of the transects look more acceptable. If the bog had originally had a convex cross-sectional shape, an even larger subsidence would have to be assumed.

Table 7.1. Results of surface reconstruction using Eq. (7.3a) with site 327 used as 'centre' site (A in Fig. 7.6). Levels of reconstruction shown in Fig. 7.5 have been added for comparison.

Site	Peat bottom z_b (m OD)	Peat depth D_1 in 1991 (m)	Surface level z_1 in 1991 (m OD)	Reconstructed surface level z_0 of Fig. 7.5 (m OD)	Surface level z_0 reconstructed using Eq. (7.3a) (m OD)
327	94.1	12.5	106.6	106.7	-
206	97.0	6.1	104.0	107.1	108.0
313	100.1	5.0	105.1	108.6	112.5
317	99.4	6.5	105.9	109.1	116.9
321	98.9	7.8	106.7	108.6	114.6
324	97.4	9.3	106.7	107.8	112.6
336	100.6	5.5	106.1	107.0	107.4
342	101.6	3.5	105.6	107.3	107.7

Hence hypothesis (b) should be dismissed as the sole explanation of the phenomenon of the increase of the level of reconstructed surface levels from centre to margin as shown in Fig. 7.5. It may, however, be a partial explanation. Therefore hypothesis (a) cannot be dismissed and consequently the assumption of the same original ϕ_o in each peat type that underlies the application of Eq. (3.9) in estimating subsidence is incorrect. Subsidence calculated by the method developed in 3.10 should therefore be named *apparent* subsidence rather than just subsidence. Shrinkage of layers determined in this way should accordingly be termed apparent shrinkage. Apparent subsidence or shrinkage can be defined in an absolute or relative sense, i.e. as a length or as a fraction of the original thickness. The relative approach is useful in comparisons between profiles. The choice is arbitrary. Relative apparent subsidence or shrinkage is defined here as

$$\varsigma_a = \frac{\overline{\phi}_o - \overline{\phi}_{o_{ref}}}{\overline{\phi}_o} \tag{7.4}$$

where

ς_a = relative apparent subsidence or shrinkage [1]

$\overline{\phi}_o$ = average volume fraction of solid (organic) matter [1] in the considered layer or profile

$\overline{\phi}_{o_{ref}}$ = average volume fraction of solid (organic) matter [1] in the reference layer or profile

ς_a seems correlated with distance to the margin. The relationship may differ by peat type and differences may reveal both effects of peat forming conditions in earlier mire stages and recent effects on $\overline{\phi}_o$. Because the hydrological processes are likely to have caused most of the differences, in Fig. 7.7 ς_a of the FSP, HSP and FP is plotted against the distance to the margin along the flow path (*cf.* 5.4) across the sampling site.

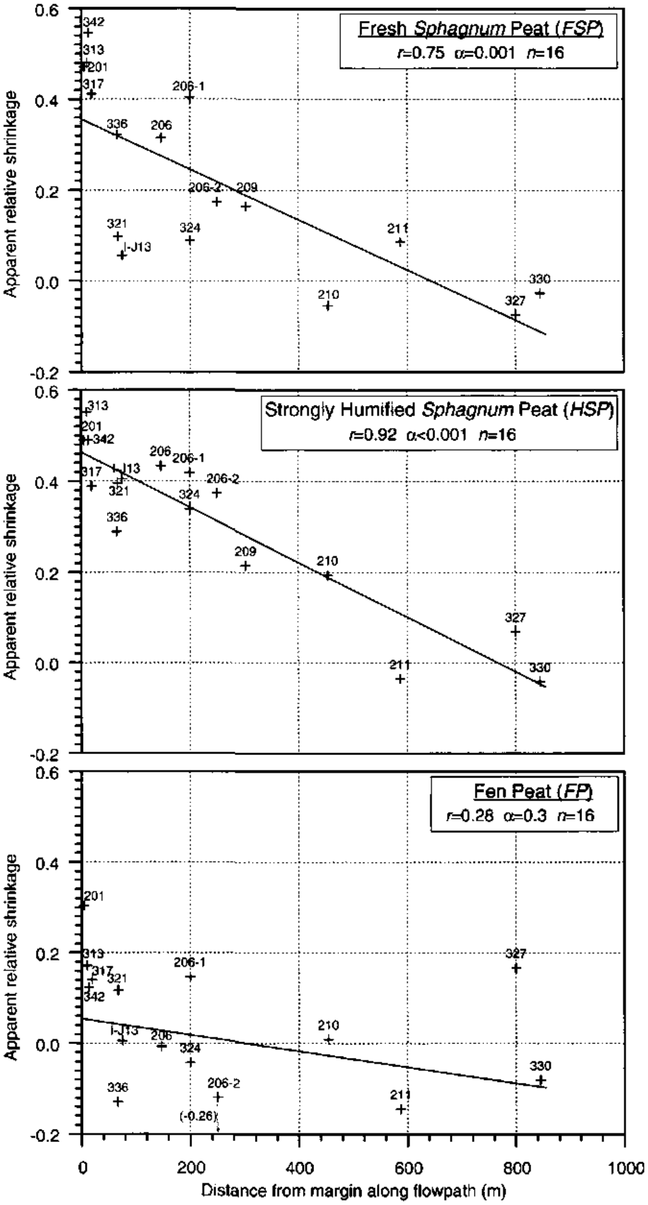

Fig. 7.7. Relationships of *apparent* relative shrinkage ς_a of the main peat types FSP, HSP and FP with distance to the bog margin on *Raheenmore Bog*.

The most significant relationship is the one of the HSP with a correlation coefficient of 0.92. The FP shows no significant relationship and the FSP a reasonably significant relationship with distance to the margin, albeit with some outliers. From the literature quoted in 2.7, one may conclude that superficial drainage has at least initially far and away its strongest impact on the upper peat layers, *i.e.* the FSP in the case of Raheenmore Bog. Drainage by an increased surface slope may be regarded as shallow drainage. Hence, the relationship for the HSP might reflect the original natural drainage conditions of Raheenmore Bog better than the one for the FSP. In the FSP, changes in surface slope and flow paths induced by human influence, are likely to have affected ς_a. This also supports the conclusion that during the stages of development of the *Sphagnum* peat the difference in drainage conditions between centre and margin, related to the convex cross-sectional shape of the bog has caused the forming of peat with a density that increased from centre to margin.

The lack of relationship in the FP may be explained by two hypotheses.

a. During the fen stage, the hydrological system of the mire must have been related to (ground)water levels in the basin and its near surroundings. Physical conditions probably differed little between centre and margin, resulting in the near absence of a relationship in the FP between ς_a and the position on the bog.

b. The combination of low piezometric levels and the locally coarse texture of the underlying till may have caused a certain collapse of the lower part of the FP as discussed in 5.5.4.

Both will be discussed in 7.4.3 in relation to results from Clara Bog West.

7.4. Clara Bog West

7.4.1. Introduction

On Clara Bog West, four transects marked SW-N, W-E, Western Mound-S and Shanley's Lough-S (Fig. 7.8) are available. The analyses were done as described for Raheenmore Bog. Fig. 7.8 shows the positions of transects and individual sites.

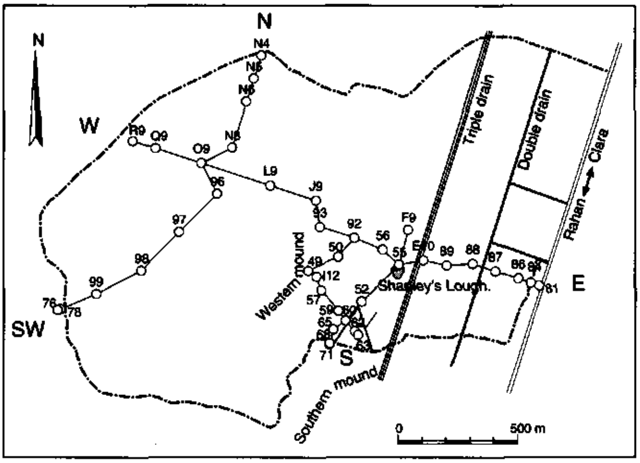

Fig. 7.8. Sampling transects and -sites on Clara Bog West.

The spatial pattern of ϕ_0 and D_0 of the three peat types will be discussed briefly. This part will be completed by a discussion on the differences in ϕ_0 between the main peat types in the transects of Clara Bog West and Raheenmore Bog. As to subsidence, Clara Bog West has some special features:

- the subsidence caused by the Clara-Rahan road
- the subsidence in the area of Shanley's Lough that may have caused its present position as an outlet area for the discharge of approximately 40% of the area of Clara Bog West
- the slightly concave shape of the present bog surface.

The reconstruction technique is basically the same as applied on the data of Raheenmore Bog.

7.4.2. Volume of solid matter per peat type: spatial patterns and comparison with Raheenmore Bog

Spatial patterns

The transects (positions shown in Fig. 7.8) are presented in Fig. 7.9, Fig. 7.10, Fig. 7.11 and Fig. 7.12 in the same way as those of Raheenmore Bog.

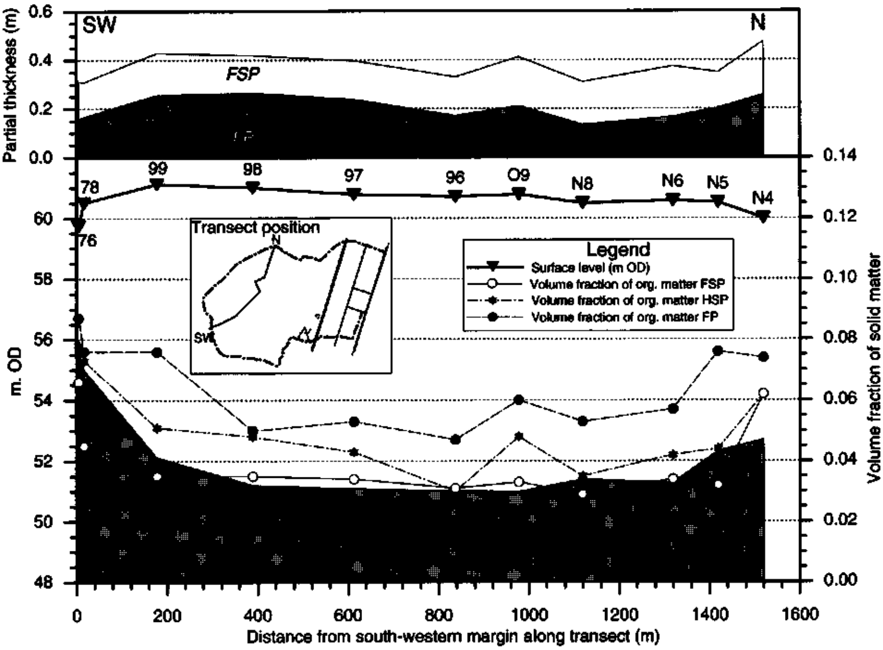

Fig. 7.9. Partial thickness D_0 and volume fraction of solid matter ϕ_0 of Fresh *Sphagnum* Peat (FSP), Strongly Humified *Sphagnum* Peat (*HSP*) and Fen Peat (FP) and levels of the peat surface and peat bottom along the SW-N transect of *Clara Bog West*.

The values of ϕ_0 have a tendency to increase from centre to margin as concluded in 4.2.3. In this respect, there is little difference with Raheenmore Bog. The vertical pattern is also similar, but the difference between ϕ_0 of FP and HSP on Clara Bog West is smaller than on Raheenmore Bog. The average partial depth D_{0p} in the central part of Clara Bog West is approximately 40 cm, about 5 cm less than in the central part of Raheenmore Bog. Smaller values of D_{0p} related to elevations in the mineral subsoil as observed on Raheenmore Bog, also occur on Clara Bog West (Fig. 7.10, sites Q9 and 92; Fig. 7.11, site 65 and Fig. 7.12, site 49).

An increase of D_0 of the FP and a corresponding decrease of D_0 of the *Sphagnum* peat towards the margin as on Raheenmore Bog is not recognisable on Clara Bog West. However, such a difference exists between the composition of the peat of the area to the W and S of Shanley's Lough (transects of Fig. 7.11 and Fig. 7.12) and of the other parts of Clara Bog West. In the former area D_0 of the FP is larger and D_0 of the *Sphagnum* peat types is smaller than in the latter. This indicates that mesotrophic conditions may have been more persistent W and S of Shanley's Lough than elsewhere on Clara Bog West. At the face bank at the end of the transect from Shanley's Lough to 'S', the HSP could not even be distinguished clearly from the FP because of wood remains occurring together with remains of species such as *Calluna* and *Sphagnum*, that indicate more ombrotrophic conditions. This is why in Fig. 7.11 no HSP is shown at sites 68 and 71. Such mixed peats were also reported in profiles described by Bloetjes and Van der Meer (1992).

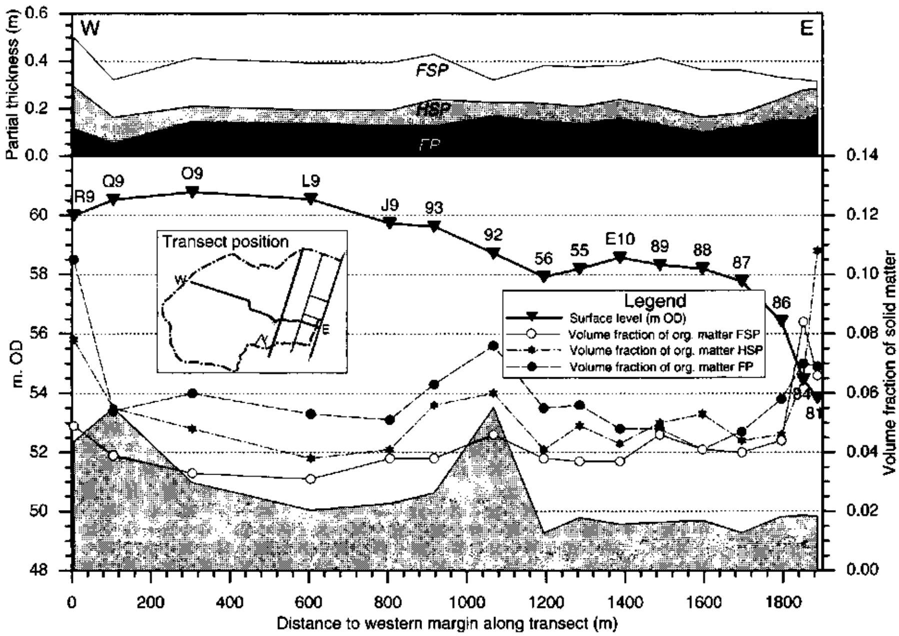

Fig. 7.10. Partial thickness D_0 and volume fraction of solid matter ϕ_0 of Fresh *Sphagnum* Peat (FSP), Strongly Humified *Sphagnum* Peat (HSP) and Fen Peat (FP) and levels of the peat surface and peat bottom along the W-E transect of *Clara Bog West.*

The area is bounded in the south by a large till mound marked as 'Southern mound' in Fig. 7.8 and in the west by the higher ground marked as 'Western mound' in Fig. 7.8 and Fig. 7.12. The Western Mound consists of till (Smyth, 1993) and is covered by peat. The peat cover on the top consists of fen peat only (*cf.* site 49 in Fig. 7.12). The southern till mound lies in the cutover zone. Morphologically it is connected with a higher area, locally known as 'The Island', which consists of till covered limestone (Smyth, 1993). It bounds the entire cutover zone S and SW of Clara Bog West. Limestone is a major component of the till (Van Tatenhove and Van der Meer, 1990). A relatively long lasting persistence of mesotrophic conditions in the part of Clara Bog between the mounds and Shanley's Lough may probably be attributed to the runoff of (ground)water with a high content of calcium from both mounds. Even upward seepage from the western mound during the fen stage is not unlikely, because it is a 'window' of relatively permeable till in the highly impervious lacustrine clay that is subjacent to most of Clara Bog. Thus, similar to Raheenmore Bog, the proximity of higher mineral grounds with a high content of limestone is likely to have caused a longer development of fen peat at the expense of *Sphagnum* peats. The average D_{0p} in the area is a few cm larger than elsewhere on Clara Bog West. Whether this difference is related to differences in water quality conditions is not clear.

Thus Clara Bog West can be divided into two different parts: the area between the mounds and Shanley's Lough on one hand and the rest of Clara Bog West on the other.

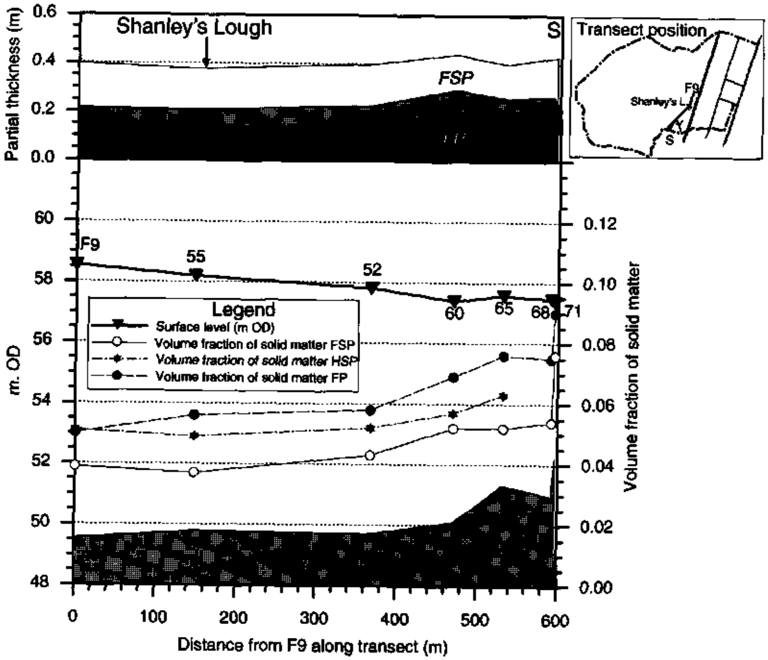

Fig. 7.11. Partial thickness D_0 and volume fraction of solid matter ϕ_0 of Fresh *Sphagnum* Peat (FSP), Strongly Humified *Sphagnum* Peat (HSP) and Fen Peat (FP) and levels of the peat surface and peat bottom along the transect from site F9 north of Shanley's Lough to the southern margin of *Clara Bog West*.

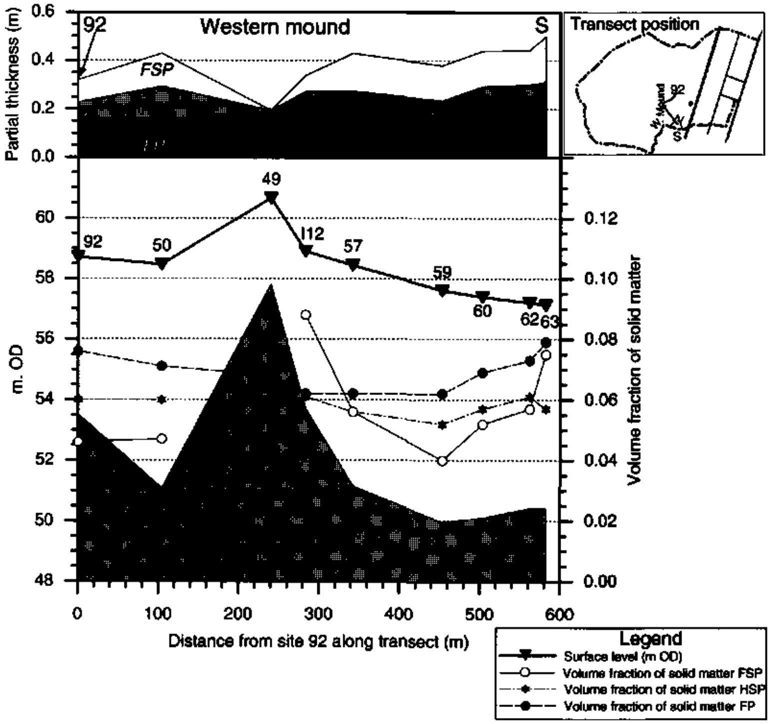

Fig. 7.12. Partial thickness D_0 and volume fraction of solid matter ϕ_0 of Fresh *Sphagnum* Peat (FSP), Strongly Humified *Sphagnum* Peat (HSP) and Fen Peat (FP) and levels of the peat surface and peat bottom along the transect from site 92 across the area of the western mound to the southern margin of *Clara Bog West*.

Comparing Clara Bog West and Raheenmore Bog

Fig. 7.13 shows the mean of ϕ_0 and its 95% confidence interval of six transects, the four of Clara Bog West and the two larger ones of Raheenmore Bog. To avoid margin effects such as subsidence during periods of different length, margin sites were not included. The excluded sites were R9, N4, 76, 78, 71, 68, 81, 84 and 86 (Clara Bog West, Fig. 7.8) and 201, 206, 313, 317, 336 and 342 (Raheenmore Bog, Fig. 7.1).

In the *Sphagnum* peat, little difference exists between the mean ϕ_0 of the two large transects SW-N and W-E of Clara Bog West and those of Raheenmore Bog. However, ϕ_0 of the *Sphagnum* peat between the mounds and Shanley's Lough, the FSP in particular, is considerably larger than elsewhere. As to the FP, the area SW of Shanley's Lough is intermediate between Raheenmore Bog and the other parts of Clara Bog West. The difference between the mean ϕ_0 of the FP of Raheenmore and of Clara Bog and its possible causes were discussed in 5.5.4.

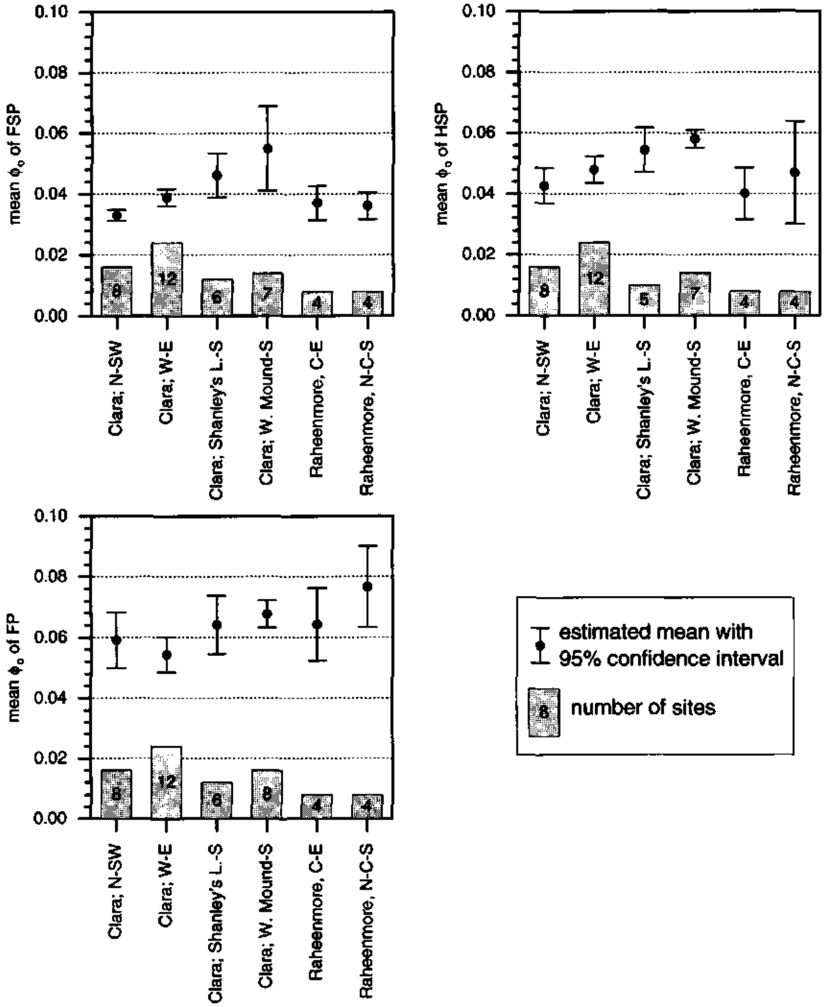

Fig. 7.13. Mean volume fraction of solid matter ϕ_0 of Fresh *Sphagnum* Peat (FSP), Strongly Humified *Sphagnum* Peat (HSP) and Fen Peat (FP) with 95% confidence intervals and numbers of sampling sites.

The overall picture suggests a considerable subsidence in the area between Shanley's Lough and the mounds. Because the largest and statistically most significant difference between this area and the other two was found in the FSP, superficial drainage (drains and increased surface slope resulting from turf cutting along the southern margin) is the most likely cause (*cf.* 4.2.3).

7.4.3. Reconstructing former bog surface levels

The transects SW-N and W-E

Because of the differences between the area between the mounds and the rest of Clara Bog West as discussed in 7.4.2, the reconstruction of surface levels based on Eq. 3.9 is discussed separately for both areas. The reference profile was synthesised from 97, J9, L9, N8 and O9 (positions shown in Fig. 7.8) by averaging ϕ_0 per peat type. Site 96 in the same part of the bog was not included because of its position in a small soak system. Hence it might not be representative of other parts of Clara Bog West. Fig. 7.14 shows reconstructed surface levels of both transects together with surface levels from levellings by OPW in 1991 and 1992.

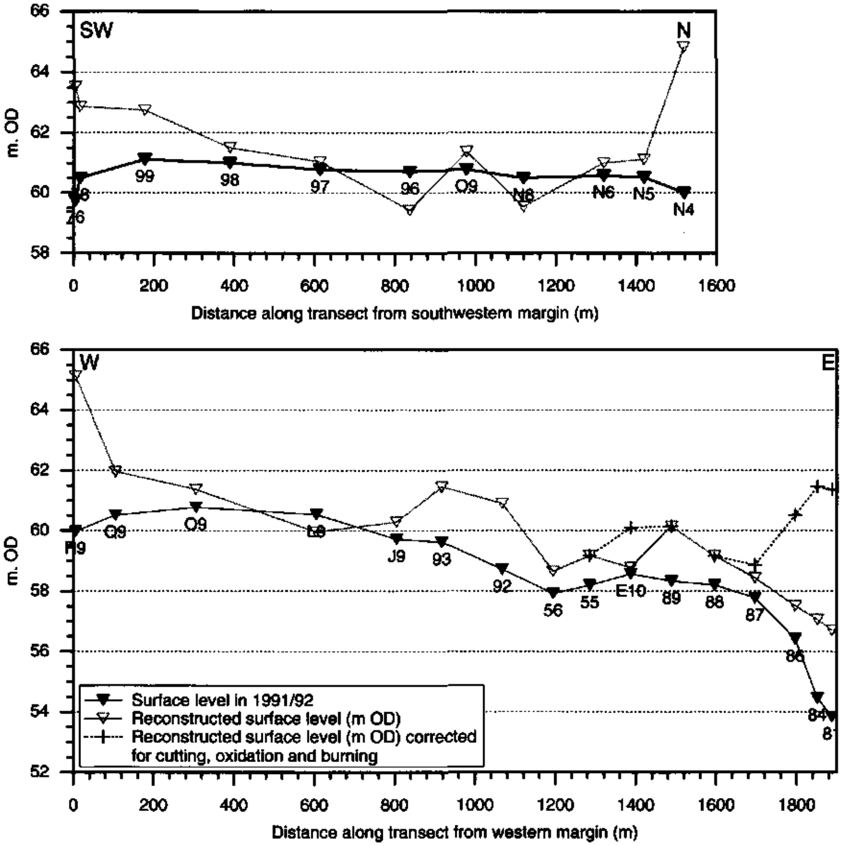

Fig. 7.14. Reconstructed surface levels and surface levels measured in 1991/92 along the transects SW-N and W-E of *Clara Bog West*. Transect W-E with and without corrections for peat losses along the Clara-Rahan road.

The highest reconstructed levels in Fig. 7.14 occur at and near the northern, western and south western margins of Clara Bog West, similar to the transect ends at the margins of Raheenmore Bog (Fig. 7.5). Applying Eq. (7.3a) with J9 and L9 as 'centre' sites yielded unlikely or even impossible surface levels between 70 and 110 m OD. This means that the effects can be largely attributed to natural differences in peat density. If an overall subsidence of Clara Bog West and a tendency of looser peat to shrink more than denser peat under comparable conditions are assumed, this may explain the unusual shape with water divides not far from the margins (e.g. site 99 in Fig. 7.9, O9 and N9 in Fig. 7.10) and the large catchment area (Fig. 6.21) that discharges *via* the area of Shanley's Lough. Such a subsidence can neither be proven nor estimated by any of the applied methods, because a reference profile that has not subsided beyond doubt is not available. However, the shape of the surface of Clara Bog West strongly suggests such a subsidence. The most likely cause is the drainage system along the Clara-Rahan road. On Clara Bog West, this system consists of the drains immediately adjacent to the road which are still effective, the double drain and the triple drain (the latter two are marked as such in Fig. 7.8). The latter two systems are now almost entirely grown in and are hardly visible in the field, but must have been effective in earlier times during several decades after the road was built.

The reconstructed surface in Fig. 7.14 suggests that either the area near Shanley's Lough has been in a relatively low position for at least several centuries or conditions for peat growth in this part have caused a relatively loose peat type that has subsided more than surrounding, possibly denser peats. Palaeobotanical research with inference on palaeohydrology might provide an answer.

The downward slope towards the Clara-Rahan road of the reconstructed surface must be attributed to loss of peat. This may be concluded from the small D_0 of the FSP near the road (Fig. 7.9 and Table 7.2). Losses should be attributed to superficial peat cutting (a face bank of 70 cm high lies 50 m to the west from site 84), oxidation of aerated peat and burning. The losses may be quantified tentatively by assuming an original D_0 of the FSP. Because the road was built across what probably was the most central and highest part of Clara Bog, a reasonable value may be inferred from the values of the sites used in synthesising the reference profile. The average D_0 of the FSP at those sites is 18.7 cm. Larger values on the transect between Shanley's Lough and the road are 19.8 and 20.3 at sites 88 and 89, respectively. Thus 18.7 cm seems a reasonable and maybe conservative estimate. Where the measured D_0 of the FSP exceeded the estimated value, the measured value was kept. At sites where an interpolation between both neighbouring points yielded a larger value than 18.7 cm, the larger value was applied. Although near Shanley's Lough, at sites 55 and 56, D_0 of the FSP is relatively small, the measured values were applied. The low measured D_0 of the FSP at site E10 may be related to losses because of its position near the triple drain. Hence the estimated D_0 was interpolated between sites 89 and 55. Table 7.2 shows measured and reconstructed D_0 of the FSP.

Table 7.2. Measured and reconstructed partial thickness D_0 of the Fresh *Sphagnum* peat (FSP) in the western part of the transect W-E.

Site	55	E10	89	88	87	86	84	81
D_0 FSP measured (cm)	16.8	14.2	20.3	19.8	17.8	8.8	4.2	3.3
D_0 FSP reconstructed (cm)	16.8	18.5	20.3	19.8	19.3	18.7	18.7	18.7

The dotted line in Fig. 7.14 represents the reconstructed surface after correction for losses by cutting, oxidation and burning. The relatively low level at the sites 88 and 87 suggests more peat losses than accounted for in Table 7.2. These might be related to the double drain that lies about halfway between the sites, but with the available data it is not possible to estimate the effect.

Although the reconstruction of the surface level of site 81, only 9 m away from the road has a tentative character, it shows that the present level of the road lies at least 6-7 m below the original surface level, even without taking subsidence at the reference sites into account.

Between the mounds and Shanley's Lough

Although the peat profiles in the area differ from those in the rest of Clara Bog West as described in 7.4.2, the reference profiles applied in the reconstruction in the transects SW-N and W-E have to be used to estimate of the subsidence in the area. There is no acceptable alternative because the entire area between the mounds is likely to have subsided considerably. Hence no profile in it is suitable as a reference.

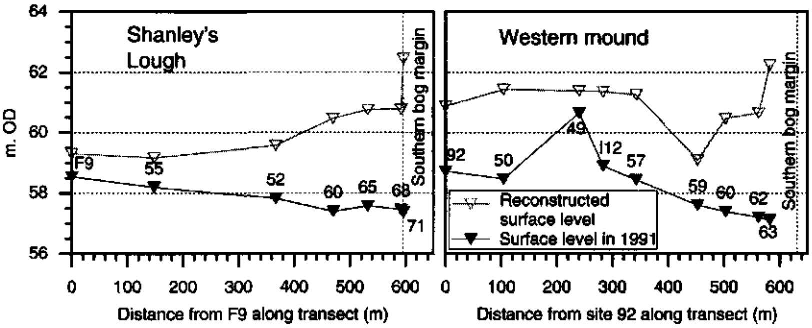

Fig. 7.15. Present and reconstructed surface levels in the area between 'mound', Shanley's Lough and southern bog margin on *Clara Bog West.*

Fig. 7.15 shows the reconstructed surface levels and those measured in 1991/92. At the margin sites 63 and 71 near the southern mound high reconstructed levels occur, similar to those on Raheenmore Bog (*cf.* 7.3.3) and at both ends of transect SW-N and the western end of the transect W-E (Fig. 7.14).

Although the reconstructed levels may not be highly accurate, the estimated subsidence of up to 3 m, excluding the margin sites, leaves little doubt that indeed a considerable subsidence has occurred. A remarkable but unexplained feature is the low reconstructed level at site 59, but even there the reconstruction suggests a subsidence of nearly 2 m.

Other evidence of subsidence is the level of the peat surface on the western mound. Its highest point is about 61 m OD, whilst the water surface of Shanley's Lough lies at approximately 58 m. The mound's western slope is shorter and less steep than its eastern equivalent. The bog surface to the west of the mound lies about 2.50 m higher than the surface around Shanley's Lough. The top of the mound is covered by a shallow layer of fen peat (Fig. 7.12, site 49). This suggests a former surface position approximately equal to the surface level of the surrounding bog. Whether or not the fen peat on the top used to have a (shallow) cover of *Sphagnum* peat that has disappeared by burning, oxidation or both is not clear. The presence of till with a high content of limestone at a small depth of 1-2 m may have prevented a transition to *Sphagnum* peat. This requires a former surface level of the bog around 62-63 m OD and suggests a subsidence of the western part of Clara Bog West, probably induced by the road and its associated drainage system by about 2 m. The subsidence in the area between the mounds would then have been about 4-5 m.

This change in the area near Shanley's Lough is likely to have occurred during the 19th century, because Shanley's Lough is not shown on the Ordnance Survey map of 1838, but it is shown on the map of 1910 (Kelly & Schouten, 1999). Hence the lake must be a relatively recent phenomenon. This information allows a more complete picture of the subsidence history of Clara Bog West to be drawn.

The subsidence was probably induced by the road and its associated drainage system. Together with the difference between properties of margin and centre peat it caused the present slightly concave shape of Clara West. The peat surface on top of the western till mound subsided relatively little because of its shallowness. Thus the mound began to form a barrier to acrotelm flow from the western part of the bog to the area in the SE. Because the supply of water from more upstream parts of the bog became impeded, the area dried out. Consequently, the subsidence increased until eventually the surface level was sufficiently low to attract flow from other parts of Clara West along a flow path around the northern and maybe also the southern end of the western mound. As the double and triple drain became clogged by *Sphagnum* growth, their draining effect gradually decreased. This and the new position as an outlet for the discharge of a large part of Clara Bog West caused a rewetting of the area, resulting in renewed peat growth. Possibly this rewetting was stimulated by a change to slightly wetter climatic conditions at the end of the 19th century, which was inferred by Van der Molen (1992) from palaeobotanic data of Clara, Woodfield and Carbury bogs. However, some doubt whether such climatic change really occurred is justified. As for Clara Bog, it would have coincided with the likely recovery from damage caused by the road. As for Woodfield Bog, a similar recovery from the bog burst of 1821 (Früh, 1897; Van der Molen, 1992) is not unlikely.

Whether the relatively small values of D_0 of the FSP near Shanley's Lough have been caused by a temporary drying out of the area or should be attributed to other causes is not clear. However, the relatively large values of the sampling sites 88 and 89 may have prevented that part from subsiding as much as the more western part of the area by causing an effective barrier against flow towards the road. The two drains in the 'V'-shaped position SW of Shanley's Lough may have contributed to the present drainage pattern by causing some further subsidence in the south.

The above hypothesis is not necessarily in disagreement with the suggestion of a (temporary) separate development of the bog area W and E of the western mound as mentioned by Ten Dam and Spieksma (1993). However, the latter hypothesis implicitly postulates a hydrological separation between both parts of Clara Bog West at some stage of mire development. Such a hypothesis should be dismissed because of the absence of till mounds or -ridges below the peat surface between the western mound, Shanley's Lough and the road and between the mound and The Island. Ample evidence of this absence is available, not only from the profiles and transects shown in this work, but also from the survey of the peat stratigraphy by Bloetjes and Van der Meer (1992) and from the geophysical survey of Clara Bog by Smyth (1993). Thus a connection along the northeastern and the southern ends of the western mound must have existed between both mire parts from almost the beginning of peat growth in the Clara Bog basin. Because the bottom of the peat between the western mound and Shanley's Lough lies 1-2 m lower than in the western part of Clara Bog West, flow around the mound might have existed during some time. However, the surface reconstruction gives no reason to believe that such a pattern has persisted until recent times. From the evidence available, it seems far more likely that Clara Bog has developed and kept a classic radial drainage pattern until the road was built.

Apparent relative shrinkage and distance to the margin

For Clara Bog West, a similar analysis of the relationship of apparent relative shrinkage ζ_a versus estimated distance to the margin along flowlines through measuring sites on the bog can be made. Fig. 7.16 is the equivalent for Clara Bog West of Fig. 7.6. Because of the disturbance of the bog along the road, lines are fitted with and without data from the sites E10 and 81-89.

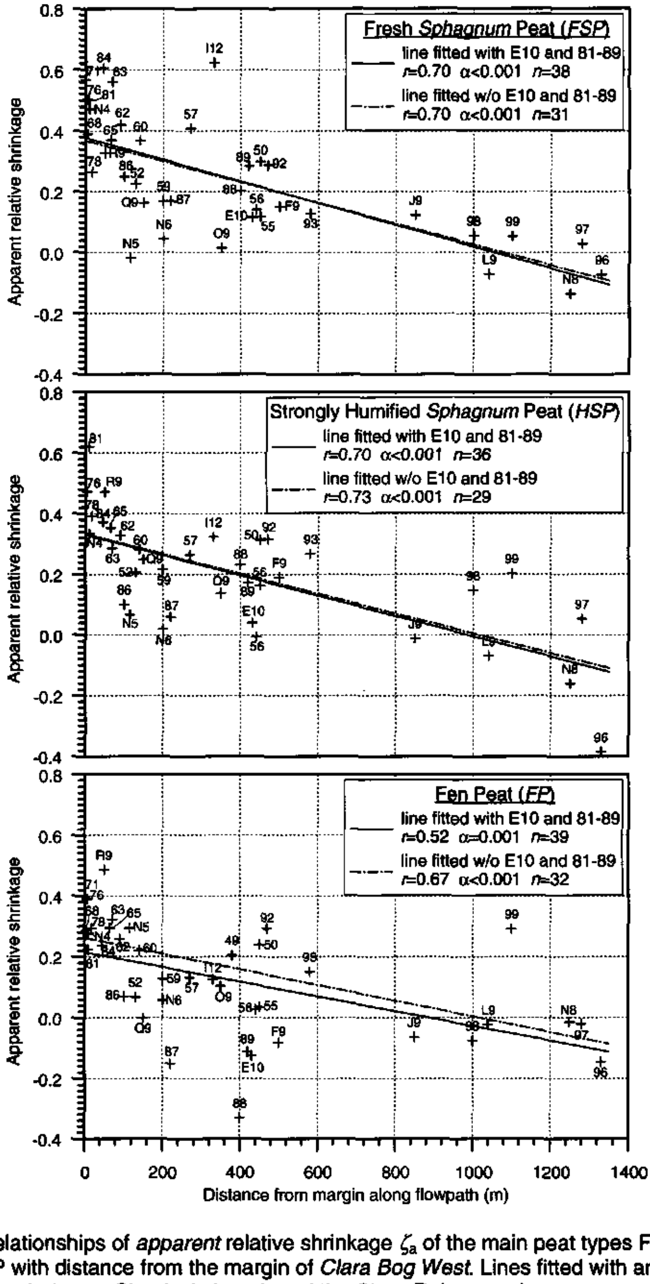

Fig. 7.16. Relationships of *apparent* relative shrinkage ζ_a of the main peat types FSP, HSP and FP with distance from the margin of *Clara Bog West*. Lines fitted with and without sites between Shanley's Lough and the Clara-Rahan road.

As for the FSP, the correlation level for Clara Bog is marginally lower than for Raheenmore Bog and there is no difference between the datasets with and without the sites between Shanley's Lough and the road. As for the HSP, the correlation level is much lower than for Raheenmore Bog, even for the set without the road sites. The level of the latter is only marginally better than for the entire set. The most likely cause is a change in flow paths resulting from subsidence during the second half of the 19^{th} century and after, caused by the road.

The higher correlation for the FP compared with Raheenmore Bog shows that the hypothesis that the low correlation for Raheenmore Bog is related to different conditions during the fen stage should be rejected. The correlation for the subset without the road sites is slightly better and gets close to the levels found for FSP and HSP. However, the second assumption that compaction of the FP is determined at least in part by differences in the hydraulic conductivity k of sediments directly underlying the peat, seems to be confirmed. Clara Bog West is underlain by an impervious lacustrine clay (*cf.* 5.5.4) with an estimated vertical resistance C of 10^4-10^5 d, except at some local buried till mounds below the peat surface. The underlying mineral substratum of Raheenmore Bog is generally of a coarser type, with a resistance that may be assumed to be accordingly smaller.

7.5. Subsidence in recent years

7.5.1. Introduction

In the autumn of 1998 data on surface level and peat depth surveys by Bord na Móna were obtained from Michael Gill of Trinity College, Dublin. The data of Raheenmore Bog are from 1948, those of Clara Bog from 1982, just before Clara Bog East was drained. Only the surface levels will be used in this section. They will be compared with the surface levels of the 100x100-m grid, levelled by OPW on both bogs. This will allow a quantitative assessment of the speed of subsidence of both bogs in recent years. Some additional survey work was done on Raheenmore Bog in 1994 (Gill and Johnston, 1999). Most of these data are identical to those of 1990, but some additional levels were measured between the points of 1990.

7.5.2. Raheenmore Bog

The base line of the Raheenmore grid of 100x100 m that was laid out in 1990 coincided with the base line of the 1948 survey (x=0 in Fig. 7.17). A cross section along the base line was analysed together with parallel cross sections at distances of 650 and 1300 yd (594 and 1189 m) and one cross section along a line perpendicular to them. Their positions are shown in Fig. 7.17.

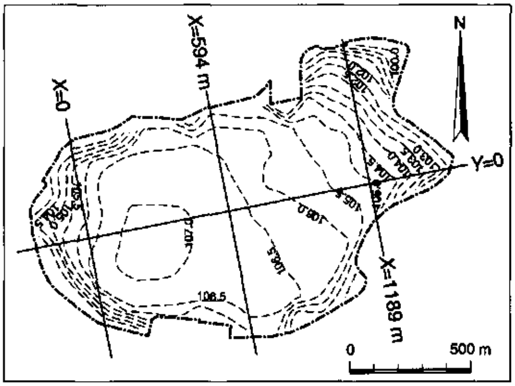

Fig. 7.17. Positions of the cross sections of *Raheenmore Bog*. Baseline denoted by "x=0".

The distance between the measuring points of the cross sections of 1948 was 100 yd. The distance in the 1990 grid was 100 m. Hence the points of 1948 and 1990 did not coincide and interpolation was needed to make comparisons. The values of 1990 were interpolated to estimate values at the sites of 1948. Because the surface level in a bog is a rather poorly defined quantity, individual data may be expected to have an uncertainty of several cm. Diagrams of the cross sections with estimated changes in surface level are shown in Fig. 7.18, Fig. 7.19, Fig. 7.20 and Fig. 7.21.

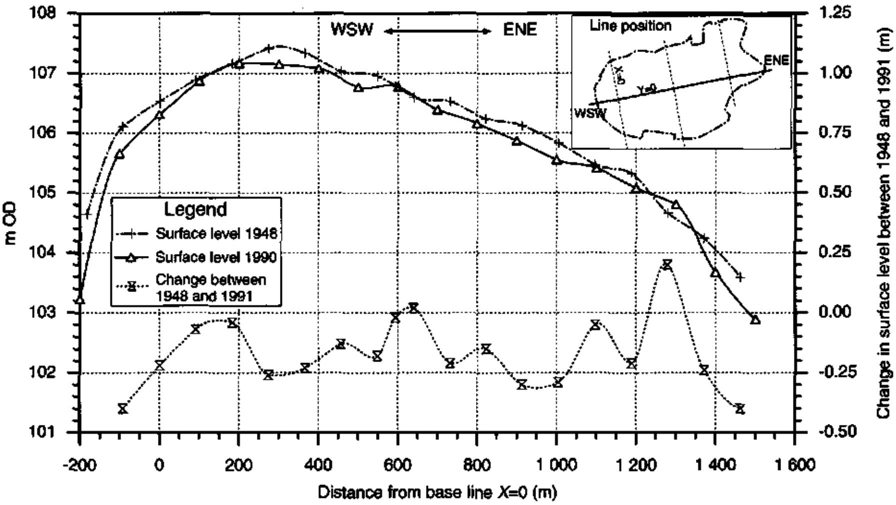

Fig. 7.18. Cross-section with surface levels of 1948 and 1990 and subsidence calculated by subtraction along the line *Y*=0 of Raheenmore Bog.

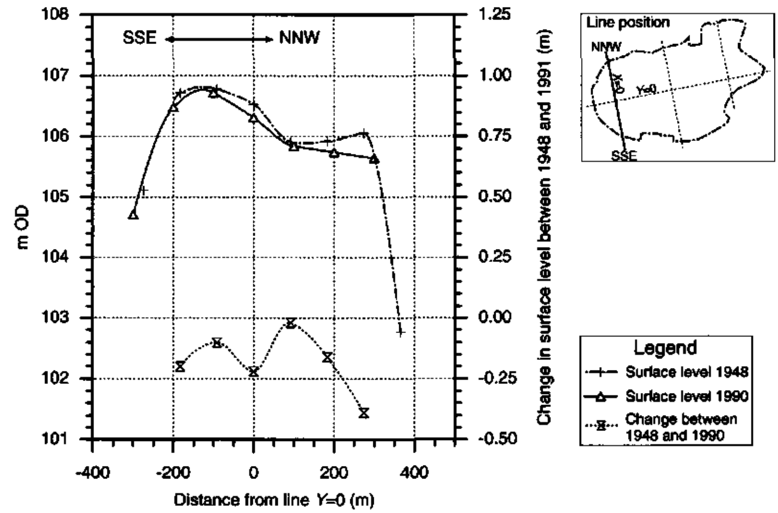

Fig. 7.19. Cross-section with surface levels of 1948 and 1990 and subsidence calculated by subtraction along the line x=0 of Raheenmore Bog.

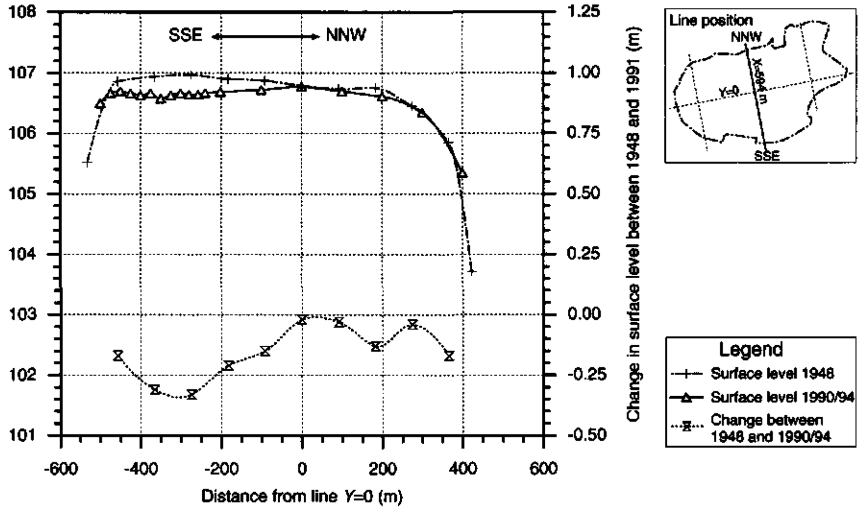

Fig. 7.20. Cross-section with surface levels of 1948 and 1990/94 and subsidence calculated by subtraction along the line x=594 of Raheenmore Bog. The 1994 data are surface levels at distances of 25 m instead of 100 m in the southern half of the cross-section.

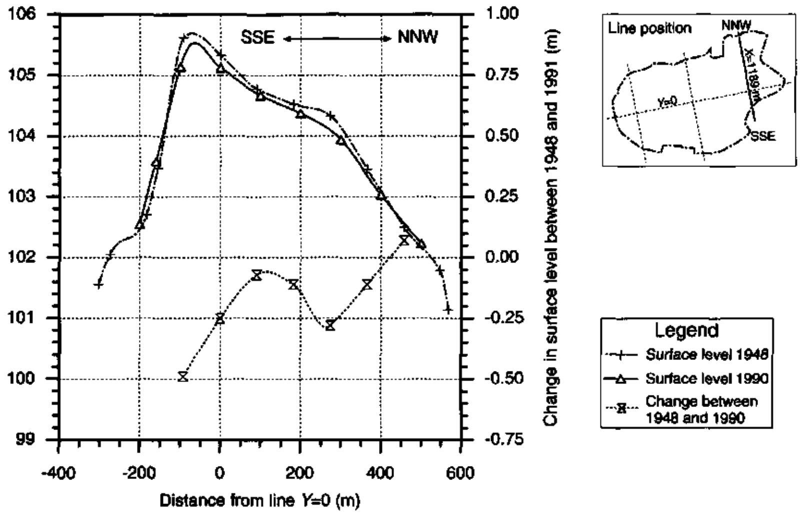

Fig. 7.21. Cross-section with surface levels of 1948 and 1990 and subsidence calculated by subtraction along the line *x*=1189 of Raheenmore Bog.

All cross-sections show subsidence values with an average of about 20 cm. The sections X=594 and X=1189 (Fig. 7.20 and Fig. 7.21, respectively) show a trend of increasing subsidence towards the south, the other two sections only show variations around a rather constant mean.

Section *x*=594 (Fig. 7.20) shows that the watershed has moved towards the bog margin since 1948. This is probably a process, similar to what has occurred at a much larger scale on Clara Bog, related to the difference in density between peat near the margin and in the centre of the bog. It seems likely that it has been caused by turf cutting at the southern margin in the years between 1948 and the early 1970's, when the bog became state property. In the part that lies now to the north of the watershed and thus has a somewhat impeded drainage, a deep acrotelm has developed locally. This may indicate that the bog is recovering there from damage inflicted in the past. Table 6.1 shows the results of all cross-sections and the bog. If a normal distribution and statistical stationarity of the obtained spatial series are assumed, the 5% confidence interval of the difference in level between 1948 and 1990 over the entire bog is from 13.5 to 21.5 cm. If translated to subsidence, the result may contain a systematic error of a few cm, caused by *Mooratmung*.

Table 7.3 shows that the average subsidence between 1948 and 1990 must have been about 4 mm a^{-1}. The remaining question is whether this subsidence was a natural phenomenon or an effect of human activities.

Table 7.3. Means and standard deviations of change in surface level between 1948 and 1990 along the different cross-sections.

Cross-section	*Y*=0	*x*=0	*x*=594	*x*=1189	Entire bog
Average change in surface level (m)	-0.185	-0.182	-0.156	-0.176	-0.176
Standard error of mean (m)	0.029	0.050	0.034	0.068	0.020
Number of sites	19	6	10	7	42

A rough check is available in the form of the three benchmarks BM1, BM2 and BM3, installed in 1991 (positions shown in Fig. 3.14). The vertical position of the steel bottom plate was recorded to measure *Mooratmung*, but it can also be used to assess long term vertical movement of the bog surface. The level was first measured on 19th April 1991. The last measurement by the author was done on 15th December 1997. In 1996 and 1997, the *Sphagnum* growth on or next to the bottom plate was also recorded. Table 7.4 shows the values for five dates.

Table 7.4. Average distances between table and bottom plate of the three benchmarks (cm) and *Sphagnum* depth (cm) on the bottom plate as developed since the installation in 1991. At BM1, the *Sphagnum* was mainly *S. magellanicum*, at BM2 mainly *S. capillifolium*. At BM3 the *Sphagnum* species was not recorded.

	BM1	BM2	BM3
19th April 1991	78.1	63.1	83.5
20th March 1992	81.4	66.1	83.9
11th March 1993	81.1	65.7	83.1
16th January 1996	87.8	68.7	81.7
Sphagnum depth	6.5	Not measured	6.3
15th December 1997	88.0	66.7	80.3
Sphagnum growth	10	6.5[1]	9

Table 7.4 shows that the original bog surface in the centre at BM1 is subsiding by more than 1 cm a^{-1}, but that the subsidence is compensated approximately by *Sphagnum* growth. The subsidence in the last two years may have stopped as a result of tests with two dam systems that blocked the discharge from parts of Raheenmore Bog. At BM3 at the margin the surface has risen slightly. This effect may be attributed to the blocking of a nearby drain in 1989. In addition to the small rise of the surface level, 9 cm of *Sphagnum* has developed. BM2 takes an intermediate position with a net rise of the surface (including *Sphagnum* growth) of a few cm. These data show that since the early 1990's the subsidence has probably stopped and at least locally turned into a small rise of the bog surface. Similar growth rates of *Sphagnum* were observed in December 1997 at a

[1] Next to plate, plate beginning to be covered

number of dip well sites where the distance from the top of the tubes to the surface had decreased since 1992 by amounts in the order of about 10 cm.

From this information the conclusion may be drawn that the surface subsidence calculated for 1948-90 has not continued after 1990, partly because of compensation of subsidence by *Sphagnum* growth and partly because the original surface has risen slightly as a result of conservation measures. Because decay and compaction in the catotelm are natural and continuing processes, a natural bog shrinks. Under natural conditions, the shrinkage is usually compensated by growth of new peat material at the surface. In situations with overcompensation, the bog surface rises, during undercompensation it subsides. Assuming an age of 8000 years for Raheenmore Bog, the average net growth has been approximately 1.5 mm a^{-1}.

A possible explanation for the net shrinkage that occurred between 1948 and 1990 could be the condition of the acrotelm. In the mid-1970's it looked very poor (Matthijs Schouten, personal communication), probably as a result of repeated burning. In such a situation surface runoff occurs frequently because of the lacking regulating effect of the acrotelm. The resulting increased drainage caused a subsidence that possibly exceeded the natural shrinkage rate. The subsidence was not or only partly compensated for by the vegetation that needed one to two decades to recover and to redevelop an acrotelm.

Effects on subsidence and deteriorated acrotelm conditions as attributed to the marginal drainage by Gill and Johnston (1999) are not confirmed. The small subsidence is more likely to have been caused by a temporarily disturbed acrotelm. The existence of the drain during about 200 years as mentioned by the same authors and the small exfiltration rate of 10-15 mm a^{-1} inferred in 5.5 are sufficient evidence for the absence of adverse effects on acrotelm conditions.

7.5.3. Clara Bog

The baseline of the survey of 1982 lies in the longitudinal direction of Clara Bog and perpendicular to the Clara-Rahan road. 13 cross sections were made perpendicular to the base line at intervals of 300 yd. On the bog, the distances between the measuring points were mostly 100 yd. For a comparison with the data of the 1991 survey with a 100x100 m grid, the 1991 data were interpolated to estimate the 1991 surface level at the measured points of the 1982 survey.

The positions of the base line of the 1982 survey and the 13 perpendicular cross-sections are shown in Fig. 7.22.

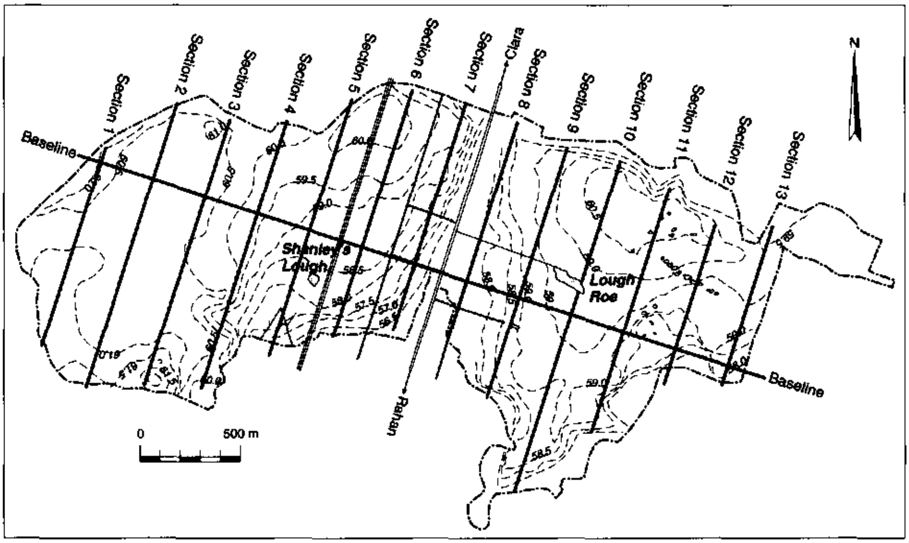

Fig. 7.22. Positions of the baseline and cross-sections of the level survey in 1982 of Clara Bog.

If statistical stationarity and a normal distribution of the data along each section are assumed, a mean with confidence interval of changes in surface level can be calculated per section. The result is shown in Fig. 7.23.

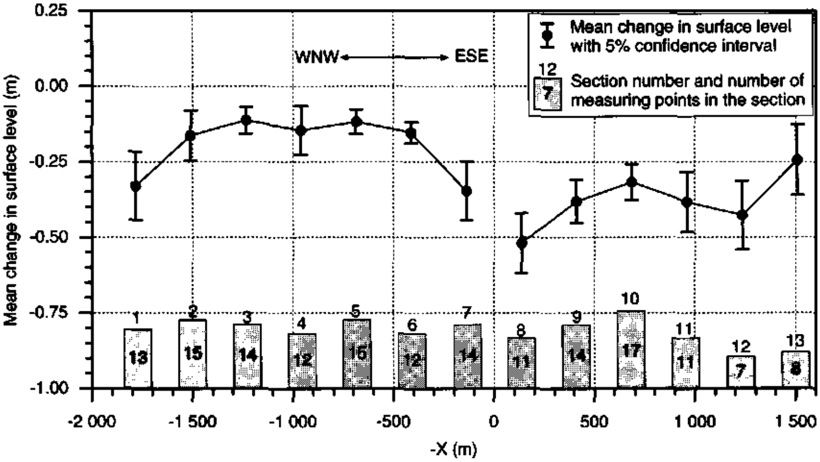

Fig. 7.23. Mean changes of the surface level from 1982 to 1991 along the sections of Clara Bog shown in Fig. 7.22 with their 5% confidence interval of the mean and the numbers of data points per section.

Fig. 7.23 demonstrates that the subsidence along the Clara-Rahan road is larger than elsewhere on the bog and that the subsidence on Clara East is larger than on Clara West.

The subsidence in the road-"corridor" continued in the 1980's at an estimated speed of about 4.5 cm a^{-1}. The subsidence on Clara East was on average about 4 cm a^{-1} versus 2 cm a^{-1} on Clara West. Without section 1, the value for Clara West is 1.5 cm a^{-1}. The larger figure for Clara East is undoubtedly related to the drains, cut in 1983. However, the value of Clara West shows that subsidence caused by the road continues. It also indicates that the inference of an overall subsidence in the central part of Clara West of 2 m over the last 150 years, made in 7.4.3 probably is a conservative estimate. The patchy pattern of deep acrotelms and the large proportion of shallow acrotelms on Clara West in Fig. 6.24 also indicates that the bog surface is still drained more rapidly than a healthy bog.

The narrow confidence intervals in Fig. 7.23 of the sections 5 and 6 that traverse the area of Shanley's Lough show that variations along the line are small and that in the 1980's subsidence rates in the region of Shanley's Lough were at the average level for the central part of Clara West. The section across Lough Roe (section 10) shows a much larger confidence interval.

The reasons for the relatively large subsidence along the western margin of Clara Bog (section 1) do not become clear from Fig. 7.23.

Therefore diagrams of the sections 1 and 10 are presented in Fig. 7.24 and Fig. 7.25, respectively.

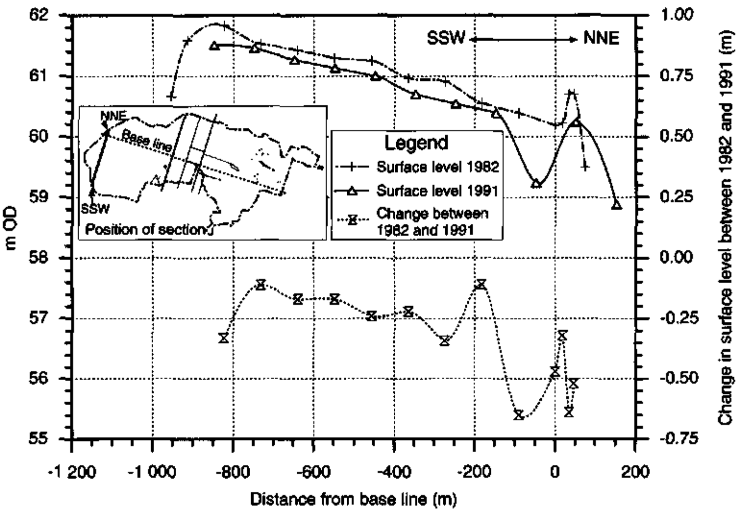

Fig. 7.24. Cross-section 1 of Clara Bog with surface levels of 1982 and 1990 and calculated subsidence.

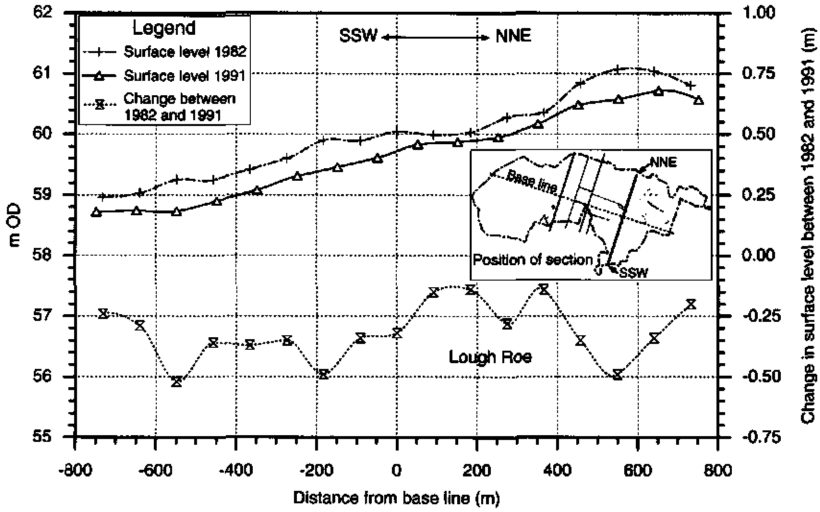

Fig. 7.25. Cross-section 10 of Clara Bog with surface levels of 1982 and 1990 and calculated subsidence.

The subsidence along Section 1 (Fig. 7.24) shows a tendency to increase toward the northwestern bog margin. This may again be related to differences between margin peat and peat in the central part of the bog. The north-western margin of Clara Bog has originated from the cutting of a bog area that stretched a few km to the north-west and formed a connection with a bog system to the north of the esker. Hence it is a part of Clara Bog where no bog margin existed in the near vicinity.

Section 10 (Fig. 7.25) shows a subsidence between 25 and 50 cm, except in the area of Lough Roe, where averages of 20 cm occur. This part of the bog indeed remained relatively wet in spite of the drainage. The section also shows that the watershed in the north has moved further northwards by 100-200 m in 10 years. This demonstrates the process of watersheds moving towards the margin in a subsiding bog where margin peat still exists.

The few available data of the benchmarks at the plots A and B show no subsidence between 1991 and 1997. A rise of 1 or 2 cm over the entire period might even be derived from them. This indicates that the blocking of the drains of Clara Bog was effective in terms of subsidence. At the drier plot C, located in a slightly sloping part of the bog, the subsidence seems to have continued, but at a rate of less than 1 cm a^{-1}.

7.6. Conclusions

- Subsidence along drained margins expands into a raised bog by acrotelm and surface flow rather than by catotelm flow. Only the initial subsidence over a few metres along a newly formed face bank may be attributed to catotelm flow. This explains observations from literature (*cf.* 2.7) that most shrinkage usually occurs in the upper peat layers.

- Both in Clara West and in Raheenmore Bog, the total amounts of solid matter in the peat vary little. In the central part of Raheenmore Bog, the partial depth D_{op} is about 45 cm, in the central part of Clara Bog West about 40 cm. At higher levels of the mineral subsoil, close to margins and above till mounds below the bog surface, D_{op} is usually smaller.
- The transects of Raheenmore Bog show a relatively large D_o of the FP close to the margin. This may indicate a longer persistence of mesotrophic conditions and possibly a slow process of a lagg being overgrown by *Sphagnum* peat. The north-eastern margin of Raheenmore Bog seems to be an example of such a process, because of the low position of both its current and reconstructed surface levels. Such phenomena were not found along the margins of Clara Bog West. However, a similar process may have occurred in the area between Shanley's Lough, the western and the southern mound, where minerotrophic conditions may have persisted during a longer period than elsewhere on Clara Bog West.
- The reconstructed original surface levels of both bogs indicate that a more compact peat has been formed along the margins and a looser peat in the centre. This has some practical consequences. The method of reconstructing pre-subsidence bog surfaces as developed in 3.10 can only be applied if the reference profile(s) and the profiles to be reconstructed are in comparable positions on the bog. Remnants of raised bogs are more sensitive to adverse effects of subsidence on vegetation along margins where the cutover zone has a considerable width than where no more than some tens of metres have been removed by cutting. Where little of the margin zone has been cut and the slope of the bog surface allows an outlet for excess water, this may eventually cause a slightly convex shape. Clara Bog West is a clear example, but the southern part of Raheenmore Bog and Clara Bog East show signs of a similar process.

  Where the margin peat has been cut away, a convex shape of the bog remnant is likely to develop, such as the near-elliptical cross-sectional shapes of subsided bog remnants Aue (1991, 1992) described.
- Because the reference profiles may also have subsided, it is not possible to reconstruct a bog surface without additional information. As for Raheenmore Bog, the available information of recent subsidence indicates that no major subsidence has occurred on most of the bog and that the bog is actually recovering from earlier damage. The marginal drain has little or no negative effect on the bog itself. As for Clara Bog West, additional information is available in the top level of the fen peat covered western mound. It leads to an inferred subsidence of the reference sites of at least 2 m since the middle of the 19th century. Levellings of 1982 and 1991show that even on Clara Bog West the process of subsidence, caused by the road and its associated

drainage continues at a speed of 1.5 cm a^{-1} in the central part and considerably more along the northwestern margin and the road. This large rate is in agreement with the relatively large proportion of shallow and non-existing acrotelms on Clara West.

- The natural difference between margin and centre peat and subsidence caused by the drainage system associated with the Clara-Rahan road that was constructed around 1840, are likely to have caused the present slightly concave shape of Clara Bog West. The subsidence in the area between the mounds and Shanley's Lough has been 4-5 m. It is probably the combined effect of the drainage system of the road and the western mound that impeded the flow of water from the central part of Clara Bog West to the area. The level of the Clara-Rahan road is at least 6-7 m below the former the bog surface and 8-9 m if subsidence at the reference sites is taken into account.
- The present flow pattern of Clara Bog West is dominated by the converging flow system that discharges along Shanley's Lough and has originated from this subsidence. The 'V'-drains SW of Shanley's Lough may have contributed to the present southward slope of the area. The original flow pattern of Clara Bog probably was a diverging and approximately radial system. The changes incurred by the drainage of the road have caused the flow towards areas closer to the margin to decrease. Consequently, the principle of the size of the upstream catchment and surface slope as determining factors for acrotelm conditions as tested in 6.3.7, has caused a decay of the acrotelm. It is likely to be responsible for the large average width of about 200 m of the zones formed by the ecotopes 'face bank', 'marginal' and 'sub-marginal', distinguished by Kelly and Schouten (1999).
- The conclusion of rather drastic changes in the flow pattern of Clara Bog West is supported by the difference between the highly significant relationship of the volume fraction of solid matter ϕ_b of the HSP of Raheenmore Bog versus distance to the margin and the much more scattered pattern of the same data from Clara Bog. The correlation level for the FSP for Raheenmore Bog is lower than the level for the HSP and differs little between both bogs. This may be related to recent changes in hydrological conditions that have affected both Raheenmore and Clara Bog.
- The lack of relationship of ϕ_b of the FP and the distance to the margin on Raheenmore Bog is related differences in the mineral substratum rather than differences in the bog. The mineral substratum is likely to be more permeable on Raheenmore Bog than on Clara Bog, where it consists of impervious lacustrine clay. The underlying process, reduction of pore pressure by exfiltration through the mineral substratum, was discussed in 5.5.4. This may also explain why the relationship found for Clara Bog West yields a level of correlation that hardly differs from the levels found for FSP and HSP.

- The subsidence caused by the Clara-Rahan road has continued during 1982-1991. From those years, systematic levelling data are available. The rate of subsidence in the central area of Clara Bog West was 1.5 cm a^{-1}, which confirms the estimated large overall subsidence of the bog caused by the road. In the north-western part and along the road, the subsidence rates were about twice as large.
- The subsidence rate over 1982-91 on Clara Bog East was about 4 cm a^{-1}, which is a combined effect of the road and the superficial drainage system, installed in 1983. After 1991 little or no subsidence has occurred in the central part of Clara Bog East. This may be regarded as the effect of the provisional blocking of the drains in 1989. In the steeper parts, the subsidence has probably continued, albeit at a smaller rate.

8. PHREATIC LEVELS AND THEIR FLUCTUATION

8.1. Introduction

Phreatic levels at or close to the surface that fluctuate little are a determining factor in the growth of raised bog vegetation and sustained acrotelm conditions. Fluctuations are the result of precipitation, evapotranspiration, discharge and storage of water. The large storage coefficient in a well developed acrotelm (*cf.* 6.2) and the level dependent acrotelm transmissivity (*cf.* 6.3.3) limit the fluctuation of the phreatic level. Precipitation and to a lesser extent evapotranspiration, are externally imposed conditions. Hence their direct effect on hydrological differences within a bog can in most cases be regarded as negiligible. The rate of downward seepage (exfiltration) as inferred in 5.5 is too small to have any substantial effect on the phreatic levels of both Clara Bog and Raheenmore Bog.

In this chapter, phreatic levels are usually given relative to the surface level, which is defined as the estimated average bottom level of the hollows within 1 m around the measuring point. This implies an uncertainty of a few cm.

The effects of internal conditions on depth are demonstrated by the temporal fluctuation patterns recorded on different parts of the bogs. They will also be expressed in statistical relationships with surface slope and acrotelm conditions. In this chapter, acrotelm conditions are represented by a single quantity, the acrotelm depth D_a. D_a can be estimated for all places on the bogs from the maps of Fig. 6.23, Fig. 6.24 and Fig. 6.25. To give some more detail than a statistical analysis of one quantity against another allows, some transects across both Raheenmore Bog and Clara West are discussed. They show surface level, mean and fluctuation of the phreatic level and acrotelm depth.

For proper analyses, three problems had to be solved: representing fluctuation in a single number, comparing means and fluctuations of observation periods of different length and dealing with possible effects of surface level fluctuation (*Mooratmung*) on measured levels. These matters are discussed first.

8.2. Conversions of phreatic level data

8.2.1. Representing fluctuations of the phreatic level as a single quantity

Fluctuations of the phreatic level have to be expressed as a single quantity to allow establishing statistical relationships with other quantities. Such a quantity should preferably be based on all values in the period considered. The sample standard deviation around the mean s_h meets this requirement. For a series of n data, s_h is defined by

$$s_h = \sqrt{\frac{\sum_{i=1}^{n}(h_i^* - \bar{h})^2}{n-1}} \tag{8.1}$$

where

h^* = depth of the phreatic level [L]

$\bar{h}$ = arithmetic mean of the depth of the phreatic level [L] over the series of n observations

This leaves the question open as to what the relationship of s_h with the real fluctuation of the phreatic level is, because data sets of phreatic levels are not necessarily in agreement with a theoretical probability distribution. A reasonable quantity to compare s_h with is the bandwidth B_{90} that contains the central 90% of the data. It is calculated as the difference of the 5th and the 95th percentile of a data set. Six sites of Raheenmore Bog and six of Clara Bog West, representing different hydrological conditions are used in the comparison. Their temporal fluctuation patterns will be discussed in 8.3.

The result is presented in Table 8.1.

Table 8.1. Standard deviations s_h, their 90% bandwidths B_{90}, the ratios of B_{90} and s_h and the numbers of data n of the phreatic levels of six sites of Raheenmore Bog and six sites of Clara Bog West.

Site	n	s_h (m)	B_{90} (m)	$\frac{B_{90}}{s_h}$
Clara Bog				
48	95	0.084	0.255	3.05
49	94	0.220	0.675	3.07
55	94	0.062	0.130	2.08
59	95	0.041	0.125	3.05
62	95	0.084	0.250	3.00
68	95	0.181	0.640	3.54
Raheenmore Bog				
206	60	0.129	0.420	3.26
212	60	0.040	0.125	3.10
313	59	0.136	0.375	2.76
319	59	0.078	0.240	3.10
328	59	0.037	0.110	3.00
346	59	0.143	0.480	3.35
Fitted equation: $B_{90} = -0.024 + 3.34 s_h \quad r = 0.986$				

Table 8.1 shows a consistent relationship of s_h and B_{90}. A relationship derived from the normal distribution is $B_{90} = 3.29 s_h$. This result differs little from the fitted equation shown in the bottom row of Table 8.1. It can be concluded that s_h is a suitable quantity to de-

scribe the fluctuation of the phreatic level in one single value and approximately one third of B_{90}. There is no significant difference between the series of Raheenmore Bog with 59 and 60 observations and those of Clara Bog with 94 and 95 observations. This means that the relationship is reasonably independent of the applied numbers of data n.

8.2.2. Effects of *Mooratmung* on measured phreatic levels

Where observation wells are shallow, *i.e.* a metre or less, the fluctuation of their reference level (top of the tube) approximately follows the fluctuation of the surface level. This almost annihilates effects of *Mooratmung* on the data when they are expressed relative to the surface. However, some phreatic tubes in clusters with deep piezometers were attached to the deep piezometers with a wooden clamp to prevent them from moving up and down with the surface. The clamp was found to have little effect and the shallow tubes in a cluster usually kept moving up and down relative to the deep ones, although possibly less than without clamp. Hence corrections on measured levels might have to be made. Because of several problems with levelling equipment, the levelling results were only partly reliable. Consequently, a sensible correction of the observed levels for effects of *Mooratmung* was impossible and possible errors in the data had to be neglected. Therefore it was necessary to assess the size of these errors. First, the surface level fluctuations involved in *Mooratmung* were quantified. They were measured at some benchmarks on both Clara Bog and Raheenmore Bog (*cf.* 3.6) that were primarily intended as a reference for piezometer levelling.

Table 8.2 gives information on the periods of observation and the size of the fluctuations of the surface level.

Table 8.2. Surface level fluctuations at the benchmarks BM 1-3 of Raheenmore Bog, BM1-2 of Clara Bog West and BM A-C of Clara Bog East.

Benchmark	Period	Number of data	Difference between highest and lowest surface level (cm)	Sample standard deviation (cm)
		Raheenmore Bog		
BM 1	19/04/91 - 20/03/92	23	6.7	1.9
BM 2	19/04/91 - 20/03/92	23	4.9	1.1
BM 3	19/04/91 - 20/03/92	23	5.6	1.6
		Clara West		
BM 1	01/05/91 - 10/07/93	49	10.9	2.5
BM 2	01/05/91 - 10/07/93	53	3.2	0.8
		Clara East		
BM A	01/05/91 - 18/10/91	12	5.9	1.7
BM B	01/05/91 - 10/07/93	12	4.1	1.3
BM C	01/05/91 - 10/07/93	12	2.6	0.9

The positions of the benchmark sites are shown in Fig. 3.13 (Raheenmore Bog) and 3.15 (Clara West). The benchmark positions of Clara East coincide approximately with the central mini-transects of the plots A (sites 10-6), B (sites 25-21) and C (sites 40-36) shown in Fig. 3.8.

In view of the small fluctuations of the phreatic level in some parts of the bogs, the standard deviations of the surface levels at the benchmarks are too large to be neglected. The question was what the difference was between the fluctuations of the surface levels and the top levels of the clamped tubes. An assessment of the difference was possible, because at 11 sites on Raheenmore Bog an additional phreatic tube had been installed that was not connected to the cluster. Four levellings with reliable equipment of these sites were available. These gave an overall sample standard deviation of the difference in surface level between clamped and unclamped phreatic tubes of 5.6 mm with the top levels. This result proves the clamping to be highly ineffective and thus gives a reasonable confidence that it caused no substantial disturbance of the data.

8.2.3. Effect of observation period length on mean and standard deviation of phreatic levels

As for Clara West, a problem in comparing data from different dip wells had to be solved. Some wells had been observed from the autumn of 1989 to the summer of 1993, whilst other sites had only been installed in the winter of 1992. If all seasons were to be represented equally, the data series of the most recently installed wells would have to be cut down to just one year. For reasons of comparability, the same should be done to the longer series. This would mean an undesirable loss of data. Working around the problem by finding relationships between mean phreatic levels $\overline{h}$ and standard deviation s_h of one year and three year series was a more attractive option. Therefore a statistical analysis was made of $\overline{h}$ and s_h over three years between 31st July 1990 and 22nd July 1993 versus $\overline{h}$ and s_h of the same wells over 23rd July 1992 to 22nd July 1993.

The maximum possible number of observed phreatic levels per well over the three year period was 78. For the one year period this number was 27. Only wells with more than 70 values in the three year period and more than 24 in the one year period were included. The selection yielded 29 series with a sufficient number of data. Fig. 8.1 shows relationships of the three-year period versus the one over a single year. The fitting procedure was the RMA method, described in 5.3.2.

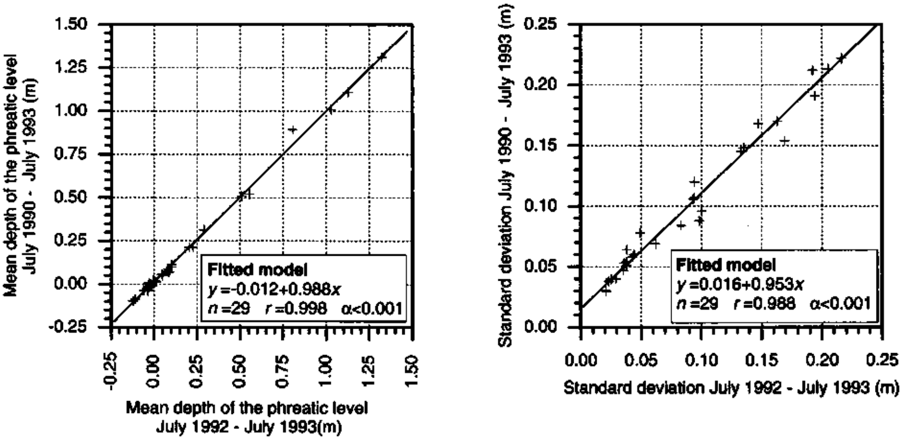

Fig. 8.1. Mean depths of phreatic levels $\bar{h}$ and their standard deviation s_h over 31st July 1990 to 22nd July 1993 versus those over 23rd July 1992 to 22nd July 1993.

Both relationships are highly significant. The correlation levels show that results from either period can serve as a reliable estimator for the other. As to $\bar{h}$, the relationship hardly shows a difference between the three-year and the one-year period. Therefore correction of $\bar{h}$ for different period lengths is unnecessary in comparisons between the one-year and the three-year data sets. The s_h over the three year period are larger than those over the one year period. Hence adjustments are needed before any analysis is made, particularly for the smaller values. Consequently, all one year s_h were corrected to estimated three year values, using the corresponding equation in Fig. 8.1.

8.3. Fluctuation patterns of phreatic levels

As a result of the interaction between vegetation, acrotelm conditions and fluctuations of the phreatic level in a raised bog, vegetation on a bog surface both indicates and influences hydrological conditions. Where phreatic levels on Clara Bog and Raheenmore Bog are relatively deep, the vegetation is usually dominated by a well developed canopy of *Calluna vulgaris*. Phreatic levels around the surface with small temporal fluctuations occur where a peat forming vegetation dominated by different *Sphagnum* species and *Eriophorum vaginatum* indicate a well developed acrotelm. Transitional areas between both comprise large parts of both bogs.

Fig. 8.2 shows three diagrams, each with series from two dip wells, of phreatic level versus time of sites on Raheenmore bog. Fig. 8.2a shows fluctuations of the area with a well developed acrotelm, Fig. 8.2c of *Calluna vulgaris* dominated margin sites with deep phreatic levels and large fluctuations. Fig. 8.2b shows two series from intermediate sites with a poorly developed or non-existent acrotelm.

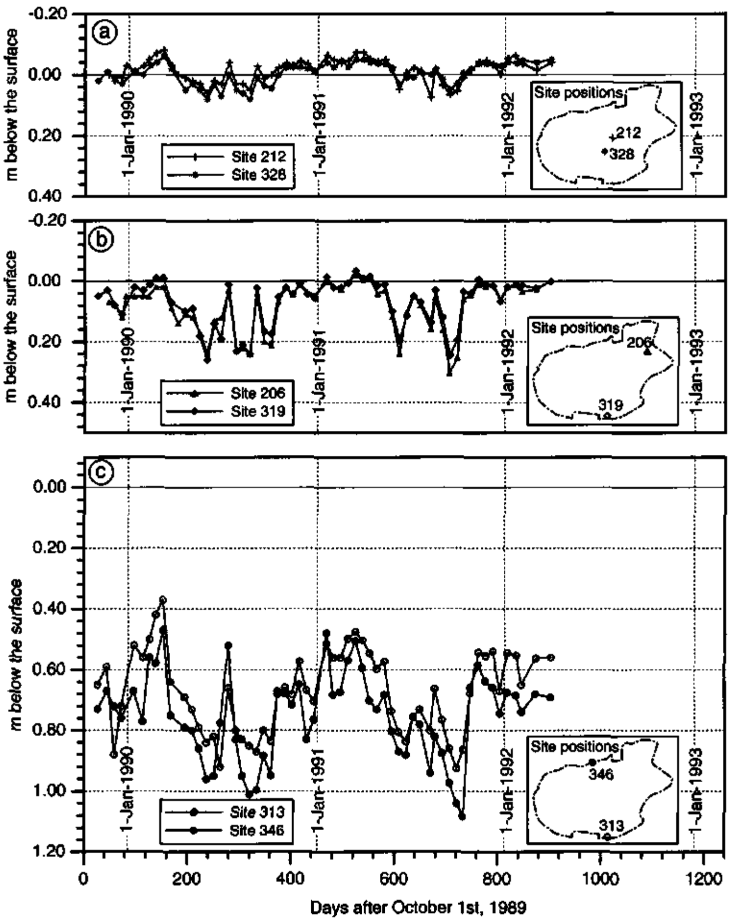

Fig. 8.2. Fluctuation patterns of phreatic levels on *Raheenmore Bog*. Patterns of areas with a well developed acrotelm (a), degraded bog (c) and intermediate areas (b).

The fluctuations increase from the centre where most areas with well-developed acrotelms occur, to the margins. Near the margins, the largest areas of degraded bog with deep phreatic levels occur.

In the centre, the total fluctuation is approximately 20 cm, considerably less than the 30 cm between mean annual highest and lowest levels inferred from literature in 2.3. The mean levels fluctuate around the surface, indicating a periodical drying of the hollows during the summer.

At the margins, the phreatic level fluctuates by about 0.50 m around a mean that is well below the surface. The increase in fluctuation with depth may be attributed largely to the downward decrease of the storage coefficient as inferred in 6.2. This is demonstrated in the curves of the intermediate sites in Fig. 8.2b. In the wet season, the fluctuation patterns are close to the surface and similar to those of Fig. 8.2a. When the phreatic level drops during the summer and reaches the deeper peat that has a smaller storage coefficient, the pattern begins to resemble that of Fig. 8.2c. Both sites of Fig. 8.2b are located in an area with a poorly developed acrotelm. If in time acrotelm growth will get a chance, the pattern might eventually change into something similar to Fig. 8.2a. In view of the ratios of calculated and actual acrotelm transmissivities found for Raheenmore Bog in 6.3.7, this is not an unlikely prospect.

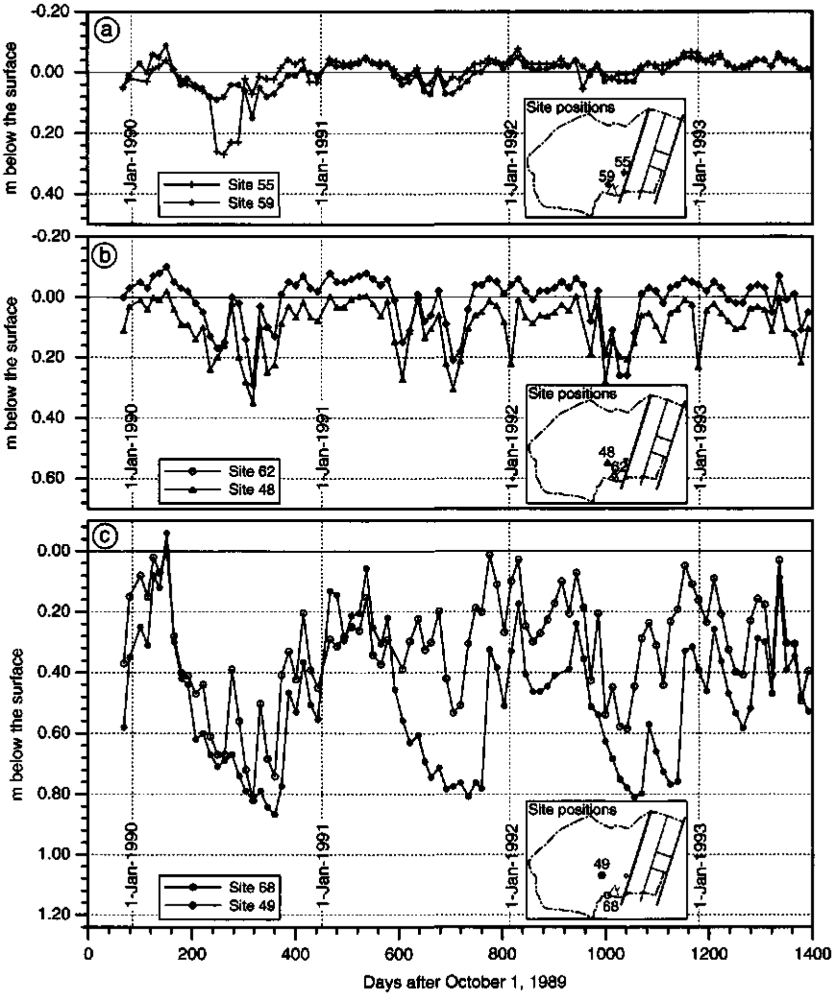

Fig. 8.3. Fluctuation patterns of phreatic levels on *Clara Bog West*. Patterns of areas with a well developed acrotelm (a), degraded bog (c) and intermediate areas (b).

Fig. 8.3 shows a similar set of diagrams of Clara Bog West. The sites are all located in the area west of Shanley's Lough because it is the part of Clara Bog where the longest series of more than 3.5 years were measured. The vast majority of the series from other parts comprises only about 1.5 years.

The differences are similar to those of Raheenmore Bog. Site 49 with its large fluctuations and deep levels is situated near the crest of the western mound where the peat is drained by the relatively steep slopes, caused by the subsidence described in 7.4.3. The other site with deep levels is 68, in the south at 4 m from a face bank. Site 68 shows signs of a quicker recovery of the phreatic level during wet periods than 49. This may be attributed to the outflow from the large catchment, which does not affect site 49 because of its elevated position (*cf.* Fig. 3.12).

A relatively large drop of the phreatic level at site 55 only a few m from Shanley's Lough occurred in the dry summer of 1990. The discharges of both Raheenmore Bog and Clara Bog measured at the gauging sites RHD1, CWD1 and CWD2 had fallen to insignificant levels of a few m^3 per day. The discharges in the summers of 1991-1993 remained larger and a similar drop of the phreatic level at site 55 did not occur again. Apparently, the phreatic level in the near surroundings of Shanley's Lough can only remain within a few cm from the surface as long as the discharge from the upstream part of the large catchment of Clara Bog West remains sufficiently large. Some losses to the ingrown triple drain system 50 m west of Shanley's Lough might have contributed to the phenomenon. At site 59, downstream of Shanley's Lough where the flow system has converged even more (*cf.* the contours in Fig. 3.12), the supply from upstream seems to have remained at a sufficient level to compensate for losses by acrotelm outflow and evapotranspiration.

The intermediate sites show patterns similar to those of Raheenmore Bog. The winter pattern resembles that of the wells with good acrotelms and the summer pattern looks more like the pattern of the areas with deep phreatic levels.

The diagrams of Fig. 8.2 and Fig. 8.3 indicate a relationship of depth and fluctuation of phreatic levels. The position of the sites on the bogs with the deepest levels and largest fluctuations close to the margin where the steepest surface slopes occur, indicate relationships with surface slope and/or proximity of the margin. It was shown in 7.2 that the jump in the phreatic level at the bog margin affects the phreatic level in the peat body over a horizontal distance of only a few m. Hence, the deep phreatic levels near bog margins should be attributed to the surface slope rather than the proximity of the margin. This is demonstrated in Fig. 8.3c, where site 49, positioned on the slope of the western mound shows even deeper levels and larger fluctuations than 68 at the bog margin. The physical background is natural drainage that becomes more effective with larger surface slopes as described in 6.3.6 and 6.3.7 and by Van der Schaaf (1996, 1998). Because of the regulating effect of the acrotelm on discharge and fluctuation of the phreatic level, the relationship is not one of a simple dependence, but rather of an interaction between acrotelm development and level and fluctuation of the phreatic level, given surface slope and flowpath length. Because flowpath length can only be estimated with a reasonable accuracy at a limited number of sites, it will only be discussed in section 8.5 on transects.

8.4. Statistical relationships

8.4.1. Introduction

The data used in this section are based on all sites with series of observations that have less than 10% of missing data. As for Clara Bog West, the analyses are based on one year and three year data series. The standard deviation s_h of one year series was converted to an estimated three-year series value using the equation shown in Fig. 8.1. For the depth $\bar{h}$ no conversion was made for reasons mentioned in 8.2.3.

The relationship of acrotelm depth D_a and surface slope I was already discussed in 6.4.4. Because the effect of the drainage of Clara Bog East obscures relationships of I and D_a, only the one of mean and fluctuation of the phreatic level will be discussed for this part of Clara Bog. An analysis of the relationship of phreatic levels and water levels in the drains will be added.

8.4.2. Surface slope and mean depth of the phreatic level

The mean depths $\bar{h}$ of Clara Bog West are based on July 1990 to July 1993 or July 1992 to July 1993, depending on the available data. The series of Raheenmore Bog comprised the two years from January 1990 to January 1992. Fig. 8.4 shows $\bar{h}$ versus surface slope I.

The relationship is based on the draining effect of the surface slope. Recharge from higher parts of the bog may reduce the effect and may thus be a partial explanation of the scatter of the points of both Clara and Raheenmore Bog. The estimating method for I is another source of

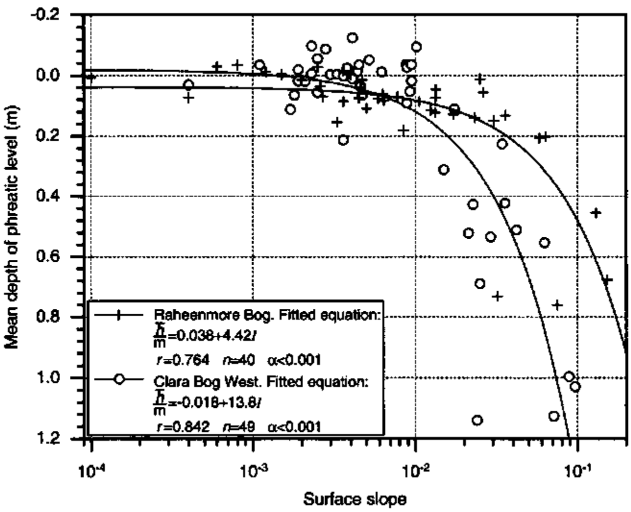

Fig. 8.4. Mean depth of the phreatic level $\bar{h}$ versus surface slope I on *Raheenmore Bog* and *Clara Bog West.*

scatter, because in most cases the result is based on five points in a 100 x 100 m^2 square. Thus the method ignores variations at a smaller local scale. More accurate values were calculated for the ends of transects (positions shown in Fig. 8.11 and Fig. 8.15) where the distance between neighbouring sites is considerably smaller than 100 m. The results of both Raheenmore and Clara Bog show a significant relationship in the statistical sense. The predictive power of the derived equation is limited, but Fig. 8.4 shows that $\bar{h}$ is insensitive to I if I is smaller than 0.007-0.01.

The slopes of both fitted lines differ, suggesting a stronger effect of I on $\bar{h}$ for Raheenmore Bog than for Clara Bog West. Whether this is a real effect or an artefact resulting from site positions remains unclear.

8.4.3. Surface slope and fluctuation of the phreatic level

The standard deviations s_h of the phreatic levels of Clara Bog West were calculated for the period of July 1990 to July 1993 or July 1992 to July 1993, depending on the available data. The s_h based on the one year period were corrected according to the equation developed in 8.2.3 in order to be comparable with the three year values. The s_h of Raheenmore Bog are all based on the two years from January 1990 to January 1992. Fig. 8.5 shows s_h versus surface slope I.

The physical explanation is the combined effect of increased drainage by steeper surface slopes and the decrease of the storage coefficient with deeper phreatic levels. As in Fig. 8.4, the scatter of the data may to some extent be attributed to the method of calculating the surface slope to differences in recharge from higher bog parts.

Both curves have an intercept -a predicted s_h for flat bog areas- of about 6 cm. No relationship seems to exist for $I<0.007$. This is a smaller value than estimated for Fig. 8.4. Unfortunately, the available data do not allow a rigid test, but if the difference really exists, it may probably be attributed to the shallower acrotelms and their more frequent absence at increasing slopes, as shown in 6.4.4.

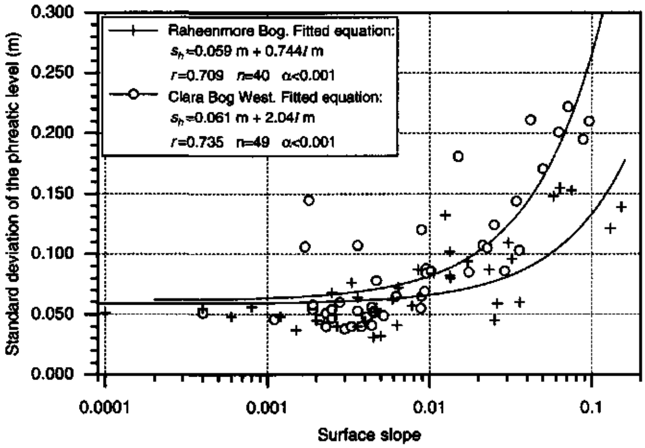

Fig. 8.5. Standard deviation of phreatic level s_h versus surface slope I for *Raheenmore Bog* and *Clara Bog West.*

Fig. 8.5 shows a divergence of the fitted lines, similar to Fig. 8.4. Like in Fig. 8.4, it is not clear whether this is a difference based on differences between the bogs or an artefact resulting from site selection.

8.4.4. Mean and fluctuation of the phreatic level

In view of the fluctuation patterns described in section 8.3 and the results obtained in 8.4.2 and 8.4.3, a positive correlation of $\bar{h}$ and s_h may be expected. No relationship of both $\bar{h}$ and s_h with I was found for small I. In these situations the average $\bar{h}$ approached 0 and s_h 5-6 cm. This implies that for small $\bar{h}$ and small s_h no more than a weak relationship between both may be expected. Therefore Fig. 8.6 shows two fitted lines, one for $\bar{h}$ <0.05 m and one for $\bar{h}$ >0.00 m.

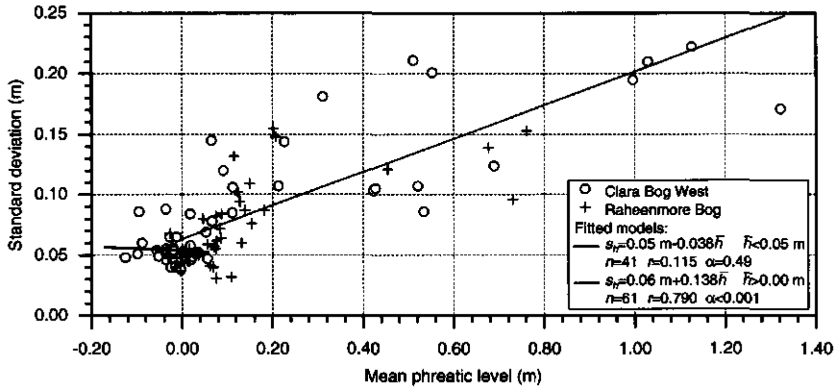

Fig. 8.6. Standard deviation s_h versus mean depth $\bar{h}$ of the phreatic level for the combined dataset of *Raheenmore Bog* and *Clara Bog West*.

Indeed Fig. 8.6 shows no relationship for $\bar{h} < 0.05$ m. The corresponding s_h lies between 5 and 6 cm, which is in agreement with the results in 8.4.2 and 8.4.3. The relationship for $\bar{h}$ >0 is highly significant as expected.

The relationship reflects the large storage coefficients in well developed acrotelms, decrease of the storage coefficient as a result of acrotelm degradation that occurs when phreatic levels in the bog are lowered and a further decrease of the storage coefficient with depth in catotelm peat.

8.4.5. Acrotelm depth and mean phreatic level

For reasons mentioned in 6.4.3, the data on acrotelm depth D_a do not allow a sensible regression analysis. Instead, the values of D_a were grouped in six classes. One class contains haplotelmic profiles, *i.e.* those where D_a=0. The results are shown in Fig. 8.7.

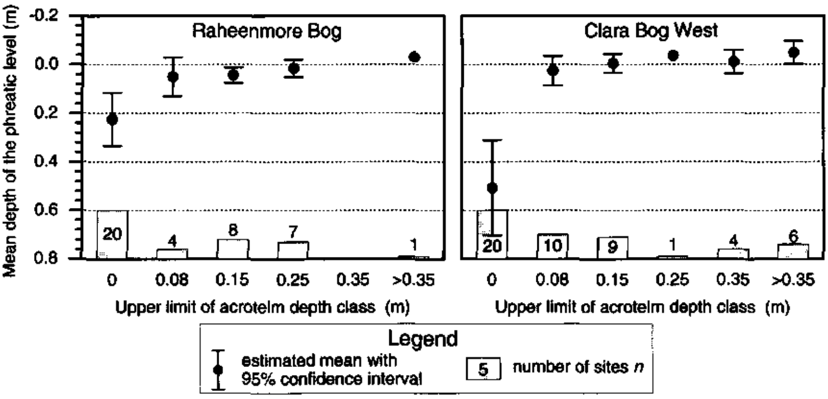

Fig. 8.7. Mean depth $\bar{h}$ of the phreatic level versus acrotelm depth D_a.

Fig. 8.7 shows that a strong relationship only exists for the difference between diplotelmic and haplotelmic bogs. In view of the relationship of $\bar{h}$ and the surface slope I derived in 8.4.2, with a plausible physical explanation and of the relationship of D_a and I that apparently exists for small D_a only, (*cf.* 6.4.4, fig. 6.29), the relationship of D_a and $\bar{h}$ cannot be independent of their causal relationship with I. The difference between the $\bar{h}$ of the haplotelmic parts of Raheenmore Bog and Clara Bog is probably due to the positioning of a relatively large number of sites in the area with ingrown drains of Raheenmore Bog, where long flow paths (*cf.* Fig. 6.20) are likely to limit the fluctuation and thus the depth of the phreatic level.

Both diagrams of Fig. 8.7 suggest a slightly higher phreatic level at large acrotelm depths in diplotelmic bog, but the differences are too small to serve as evidence for a relationship of D_a and $\bar{h}$ under such conditions.

8.4.6. Acrotelm depth and fluctuation of the phreatic level

Because of the difference in storage coefficient μ between the loose and only slightly humified acrotelm peat and the more compact and more humified catotelm peat, a relationship between D_a and s_h is likely. For the analysis, the acrotelm depths were grouped in the same classes as in Fig. 8.7. The result is given in Fig. 8.8.

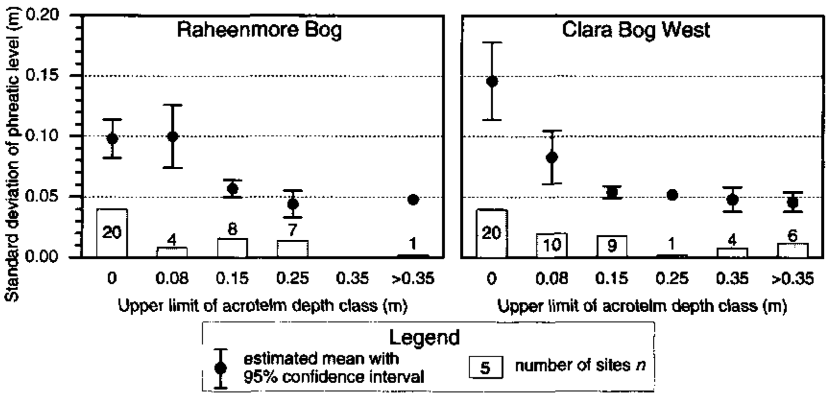

Fig. 8.8. Standard deviation s_h of the phreatic level versus acrotelm depth D_a.

For haplotelmic bog, s_h of Raheenmore Bog is considerably smaller than of Clara Bog. This difference may at least in part be attributed to the positions of selected sites as mentioned in 8.4.2 and 8.4.3.

A remarkable difference with Fig. 8.7 is that there is not just a differentiation between haplotelmic and diplotelmic bog. In the diplotelmic areas, the class with the smallest D_a also has significantly larger fluctuations than classes with deeper acrotelms. Where D_a is about 10 cm or more, s_h has a value around 5 cm, almost independent of D_a. The physical explanation is the value of s_h of 5 cm for the larger D_a, which implies a bandwidth B_{90} of about 15 cm. If the highest phreatic levels are assumed at 5-10 cm above the surface level, the phreatic level remains inside (or above) the acrotelm for more than 90% of the time if D_a>10 cm. In shallower acrotelms, the phreatic level may be in catotelm peat during larger parts of the dry season, causing fluctuation patterns shown in Fig. 8.2b and Fig. 8.3b.

8.4.7. Drain levels and mean and fluctuation of the phreatic level on Clara Bog East

The positions of the 'plots' on Clara Bog East with three mini-transects each are shown in Fig. 3.8, the configuration of a mini-transect in Fig. 3.9. The main hydrological question in relation to the drains was their effect on mean and fluctuation of the phreatic level. 50 observations of each dip well were obtained from November 1989 to mid October 1991.

The relationships of $\bar{h}$ and drain levels h_d and the one between $\bar{h}$ and s_h are discussed. The sites at 2 m from the drains are analysed separately from those halfway between the drains. To maintain comparability of the data, the average of the surface levels in the transect directly next to the drains and those at the three dip wells was used as a synthetic 'surface level' for all five sites of the transect.

Dip wells at 2 m from the drains have an 'a' or 'b' added to the plot name, those halfway between drains an 'm'. Thus 'A.3a' and A.3b' are the two wells of plot A.3 at 2 m from the drain, 'A.3m' is the well halfway between the drains of the same plot.

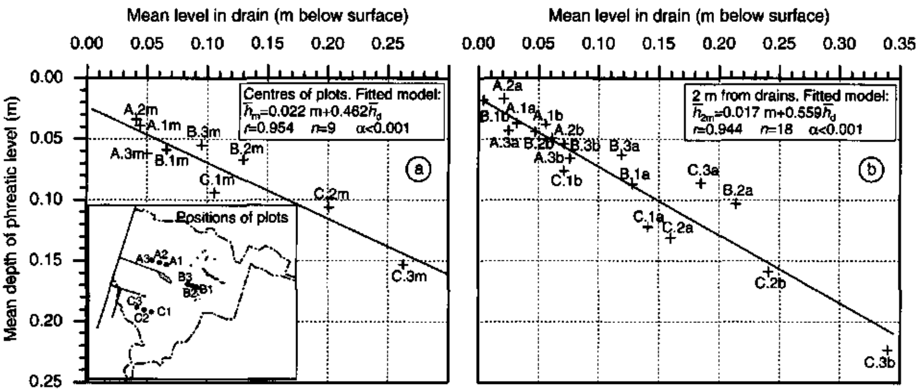

Fig. 8.9. Mean phreatic level $\bar{h}_m$ halfway between the drains (a) and mean phreatic level $\bar{h}_{2m}$ at 2 m from the drains (b) versus mean drain level $\bar{h}_d$ on *Clara Bog East*.

Fig. 8.9 shows mean depths of phreatic levels $\bar{h}_m$ of the centre well and $\bar{h}_{2m}$ of the wells at 2 m from the drains, versus mean drain levels $\bar{h}_d$. For the comparison with $\bar{h}_{2m}$, $\bar{h}_d$ was calculated for the drain closest to the well. For the comparison with $\bar{h}_m$, $\bar{h}_d$ was calculated as the average of both drains at the ends of the mini-transect.

The diagram shows a significant relationship of phreatic levels and drain levels, with a slightly steeper fitted line for the sites at 2 m from the drains. This difference suggests only a slight decrease of the effect of the drains over distances of about 10 m. Although the effect of the drain levels is obvious and the relationship seems almost perfectly linear, deeper drain levels do not result in equally deep phreatic levels. This effect may be attributed to the downward decrease of the hydraulic conductivity that causes a larger convexity of the phreatic level at deeper phreatic levels for the same specific discharge.

The result shown in Fig. 8.9 means that effective drain blocking should bring phreatic levels up to almost the surface. Thus possibilities for renewed acrotelm development are likely to be created.

Fig. 8.10 shows s_h versus $\bar{h}$ with fitted straight line for Clara Bog East.

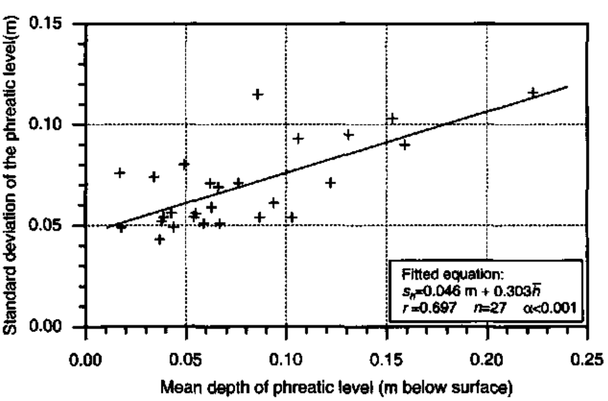

Fig. 8.10. Standard deviation s_h versus mean depth $\bar{h}$ of the phreatic level of the plots A-C on *Clara Bog East.*

The fitted line in Fig. 8.10 has almost the same position as the part of the curve for $\bar{h} < 0.25$m in Fig. 8.6. Also similar to Fig. 8.6, the relationship for the shallowest levels seems to be very weak. This is confirmed by the correlation coefficient for $\bar{h} < 0.10$m. The value is 0.287 for 20 data points and the statistical significance $\alpha \approx 0.22$. From this it can be concluded that the relationship of $\bar{h}$ and s_h is approximately the same as on Raheenmore Bog and Clara West and that the partially blocked drains have little effect on it.

8.5. The transects

8.5.1. Raheenmore Bog

Introduction

The positions of the transects C-E and N-C-S on Raheenmore Bog are shown in Fig. 8.11. The available data were analysed over a period of two years, starting on 21st January 1990. This yielded a maximum of 52 data values from the wells of the C-E and of 51 from those of the N-C-S transect. Wells with less than 46 observed data values in the period were discarded.

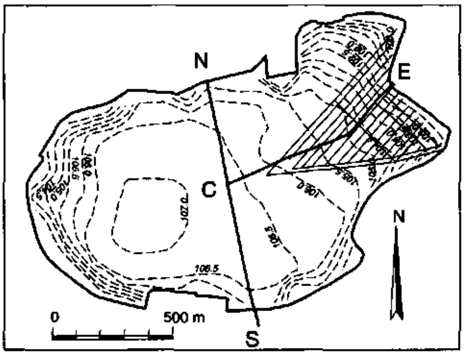

Fig. 8.11. Positions of the transects N-C-S and C-E on *Raheenmore Bog.* Transect N-C-S extends into the cutaway at the southern bog margin.

The C-E transect is almost parallel to the direction of the surface slope over its entire length. Thus a cross section gives a reasonably accurate picture of the surface slope. Most of it is situated in the area with old, mostly infilled drains (Fig. 8.11). The central part of the N-C-S transect lies in the bog's relatively undisturbed central area where it is approximately perpendicular to the direction of the surface slope of about 0.001-0.004. Towards the margins, the direction of the surface slope becomes parallel to the transect. The small surface slope values in the centre do not disturb the overall picture in a cross section to a large extent.

Transect C-E

Fig. 8.12 shows surface level z_s, $\bar{h}$ and s_h and estimated D_a against distance along the transect.

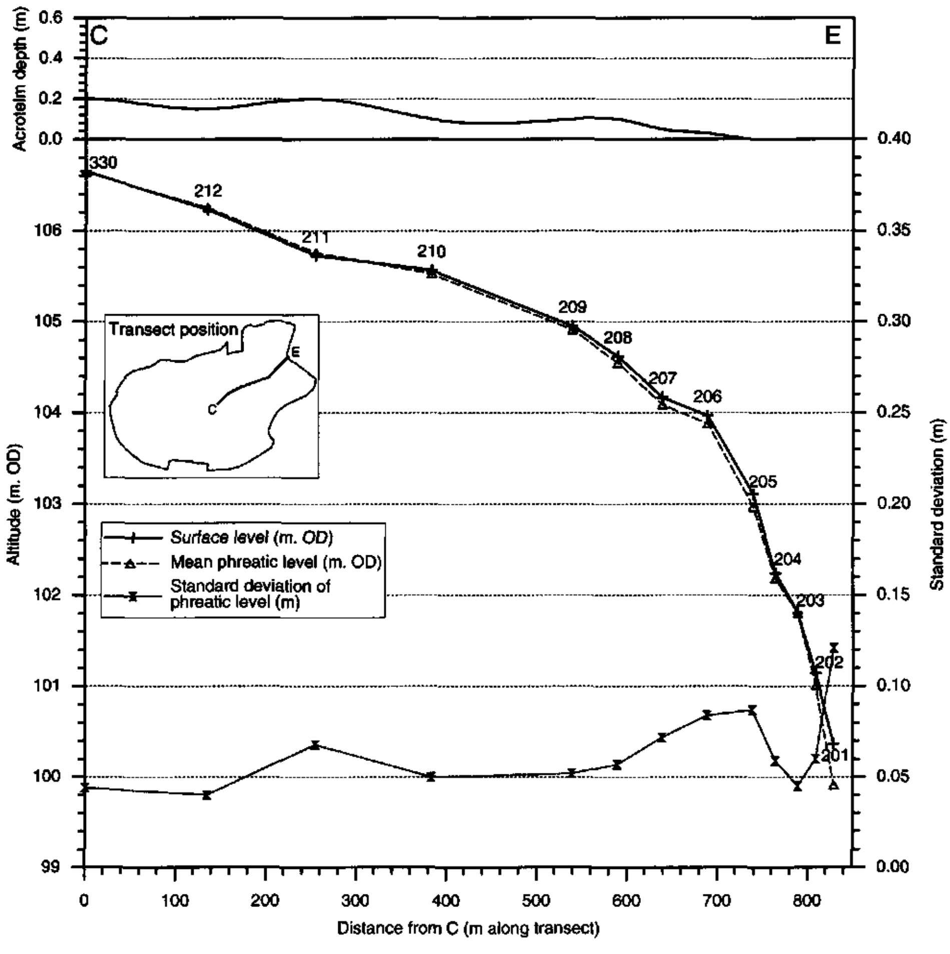

Fig. 8.12. Surface level z_s, mean $\bar{h}$ and standard deviation z_s of the phreatic level and acrotelm depth D_a (estimated from Fig. 6.23 and interpolated with cubic spline) along the transect C-E of *Raheenmore Bog*.

The presence of an acrotelm along the upper 80% of the transect in spite of the relatively steep slope between sites 209 and 206, may be attributed to the long flow path (*cf.* 6.3.6) the transect is positioned in. At the steepest part -below site 206- only haplotelmic bog was found.

The values of $\bar{h}$ and s_h show a tendency to increase with the surface slope I, in accordance with the statistical relationships developed in 8.4.2 and 8.4.3. Between sites 204 and 202, $\bar{h}$ and particularly s_h show a remarkable drop to values, characteristic of the central part of the bog but without acrotelm development. Both sites are positioned in a part where the surface level lies a little below its surroundings and consequently converging flow occurs. Although this may explain the values of $\bar{h}$ and s_h, it does not explain the absence of an acrotelm. However, it might develop with the overall recovery of the acrotelm of Raheenmore Bog concluded in 6.3 and 6.4.

Transect N-C-S

Fig. 8.13 shows z_s, $\bar{h}$, s_h and D_a against distance along the northern half of the transect and Fig. 8.14 along the southern half.

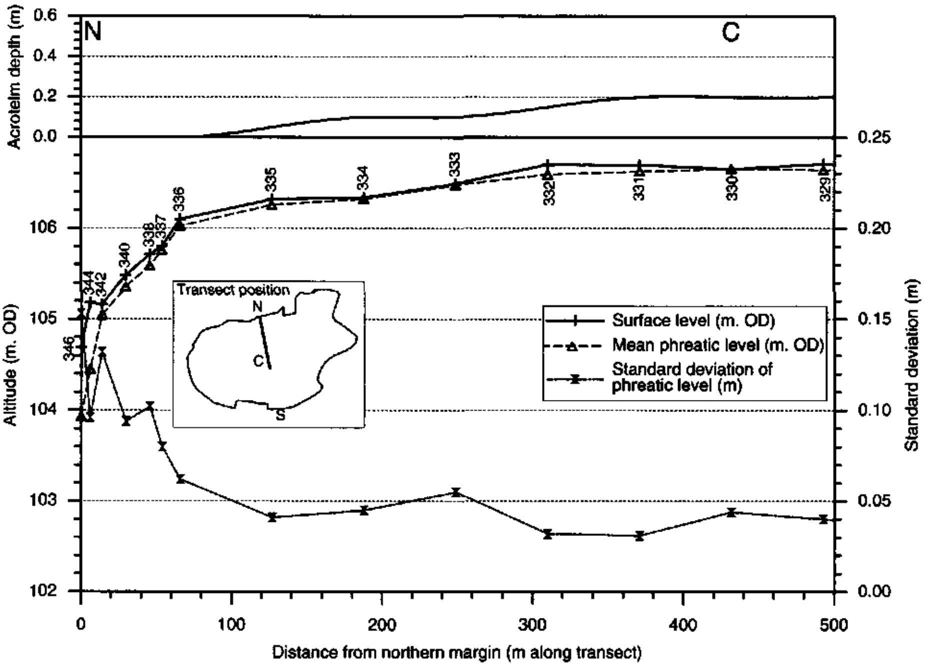

Fig. 8.13. Surface level z_s, mean $\bar{h}$ and standard deviation z_s of the phreatic level and acrotelm depth D_a (estimated from Fig. 6.23 and interpolated with cubic spline) along the northern half of the transect N-C-S of *Raheenmore Bog*.

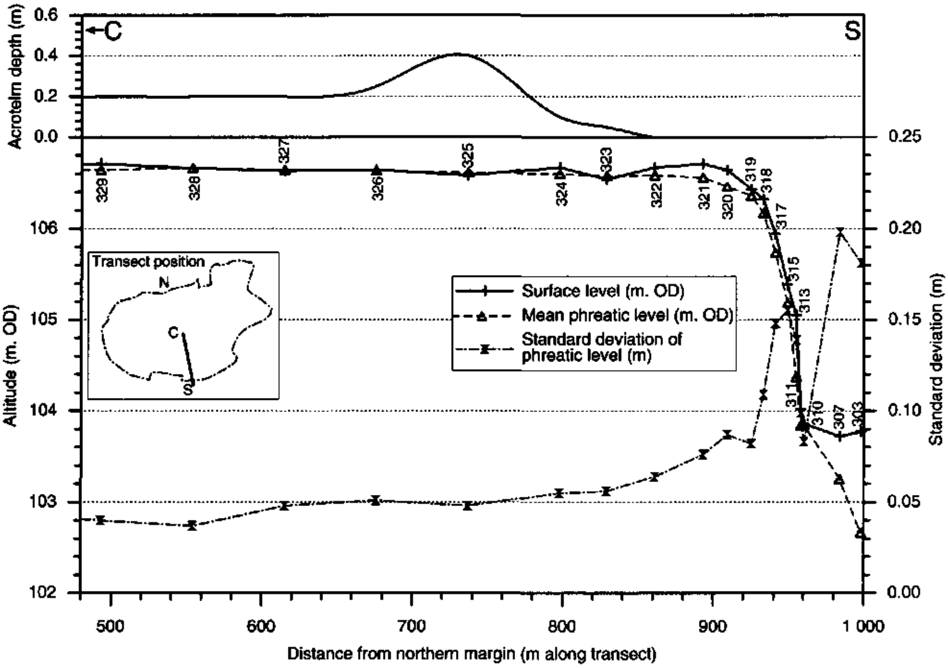

Fig. 8.14. Surface level z_s, mean $\bar{h}$ and standard deviation z_s of the phreatic level and acrotelm depth D_a (estimated from Fig. 6.23 and interpolated with cubic spline) along the southern half of the transect N-C-S of *Raheenmore Bog*.

In the flat central area, $\bar{h} \approx 0$ and $s_h \leq 5\,\text{cm}$, indicating seasonal fluctuations below 20 cm, similar to those at the upper end of the transect C-E. Generally speaking, s_h in flat areas is 1-2 cm smaller than suggested in Fig. 8.5. This difference may be related to the conventional regression technique that was applied in 8.4.3, which underestimates the slope and thus overestimates the intercept (*cf.* 5.3.2).

At the northern end of the transect, the situation is entirely in agreement with the statistical relationships developed in 8.4. Where the surface slope I steepens near site 336, $\bar{h}$ and s_h increase and D_a becomes 0.

At the southern end, some 'anomalies' occur. One is the small watershed between sites 322 and 320 where $\bar{h}$ and s_h increase and the acrotelm is absent in spite of the small surface slope. The watershed may impede the discharge in the upstream part of the bog to some extent, which would explain the deep acrotelm at site 325. The increase of $\bar{h}$ and s_h in the sloping part towards the margin is in agreement with the relationships. Along the extension into the cutaway, the values of $\bar{h}$ and s_h decrease sharply and then increase again. The decrease may be attributed to water drained from the bog. This is a common situation at artificial face banks where often a strip of open water occurs that is fed by the bog. $\bar{h}$ and s_h increase again towards the deep drain that bounds the transect at 2 m south of site 303.

8.5.2. Clara Bog West

Introduction

The positions of two transects on Clara Bog West, A-A' and SW-E are shown in Fig. 8.15. Transect SW-E is split up at Shanley's Lough into SW-SL and SL-E.

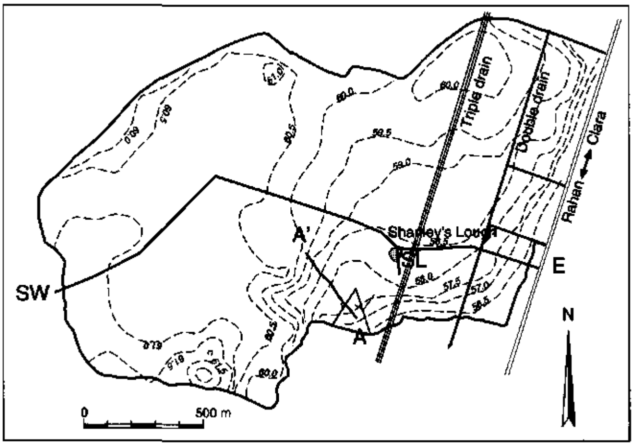

Fig. 8.15. Positions of the transects SW-E and A'-A on *Clara Bog West*.

Other wells, including a transect consisting of sites 46-72 and a number of scattered sites around Shanley's Lough (positions shown in Fig. 3.12) are not included in the transect descriptions. The line 46-72 lies almost parallel to the surface level contours and a diagram of the transect would not show possible relationships of surface slope with the mean and the fluctuation of phreatic levels. However, all available well data were included in the statistical analyses in section 8.4.

Most data series of the sites of transect SW-E covered one single year. Based on the results of 8.2.3 the s_h were converted to estimated three year values. The $\bar{h}$ were not adjusted.

Transect A'-A

Fig. 8.16 shows z_s, $\bar{h}$, s_h and D_a along the transect A'-A over 31st July 1990 until 22nd July 1993. The data of the A'-A transect were all three year series.

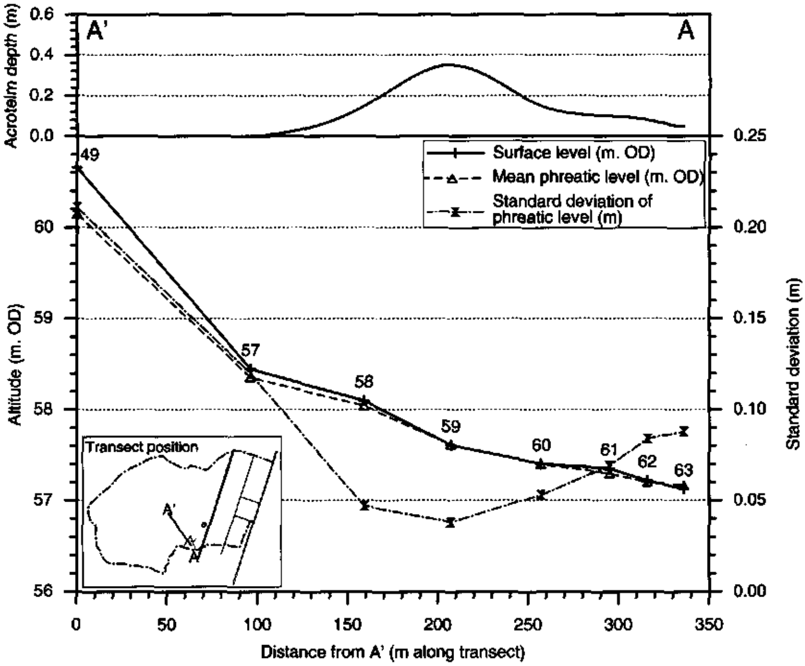

Fig. 8.16. Surface level z_s, mean $\bar{h}$ and standard deviation z_s of the phreatic level and acrotelm depth D_a (estimated from Fig. 6.24 and interpolated with cubic spline) along the transect A'-A of *Clara Bog West*.

Site 49 is situated not far from the crest of the western mound (Fig. 7.8) and site 57 lies near the bottom of the slope towards the flatter area of Shanley's Lough. The steep slope at sites 49 and 57 shows results in agreement with the relationships developed in 8.4: large s_h, the mean phreatic level well below the surface and no acrotelm. At the flatter part at 58, 59 and 60, the situation is also as expected: small s_h, $\bar{h}$ close to zero and a well developed acrotelm. Anomaly starts at site 61, where s_h takes on large values that increase towards the end of the transect in spite of the small $\bar{h}$ and the presence of an acrotelm, even though it is shallow. Some partial explanations are:

a. The surface slope increases to about 0.02 almost immediately beyond site 63 (Fig. 3.12)

b. Near site 63 cracks may have developed that drain the peat,

c. The proximity of one of the two drains, positioned in a "V".

In view of the continuing peat cutting at the southern bog margin, a few tens of metres from site 63 may be an indication that the acrotelm in this part is dying and that the anomaly is a sign of changing conditions. The converging flow system of the large catchment area of Clara Bog West (Fig. 6.21) has probably prolonged the life of the acrotelm, in spite of the effects of nearby cutting.

Transect SW-SL

The transect lies between an old face bank at the present south-western bog margin and Shanley's Lough. Most of it is positioned in a long flow path from the western part of Clara Bog West to the area of converging flow near Shanley's Lough. The cross section is shown in Fig. 8.17.

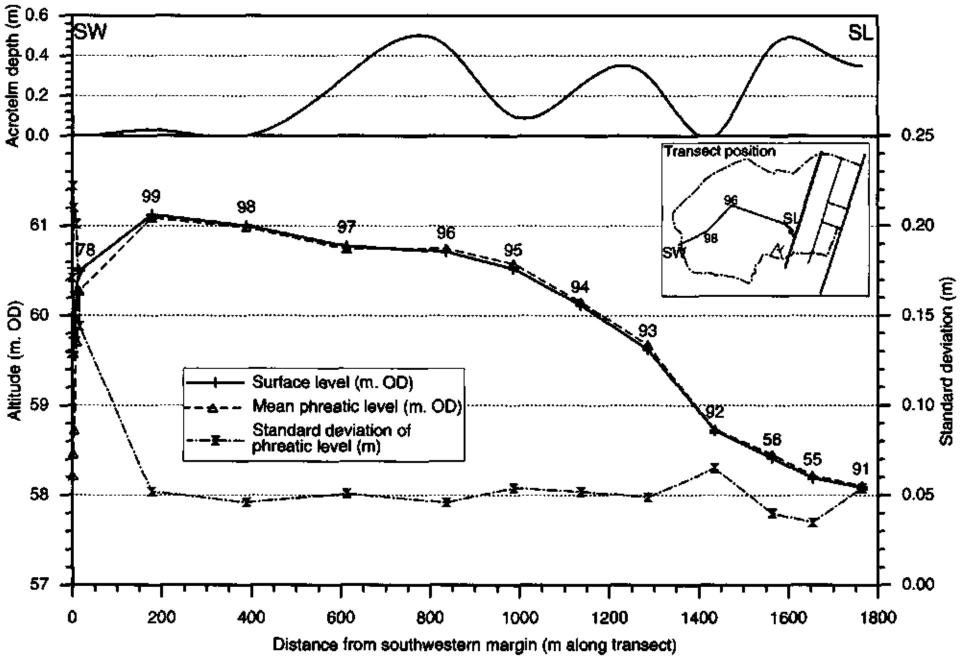

Fig. 8.17. Surface level z_s, mean $\bar{h}$ and standard deviation z_s of the phreatic level and acrotelm depth D_a (estimated from Fig. 6.24 and interpolated with cubic spline) along transect SW-SL of *Clara Bog West*. Standard deviations are based on the period of 23rd July 1992 to 22nd July 1993 and corrected for the period 31st July 1990 to 22nd July 1993, using the equation in Fig. 8.1. An enlargement of the face bank on the left is shown in Fig. 8.18.

Because the horizontal scale prevents the situation at the face bank at the south-western end from showing up in the diagram properly, a section of the south-western end is shown in Fig. 8.18 at a larger horizontal scale. The acrotelm depth in this part is zero at all sites and therefore not shown.

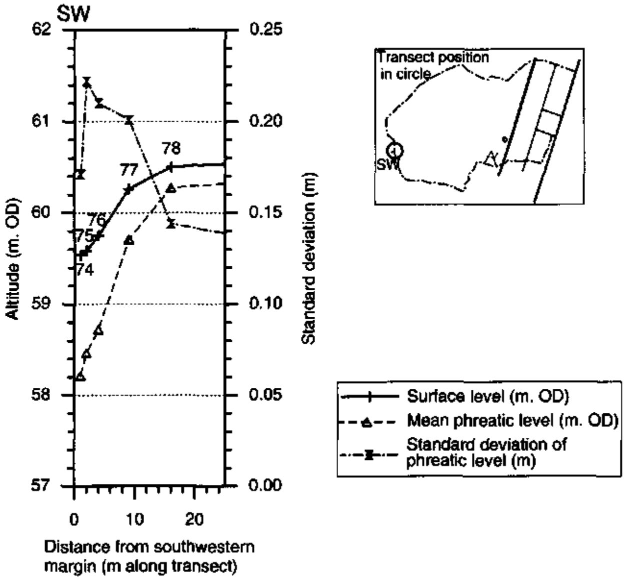

Fig. 8.18. Surface level z_s, mean $\bar{h}$ and standard deviation z_s of the phreatic level at the face bank at the south-western end of transect SW-SL of *Clara Bog West*. Standard deviations are based on the period of 23rd July 1992 to 22nd July 1993 and corrected for the period 31st July 1990 to 22nd July 1993, using the equation in Fig. 8.1. The entire transect is shown in Fig. 8.17.

At the south-western face bank, the depth of the phreatic level is more than 1 m below the surface, decreasing to a mere 20 cm over only 15 m despite the surface level at site 78, which is about a metre above that of site 74. This rise of the mean phreatic level of more than 2 m over a horizontal distance of just 15 m confirms that the direct effect of a face bank on the phreatic level in a bog is limited to a narrow zone as derived in 7.2. The value of s_h increases towards the face bank but shows a sudden drop at site 74 at a distance of 1 m from it. This must be attributed to the presence of a 1-3 m wide strip of open water, in the cutaway immediately below the face bank.

The diagram of Fig. 8.17 shows a watershed at site 99. Its real position is closer to site 78 than to 99. As pointed out in 7.4, this watershed position close to the margin is likely to have been caused by subsidence induced by the bog road and its associated system of drains. Hence it must be of recent origin. It results in a short flow path at sites 99 and 98. This could have explained the absence of a well developed acrotelm. However, the surface slope is sufficiently small for acrotelm development. Contrary to the watershed at sites 320-322 on Raheenmore Bog- $\bar{h}$ and s_h are small enough. The shallow acrotelm at site 99 might indicate a beginning acrotelm development, but it certainly is no evidence of it.

From site 92 to 56, the transect is not perpendicular to the surface contours. This makes the cross section misleading, particularly at site 92 where the surface slope is influenced by the outskirts of the western mound and is considerably larger than Fig. 8.17 suggests. This explains the local increase of s_h and the absence of an acrotelm. Along other parts of the transect, the phreatic level fluctuates about the surface and s_h is almost constant. Exceptions are the already discussed south-western end and the area near Shanley's Lough, where s_h is limited by the large proportion of open water (*cf.* the large storage coefficients μ at site CWG1 derived in Fig. 6.5).

Transect SL-E

The transect lies between Shanley's Lough and the Clara-Rahan road. Its lower part is perpendicular to the surface contours, its upper 200 m is not. However, the slope in the latter area is only about 0.003 to the south. Hence the cross section shown in Fig. 8.19 gives a reasonably accurate picture of the situation.

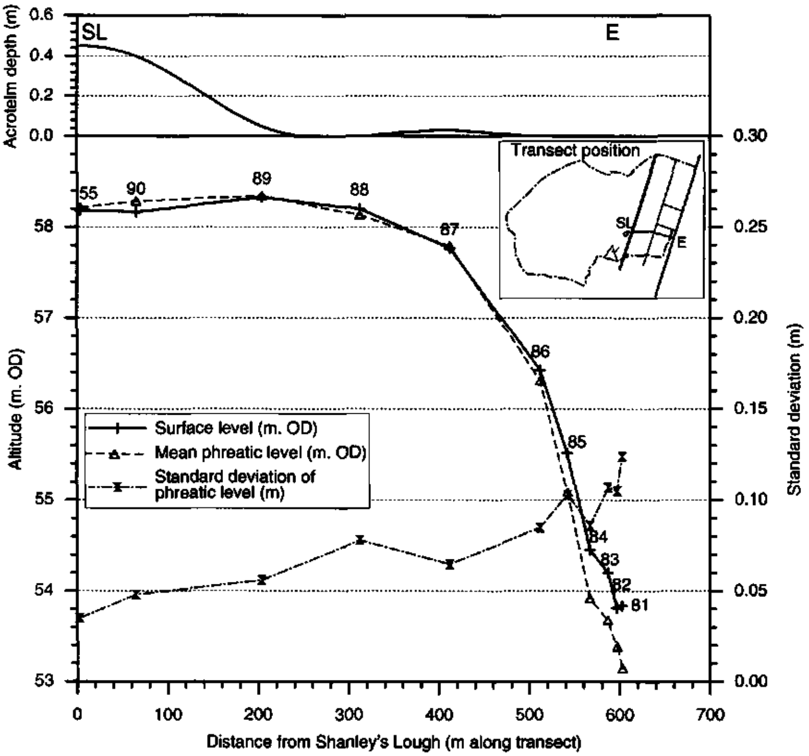

Fig. 8.19. Surface level z_s, mean $\bar{h}$ and standard deviation z_s of the phreatic level and acrotelm depth D_a (estimated from Fig. 6.24 and interpolated with cubic spline) along transect SL-E of *Clara Bog West*. Standard deviations are based on the period of 23rd July 1992 to 22nd July 1993 and corrected to represent the period 31st July 1990 to 22nd July 1993, using the equation in Fig. 8.1.

The cross section shows a watershed at site 89. Like the one between 78 and 99, is probably of recent origin and cause by the road-induced general subsidence of Clara Bog. Again, the flow path is short and it barely has an acrotelm, even though the surface slope and the value of $\bar{h}$ give no reason to believe that the area is unsuitable for such a development. However, s_h seems a little large. Burning may be an explanation of the situation. A recent bog fire occurred here in 1994.

The slightly lower surface position at 90 is probably related to the position of the triple drain about 10 to the east of site 90. It prevents discharge towards the road from the flow system that converges to the area of Shanley's Lough. The mean phreatic level, s_h and the acrotelm depth at site 90 indicate that it has no draining effect in this part of the bog any longer.

Downslope of 87, the bog is haplotelmic and $\bar{h}$ and s_h increase with the surface slope in agreement with the relationships developed in 8.4.2 and 8.4.3.

8.6. Discussion and conclusions

- There is a marked difference between depths and fluctuations of the phreatic levels in the central areas of the bogs and those in the margin zone. In the central area, the phreatic levels fluctuate around the surface level. Standard deviations s_h based a measuring interval of approximately two weeks and an observation period from summer 1990 to summer 1993 were around 5 cm, indicating a bandwidth B_{90} of the central 90% of the observed values of 15 to 20 cm. These values are about 10 cm smaller than inferred from literature in Chapter 2. The difference may be related to climatic differences, because the values used were mostly from continental Europe.
- Along margins, the phreatic levels are deeper. Averages range from 0.25 to 1.25 m. The fluctuations are also larger: s_h can have values of up to 22 cm, indicating a B_{90} of up to approximately 70 cm or the three year period of 1990-1993.
- The mean depth of the phreatic level $\bar{h}$ is mainly related to the surface slope I because a larger surface slope means a more effective drainage. On slopes smaller than 0.07 to 0.01 no relationship was found. The upstream length of the flow path affects the relationship in that a longer flow path tends to cause smaller values of $\bar{h}$. The effect seems stronger in the event of converging flow. Diverging flow, e.g. in the proximity of watersheds within the bog seems to have an opposite effect.
- The proximity of a face bank has a limited direct effect on $\bar{h}$, but affects it indirectly by causing an increase of I. A strongly positive correlation of $\bar{h}$ and s_h was found. It is mainly attributed to the downward decrease of the storage coefficient μ. The significant relationship of s_h and I must be attributed to the combined effects of I on $\bar{h}$ and of $\bar{h}$ on s_h and thus does not reflect a direct causal relationship.

- The relationships of $\bar{h}$ and s_h found for Clara Bog (West and East) and Raheenmore Bog differ little. This indicates a similar decrease of μ with depth in both bogs involved. In all cases, the relationship was found to be weak for $\bar{h} < 10$ cm. This suggests an effect of the large storage coefficients μ in the acrotelm. However, the lack of relationship included haplotelmic bog areas. Although even in haplotelmic profiles the largest μ may be expected to occur near the surface, the weak correlation might also be related to the presence of some open water in nearby pools and hollows.
- On Clara East, a highly significant linear relationship of $\bar{h}$ and drain level was found for the shallow drainage system. It suggests that an effective blocking of the drains will restore conditions with small $\bar{h}$ and s_h. The phreatic levels deeper than 5 cm are all significantly above the drain level, which can be explained by a strong decrease of the hydraulic conductivity with depth.
- At sites with a haplotelmic bog profile, *i.e.* the acrotelm depth D_a=0, $\bar{h}$ was significantly larger than at sites where D_a>0. The data for D_a>0 suggested a slight decrease of $\bar{h}$ with increasing D_a, but insufficient for a statistically significant relationship. A significant relationship of D_a and s_h was found for D_a<10 cm. For larger D_a the data suggest a slight decrease of s_h with increasing D_a, but again insufficient for statistical significance. The physical explanation is the value of s_h of about 5 cm that occurs in conditions with a well-developed acrotelm. Where D_a>10 cm, the phreatic level rarely falls below the acrotelm and thus remains inside the material with a large storage coefficient.
- The relationship of D_a with $\bar{h}$ and s_h derived for small D_a does not answer questions as to causality, *i.e.* whether the presence of an acrotelm causes small $\bar{h}$ and s_h or whether small $\bar{h}$ and s_h facilitate acrotelm growth. $\bar{h}$ and s_h are independent of I if I is smaller than 0.007-0.01. In earlier work (Van der Schaaf, 1996) this author concluded that on both bogs well developed acrotelms hardly occur on steeper slopes than 0.01. This suggests a crucial role of surface slope, even though flow path length is a second determining factor (*cf.* 6.4.4). The causal relationship would then be surface slope → value of $\bar{h}$ and s_h → acrotelm development. However, an acrotelm does not occur on all sites with small $\bar{h}$ and s_h. Examples are sites 203 and 204 of Raheenmore Bog and sites 87, 88, 89, 98 and 99 of Clara Bog.
- All these sites are positioned in areas where disturbance by subsidence has occurred during the last 100 years. This may mean that in these areas an acrotelm has not yet had sufficient time to develop. The acrotelm growth model developed in 6.5 indicates that the process of acrotelm development may start slowly and that it may speed up considerably as soon as a beginning acrotelm growth affects local hydrological conditions. If this is correct, infrequent burning (e.g. once in 15 years) may be sufficient to prevent acrotelm development. This may mean that an acrotelm may de-

velop rapidly, once a small depth has developed or that it may recover rapidly as long as a shallow depth remains after disturbance and subsequent restoration measures. This could mean that the chances for acrotelm recovery after effective drain blocking on Clara Bog East are good, because acrotelm remnants still occur in large areas (Fig. 6.25). The blocking was carried out in 1996 and a first impression of *Sphagnum* growth in December 1997 was that it was indeed beginning to develop abundantly.

9. THE WATER BALANCES

9.1. Introduction

This chapter deals with the water balances of Raheenmore Bog and Clara Bog West. Of Clara Bog East, insufficient data are available.

The water balance over a certain period of time of both Raheenmore Bog and Clara Bog West can be written in terms of average fluxes Q [L^3T^{-1}]:

$$\overline{Q}_P + \overline{Q}_E + \overline{Q}_a + \overline{Q}_{hc} + \overline{Q}_e + \Delta S = 0 \tag{9.1}$$

where

$\overline{Q}_P$ = Precipitation flux

$\overline{Q}_E$ = Evapotranspiration flux

$\overline{Q}_a$ = Acrotelm discharge flux, including surface flow and discharge by open water

$\overline{Q}_{hc}$ = Lateral discharge *via* the catotelm

$\overline{Q}_e$ = Exfiltration flux from the catotelm

ΔS = Release of water from storage.

A flux is assumed positive when it enters the bog and negative when it leaves it. Consequently, ΔS is positive when the storage has decreased over the period.

The terms $\overline{Q}_{hc}$ and $\overline{Q}_e$ were quantified in Chapter 5. Over the field work period of 1989-1993, they were nearly constant in time and small compared with other balance terms such as $\overline{Q}_P$, $\overline{Q}_E$ and $\overline{Q}_a$.

In this chapter, the catchment sizes are discussed first, followed by the results of the different precipitation measurements, evapotranspiration and release of water from storage. Available time and equipment did not allow longer series of lysimeter measurements than one year on both Raheenmore Bog and Clara Bog. Evapotranspiration in other periods, estimated as a remainder in the water balance will also be discussed. The evapotranspiration is also compared with Penman E_0 of the meteorological stations Birr and Mullingar and the one on Clara Bog itself, an automatic weather station that was operational after mid-1992. The evapotranspiration of different vegetation elements, *Sphagnum* in particular and its relationships with weather conditions is also discussed.

9.2. Catchment sizes

Because the discharge across the measuring weir in each bog was generated in a catchment that was a part of the bog area, the size of these catchments had to be estimated. This was done using the 100m x 100m surface level grid and derived surface level gradients (*cf.* 5.4). The flow pattern was assumed to follow the surface level gradients. Fig. 9.1 shows the estimated catchment of Raheenmore Bog. In the north-east, the area is bounded by the interception drain that was cut to divert runoff water to the measuring weir (position shown in Fig. 3.13). The estimated size of the catchment as shown in Fig. 9.1 is 28 ha.

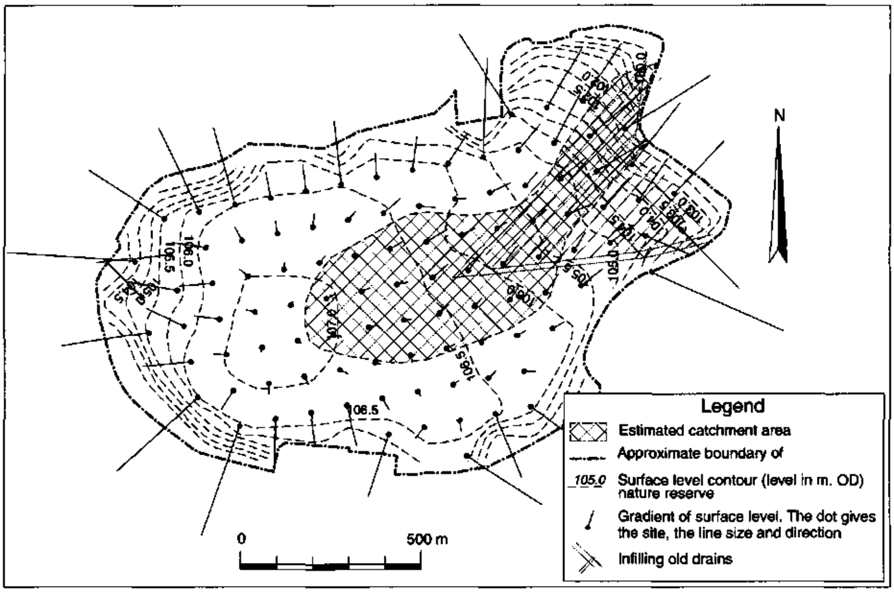

Fig. 9.1. Flow pattern and estimated catchment of *Raheenmore Bog*.

Fig. 9.2 shows the estimated catchment of Clara Bog West. Its estimated size is 98 ha. It is bounded by the screens at the discharge weirs CWD1 and CWD2 (positions shown in Fig. 3.14) in the south and comprises most of the area north of the weirs and much of the western area of Clara Bog West. Its position and shape emphasise the unusual flow pattern of Clara Bog; the probable causes were discussed in 7.4.3.

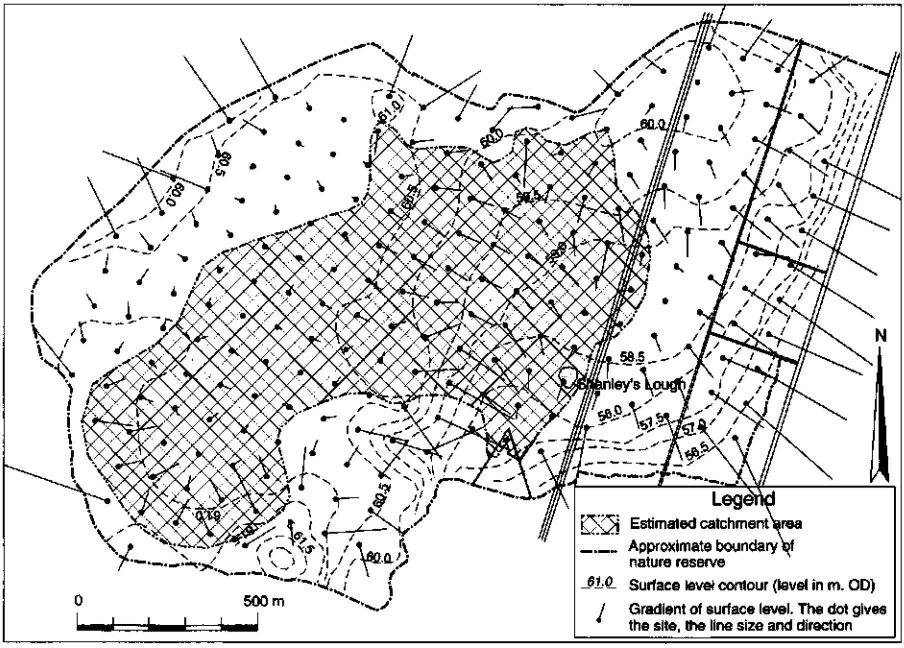

Fig. 9.2. Flow pattern and estimated catchment of *Clara Bog West*.

9.3. Precipitation

9.3.1. Raheenmore Bog

As a check on the coherence of rain gauge data, Fig. 9.3 shows averaged one week sums of the two 127 cm^2 hand gauges (positions shown in Fig. 3.13) against one week sums of the 324 cm^2 siphon gauge RHR1 and of the 324 cm^2 tipping bucket gauge RHR2. The data of RHR1 cover the period of September 1990 to July 1992 and those of RHR2 the period July 1992 to the end of May 1993. The siphon gauge was replaced by the tipping bucket gauge because it developed too frequent failures. The tipping bucket gauge had a resolution of 0.01" and was installed in July 1992. The lines in the diagrams of Fig. 9.3 were fitted using the RMA regression method (*cf.* 5.3.2).

Both diagrams of Fig. 9.3 show a very good correlation. However, the siphon gauge recorded about 6% less rain than the hand gauges, whilst the average results of the tipping bucket gauge differed less than 2% from those of the hand gauges.

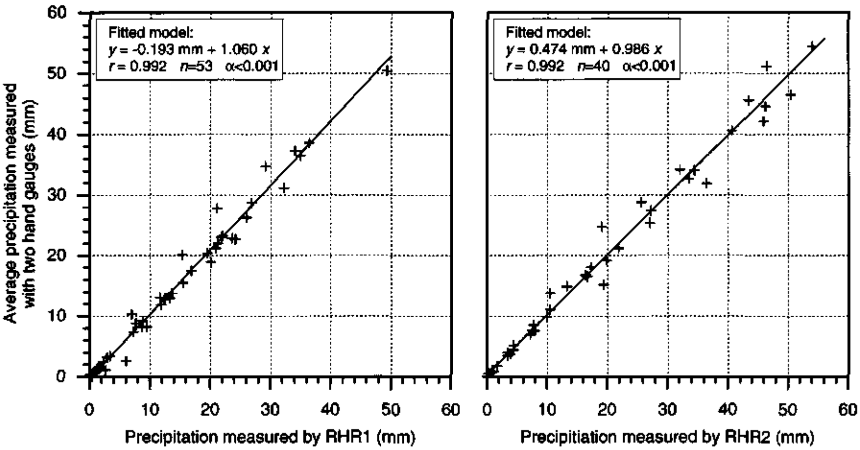

Fig. 9.3. Weekly precipitation sums measured with the two 127 cm^2 hand gauges versus sums from the recording gauges RHR1 (324 cm^2 siphon) and RHR2 (324 cm^2 tipping bucket).

These differences between the recording gauges may probably be attributed to differences in shape and resulting wind effects. The siphon gauge had a diameter of about 0.5 m below the orifice and a height of about 0.6 m. These dimensions are likely to have a considerable effect on the wind directly above the orifice. Such effects may cause reductions of the amount of measured precipitation (De Bruin, 1977, Sevruk, 1989a, 1989b, Sevruk and Klemm, 1989), sufficient to explain the difference of 6%. The tipping bucket gauge was only 21 cm in diameter over its entire height of 40 cm, which resulted in a smaller disturbance of the wind above the orifice. The effect was reduced even more because the gauge was positioned in a *Calluna* vegetation with tops just below the rim of the orifice. Disturbances of the wind above the orifice usually cause lower measured values (De Bruin, 1977). The tipping bucket indeed yielded slightly (1%) larger sums than the hand gauges. Thus the tipping bucket gauge probably produced the best results with the hand gauges in a good second place. Because the data of the hand gauges cover the entire observation period, their data will be used in the water balance calculation of Raheenmore Bog. The few gaps in the data were filled in using the relationships in Fig. 9.3.

9.3.2. Clara Bog

A coherence test on recorded precipitation data was also done with the data from Clara Bog, where the 35 cm high 400 cm^2 tipping bucket gauge CWR1 had worked with only a few minor failures. Its results were compared with the averaged result of the two 127 cm^2 hand gauges (Fig. 9.4, positions shown in Fig. 3.14).

The relationship shows sums for the two hand gauges that were up to 10% larger than for the tipping bucket. Although an orifice area of 400 cm^2 is likely to catch a little less rain than one of 127 cm^2, this does not explain a difference of 10%. Deij (1968) mentioned differences of about 1% between 200 and 400 cm^2 gauges. Hence the difference between precipitation sums from a gauge with an orifice area of 400 cm^2 orifice and from one of 127 cm^2 should probably be less than 2%. Two other possibilities are the rather small depth of 7 cm at the rim of the orifice of the recording gauge CWR1 and its tipping mechanism. The latter was of a light plastic construction and showed light wear on its bearings when the gauge was removed from the bog in July 1993. Both may have caused systematic errors in the measuring results. Hence the averaged result of the two hand gauges is likely to be the more reliable one and will be used in the water balance computations. The few gaps in the series were filled in using the recorder data and the fitted equation of Fig. 9.4. All gauges were positioned in approximately 20 cm high vegetations dominated by *Calluna vulgaris* and *Eriophorum vaginatum*.

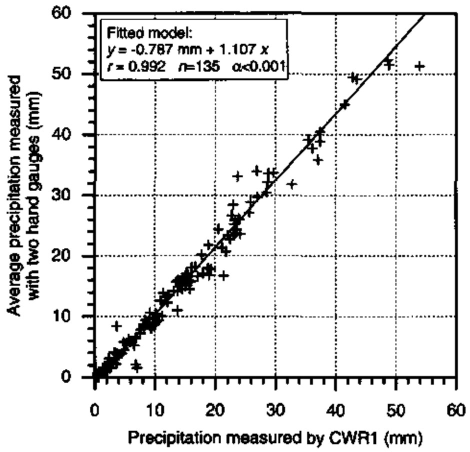

Fig. 9.4. Weekly precipitation sums measured with the two 127 cm^2 hand gauges versus sums recorded by the recording gauge CWR1 (400 cm^2 tipping bucket).

9.3.3. Comparing precipitation sums of the bogs with the nearest meteorological stations and 30 year normals

To find how the results compare with observations of the nearest meteorological stations of Met Éireann (Irish Meteorological Service), sums over the four meteorological seasons from summer 1990 to spring 1993 were calculated and compared with those of the stations Birr and Mullingar. The winter season comprises December, January and February, the spring March, April and May, etc. No data of Athlone and Lullymore (closed down) were available. The positions of the Met Éireann stations are shown in Fig. 3.1. Because no data of the last days of July and the month August were recorded on the bogs, the summer of 1993 could not be included in the comparison. The bar diagram of Fig. 9.5 shows the result.

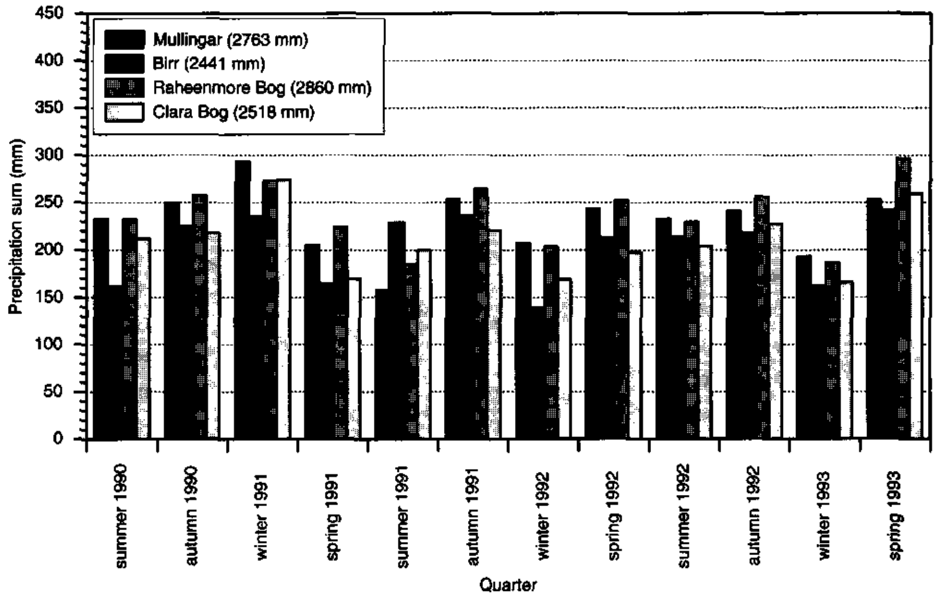

Fig. 9.5. Precipitation sums over the seasons winter, spring, summer and autumn ('winter' includes the months December, January and February, 'spring' March, April and May, etc.) of the Met Éireann stations Birr and Mullingar and of the *Raheenmore Bog* and *Clara Bog* measuring sites. Figures in parentheses behind the station names are totals in mm over the entire three-year period.

Fig. 9.5 shows that the results agree well with those of the meteorological stations. In most quarters, the precipitation sum of Clara Bog differs little from the sum of Birr, which indeed is the station nearest to Clara Bog. The sums of Raheenmore Bog are almost equal to those of Mullingar, the station nearest to Raheenmore Bog. On average, the sums of Raheenmore Bog exceed those of Clara Bog by about 13%. The difference may probably be attributed to the difference in elevation: up to 62 m OD for Clara Bog and 107 m OD for Raheenmore Bog.

Another point is the extent to which the obtained precipitation values deviate from average. For a comparison, 30-year means (1951-80) of monthly sums of the meteorological stations of Met Éireann are available. Of the bogs no such data exist, but surrogate values can be estimated for each month from the three available monthly sums of the bogs from summer 1990 to spring 1993 and those of the reference stations Birr (for Clara Bog) and Mullingar (for Raheenmore Bog) using the equation

$$\overline{P}_{\text{bog}} \approx \overline{P}_{\text{ref}} \frac{\sum_{i=1}^{3} P^{*}_{i_{bog}}}{\sum_{i=1}^{3} P^{*}_{i_{ref}}} \tag{9.2}$$

$\overline{P}_{\text{bog}}$ = estimated 30-year monthly precipitation mean [L] of the bog

$\overline{P}_{ref}$ = 30-year monthly precipitation mean [L] of the reference station

P^* = measured one-month precipitation sum [L]

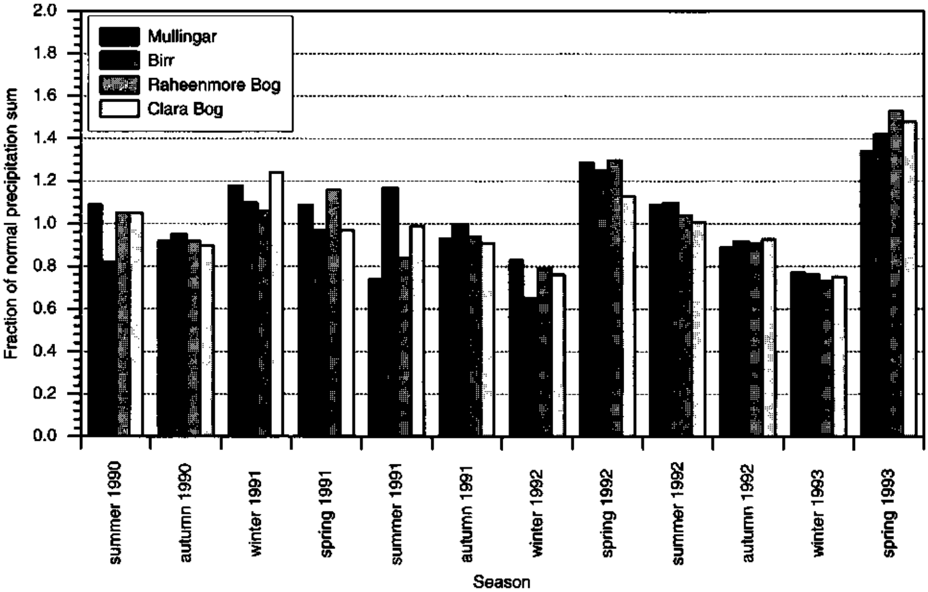

Fig. 9.6. Precipitation sums over the seasons winter, spring, summer and autumn 1990-93 at the Met Éireann stations Birr and Mullingar and of the *Raheenmore Bog* and *Clara Bog* measuring sites, expressed as a fraction of the 30 year mean. Means of the bog sites were estimated according to Eq. (9.2).

Fig. 9.6 shows that most seasons during the field project did not deviate strongly from to normal, except the dry winters of 1992 and 1993 and the extremely wet spring of 1993. Among the individual stations, Raheenmore Bog had a relatively dry summer in 1990 and 1991.

9.4. Evapotranspiration

9.4.1. Raheenmore Bog

The sixteen lysimeters in Raheenmore Bog were operated from 7th April 1991 to 13th April 1992 and weighed 52 times at regular intervals. Hence the average time interval between weighing was slightly more than a week. As mentioned in 3.11, the lysimeters contained four different vegetation elements, all with a variant with a well and a poorly developed acrotelm.

The water level inside the lysimeters was kept to a level relative to the surface that resembled prevailing conditions on the bog as closely as possible. This was accomplished by adding or removing water whenever necessary. Added water was surface water from the bog. Although it was tried to anticipate on expected weather conditions, overflow from the lysimeters could not be prevented at all times. During wet periods, inflow also occurred a few times. This resulted in some missing data. The data set consisted of averages of pairs of lysimeters with the same vegetation element and acrotelm condition. If one of both values was obviously wrong, the result of the other lysimeter was used.

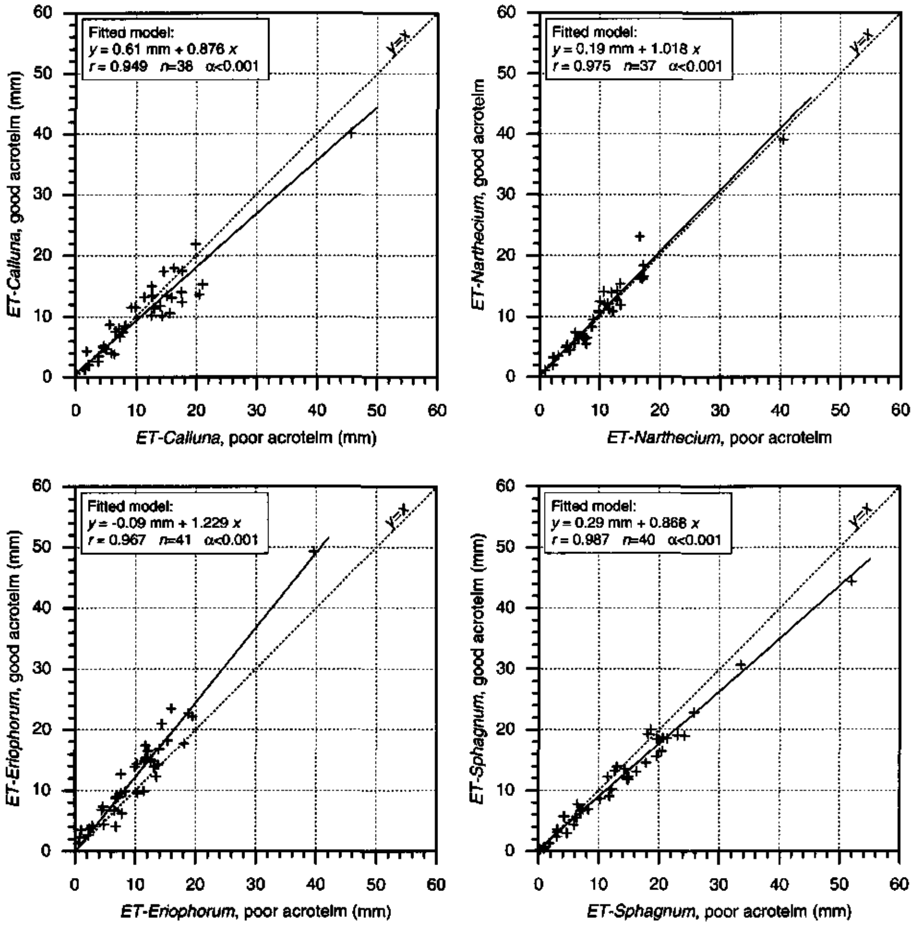

Fig. 9.7. Evapotranspiration sums *ET* over approximately one week periods of the lysimeters on *Raheenmore Bog* with a well developed ('good') acrotelm versus those of lysimeters with a poorly developed acrotelm. All data are averages of lysimeter pairs without estimated values. The single large value around 40 mm in all graphs is the result of a 2½-week period between successive weighings in July 1991.

When both lysimeters produced erroneous results, their averages were estimated from other averages, preferably of the same vegetation, using linear regression. Eventually 7% of the averages of pairs were estimated in this way.

Fig. 9.7 shows averaged evapotranspiration sums of lysimeter pairs with a well developed ('good') acrotelm against those of lysimeter pairs with a poor acrotelm. The set contains no estimated values. Lines were fitted using the RMA regression method (*cf.* 5.3.2). The diagrams in Fig. 9.7 show reasonably coherent results, but the deviations in slope of the fitted regression lines also indicate considerable systematic differences between the lysimeters. The average of the regression coefficients is about 1. This means that the hypothesis that acrotelm conditions have an effect on evapotranspiration should probably be rejected and that differences in the leaf area index (LAI) are likely to be the one and only explanation.

The LAI was measured five times in May to October 1991 (*cf.* 3.11). After October 1991, little change occurred until the test was ended in April 1992. Table 9.1 shows that the differences between the lysimeters can be reasonably well explained by differences in the LAI (or its replacement). The reduction in the area of living *Sphagnum* capitula that occurred in the summer of 1991 was stronger in the lysimeters with good acrotelms than in those with poor ones. This may be due to a difference in species rather than acrotelm conditions. The lysimeters with a poor acrotelm were dominated by *S. magellanicum*, those with a good one contained mostly *S.* papillosum. *Sphagnum* does not transpire in the strict sense, because the evapotranspiration process in *Sphagnum* is not biologically controlled. The plants have no rhizoids, water conducting tissue, cuticles or stomata. Thus the evapotranspiration rate depends on upward capillary flow towards the *Sphagnum* surface. Hence reduction of evapotranspiration depends on the depth of the phreatic level and the compactness of the *Sphagnum* lawn or hummock. When the supply of water becomes insufficient, the capitula dry out and die, thus reducing the evapotranspiration rate. *S. papillosum* is very sensitive to phreatic levels that are only little below the surface (Ivanov, 1981; Schouwenaars, 1993). *S. magellanicum* is more able to maintain upward capillary flow and thus to keep its capitula alive during dry summer periods and associated deeper phreatic levels than *S. papillosum* (Ivanov, 1981).

Thus it seems likely that direct effects of acrotelm conditions on evapotranspiration under the given circumstances did not occur.

Table 9.1. Leaf area indices (LAI) in m^2m^{-2} of the vegetation in the lysimeters. In August 1991, the LAI of the *Calluna* lysimeters, was replaced by the total length of the green branches per lysimeter (shown in italics), because measuring the LAI itself was extremely time consuming. As for the *Sphagnum* lysimeters, the value (in italics) shows the fraction of the surface covered by living capitula.

	Calluna vulgaris Acrotelm condition				*Narthecium ossifragum* Acrotelm condition			
Date	poor	poor[1]	good	good[2]	poor	poor	good	good
16th April 1991	3.2	2.4	2.0	2.3	0.1	0.1	0.0	0.0
8th June 1991	-	-	-	-	1.2	1.5	0.8	1.0
3rd August 1991	*39 m*	*26 m*	*18 m*	*37 m*	1.0	1.2	1.0	1.6
28th August 1991	-	-	-	-	1.0	1.2	1.9	2.6
1st October 1991	-	-	-	-	0.6	0.6	0.6	1.2
4th November 1991	*39 m*	*26 m*	*20 m*	*46 m*	-	-	-	-
	Eriophorum vaginatum Acrotelm condition				*Sphagnum sp.* Acrotelm condition			
Date	poor	poor[3]	good	good[4]	poor	poor	good	good
16th April 1991	0.2	0.2	1.1	0.3	*0.9*	*1.0*	*1.0*	*1.0*
8th June 1991	0.7	0.6	1.5	1.0	*1.0*	*1.0*	*1.0*	*0.9*
3rd August 1991	0.6	0.6	1.8	1.1	*0.9*	*0.9*	*0.7*	*0.6*
28th August 1991	0.9	0.8	2.8	1.1	*1.0*	*1.0*	*0.9*	*0.6*
1st October 1991	0.5	0.4	1.2	0.8	*1.0*	*1.0*	*0.9*	*0.8*
4th November 1991	-	-	-	-	-	-	-	-

Monthly evapotranspiration values of the Raheenmore Bog catchment were calculated from the lysimeter results as an average weighted by the estimated fraction of the catchment area (Fig. 9.1) that was occupied by the respective vegetation elements. The results are shown in Table 9.2, together with monthly sums of precipitation on the bog and potential evapotranspiration data from the meteorological stations Birr and Mullingar, based on the Penman open water equation

[1] The lysimeters had an initial fraction of moss cover of 0.4, increasing to 0.6 at the end the growing season (mainly *Hypnum jutlandicum* and some *Sphagnum sp.*).

[2] The lysimeters had an initial fraction of moss cover of 0.3, increasing to 0.8 at the end the growing season (mainly *Sphagnum magellanicum* and *S. capillifolium*).

[3] The lysimeters had an initial fraction of moss cover of 0.3, increasing to 0.5 at the end the growing season (mainly *Sphagnum magellanicum*).

[4] The lysimeters had an initial fraction of moss cover of 0.3, increasing to 0.6 at the end the growing season (mainly *Sphagnum capillifolium, S. magellanicum and S. papillosum.*).

$$E_o = \frac{\frac{\Delta(R_n - G)}{\lambda} + \gamma E_a}{\Delta + \gamma} \quad (9.3)$$

where

E_o = open water evaporation rate $[ML^{-2}T^{-1}]$, here expressed in kg m^{-2} s^{-1}

Δ = slope $\frac{de_a}{dT_a}$ $[ML^{-1}T^{-2}\theta^{-1}]$, *i.e.* the first derivative of the function of saturated water vapour pressure e_a versus air temperature T_a, here expressed in kPa K^{-1}

R_n = net radiation $[MT^{-3}]$ flux density, here expressed in W m^{-2}

G = heat flux density into the water body $[MT^{-3}]$, here expressed in W m^{-2}

λ = latent heat of vaporisation $[L^2T^{-2}]$ ($\approx 2.45*10^6$ J kg^{-1})

γ = psychrometric constant ($\approx$ 0.0666 kPa K^{-1}, based on an atmospheric pressure of 101 kPa)

E_a = isothermal evaporation rate $[ML^{-2}T^{-1}]$, here expressed in kg m^{-2} s^{-1}

E_a is obtained from

$$E_a = \frac{f(u)}{\lambda}\left(e_s(T_2) - e_2\right) \quad (9.4)$$

where

f(u) = an empirical function of the wind speed u_2 $[LT^{-1}]$ at 2 m height. In Penman's original approximation as applied in Ireland, $f(u) = 37 + 40u_2$ (adjusted for the applied units, dimensions ignored).

$e_s(T_2)$ = saturated water vapour pressure $[ML^{-1}T^{-2}]$, here expressed in kPa at the temperature T_2 at 2 m height

e_2 = actual water vapour pressure at 2 m height $[ML^{-1}T^{-2}]$, here expressed in kPa.

The data of Birr and Mullingar as obtained from Met Éireann had been corrected for grassland by

$$ET_p = f_g E_o \quad (9.5)$$

where

ET_p = potential evapotranspiration for grassland $[ML^{-2}T^{-1}]$

f_g = crop factor [1] for grassland

Met Éireann applies a value of 0.75 for f_g. It is based on research work described by Connaughton (1967). The Penman E_o values of Birr and Mullingar were calculated from the available ET_p.

Table 9.2 shows that the lysimeter evapotranspiration over the entire period was 70 mm below the Penman E_o of the nearest weather station Mullingar, but the result exceeded the grassland value (457 mm) calculated from Eq. (9.5) by more than 80 mm.

Table 9.2. Monthly sums of lysimeter evapotranspiration (mm) per species and overall sums, weighted by area per species, precipitation (mm) and excess precipitation (mm) of *Raheenmore Bog* over 7th April 1991 through 6th April 1992 and monthly sums of calculated Penman open water evaporation E_o (mm) at the stations Birr and Mullingar. For the bog measurements, April is 7th through 30st April 1991 and 1st through 6th April 1992. As for the data of Birr and Mullingar, April is April 1991.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar		
Species	Lysimeter evapotranspiration												Sum	Weight
Calluna	51	78	59	70	57	46	25	15	14	13	29	53	510	0.15
Narthecium	47	66	55	64	50	39	19	15	13	11	23	51	454	0.05
Eriophorum	50	72	64	73	61	49	29	13	16	13	32	55	526	0.35
Sphagnum	54	98	74	80	67	58	27	9	12	11	27	50	568	0.45
Weighted sums	52	84	67	75	63	52	27	12	14	12	28	53	539	1.00
	Precipitation												Sum	
	91	12	97	56	33	61	108	97	70	77	57	99	858	
	Excess precipitation												Sum	
	39	-72	30	-19	-30	9	81	85	56	65	29	46	319	
	Penman E_o												Sum	
Birr	61	91	92	91	77	55	21	5	1	1	21	35	552	
Mullingar	77	101	99	107	81	63	21	4	0	1	17	37	609	

The lysimeter evapotranspirations exceeded the Penman evaporations in all months from October through March. The *Sphagnum* lysimeters had the largest overall evapotranspiration, but in the winter months it was exceeded by the *Eriophorum* lysimeters. This result was probably caused by interception on the dead leaves of *Eriophorum* that stood partly above the surface during the winter. A reduction in *Sphagnum* evapotranspiration may have occurred as a result of the precipitation deficit of May, July and August and subsequent dying of capitula. Because this process also occurred in a part of the lysimeters, it is assumed that the values in Table 9.2 are a reasonable approximation to the average *Sphagnum* evapotranspiration on the bog. The smallest evapotranspiration was found in the *Narthecium* lysimeters. Although the *Narthecium* leaves were abundant during the summer months, the evapotranspiration was consistently below the level of the other lysimeters during the entire year.

9.4.2. Clara Bog

The Clara Bog lysimeter field was operated from 24h July 1992 to 28th July 1993. The fifteen lysimeters were weighed 48 times during this period. As mentioned in 3.11, the lysimeters contained five different vegetation elements. Because the experiment on Raheenmore Bog had shown no direct effect of acrotelm quality on evapotranspiration, the lysimeters were not divided into groups with good and poor acrotelms. On request of the ecological section of the working group, two groups of *Calluna vulgaris*, one from the wet area and one from a burnt area, were distinguished. Each vegetation element was represented in three lysimeters. Results of each triple were averaged. Bog evapotranspiration was calculated as a weighted average of these averages, similar to the calculation for Raheenmore Bog in Table 9.2. The water levels in the lysimeters were kept at levels comparable to those in the bog, usually 3-10 cm below the surface, depending on expected weather conditions.

The lysimeter site was positioned about 100 m from an automatic weather station, operated by University College Galway. It produced hourly recordings of net and global radiation, wind speed, air temperature and relative humidity. From the data, Penman E_0 was calculated for the entire period the lysimeters were operated. To maintain comparability with the data of Met Éireann, Eq. (9.3) and (9.4) were applied. The ground flux G was assumed to be zero. T_2 , u_2 and e_2 were obtained from the weather station as daily averages. e_s was approximated by

$$e_s \approx 0.6108 \exp\left(\frac{17.27 T_2}{T_2 + 237.3°\text{C}}\right) \text{kPa} \tag{9.6}$$

(Feddes and Lenselink, 1994), where T_2 is expressed in °C. The resulting E_0 is expressed in kg m^{-2} s^{-1}, which is numerically equal to mm s^{-1}.

As on Raheenmore Bog, the lysimeter results were sometimes affected by overflow and inflow after heavy rainfall. Consequently, 20% of the week sums of lysimeter triples had to be estimated. This was preferably done by linear regression using data from triples with a reliable result. At four occasions, extreme rainfall caused overflow in all lysimeters and the weekly sums of lysimeter evapotranspiration had to be estimated by regression using Penman E_0 of the Clara Bog weather station. During one week in August and one in September 1992, the water level in the lysimeters had fallen to 30-45 cm below the lysimeter surface, much deeper than in most of the bog. Because reduction of lysimeter evapotranspiration was likely, the data of these weeks were also estimated by linear regression from Penman E_0. Thus a total of 10% of the values, included in the 20% mentioned above, were estimated from meteorological data. Assuming an average error of 25% in the estimated values, this would have caused a worst-case 5% additional error in the overall result.

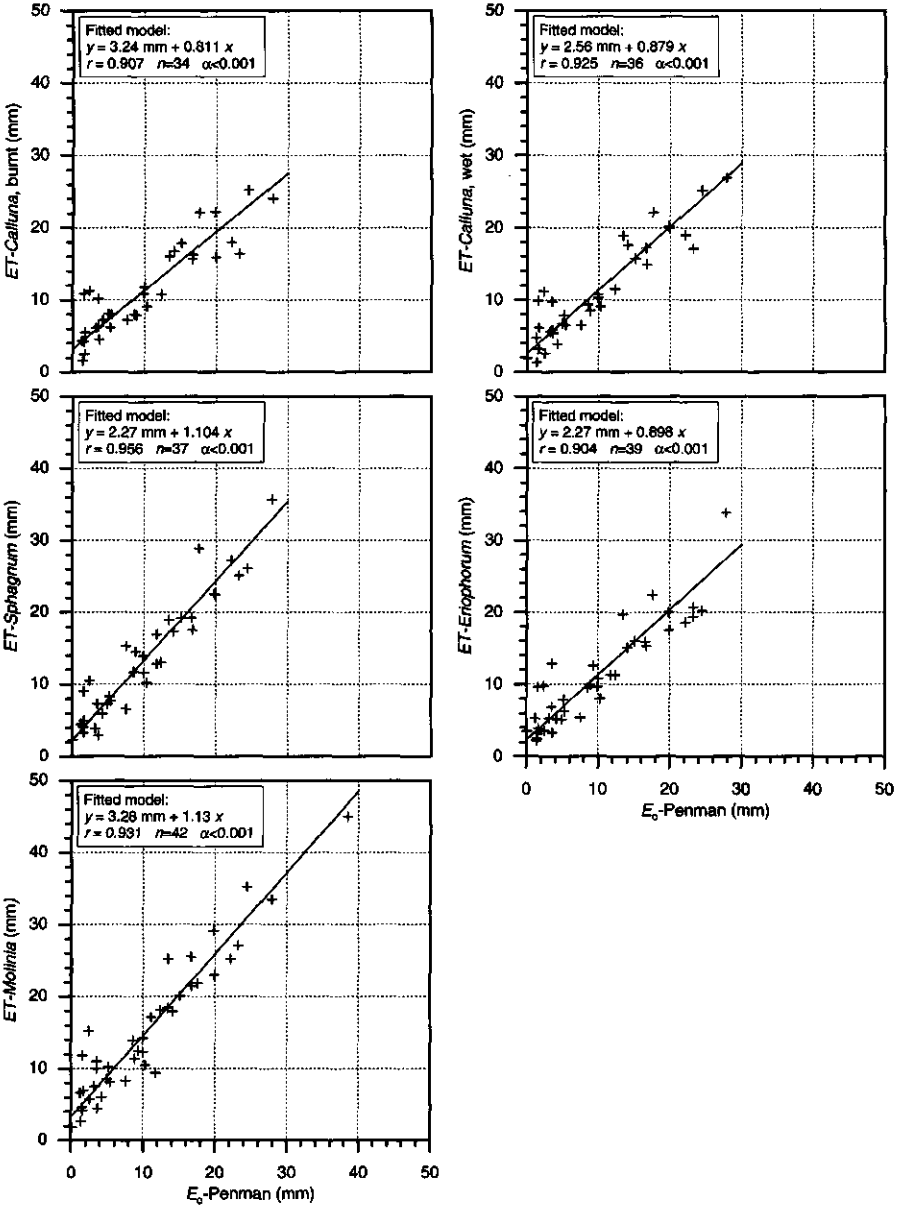

Fig. 9.8. Lysimeter evapotranspiration sums over approximately one week periods versus sums of Penman open water evaporation E_o, calculated from data of the weather station on *Clara Bog*.

Fig. 9.8 shows fitted statistical relationships of approximately weekly sums of lysimeter evapotranspiration sums versus Penman E_o, calculated from the data of the weather station on Clara Bog. Although the overall correlations are reasonable, the diagrams show some relatively large differences for the evaporation ranges below 10 mm. They include winter values. Because the winter evapo(transpi)rations of the lysimeters are usually small, but larger than Penman values (*cf.* Table 9.2 and Table 9.4), all diagrams of Fig. 9.8 show positive intercepts.

To compare correlations within the set of lysimeter data with lysimeter/Penman correlations, Table 9.3 shows a correlation matrix that involves both. The correlation between the lysimeter results tends to be stronger than between lysimeter and Penman results, but is still reasonable for the latter.

Table 9.3. Correlation matrix of weekly evapotranspiration sums of lysimeter triples with Penman open water results of the automatic weather station on Clara Bog. Numbers of data pairs in parentheses.

	Calluna, burnt	*Calluna*, wet	*Sphagnum*	*Eriophorum*	*Molinia*	Penman
Calluna, burnt	1 (34)					
Calluna, wet	0.976 (34)	1 (36)				
Sphagnum	0.939 (33)	0.962 (34)	1 (37)			
Eriophorum	0.937 (34)	0.963 (36)	0.962 (35)	1 (39)		
Molinia	0.951 (34)	0.969 (36)	0.938 (35)	0.932 (38)	1 (42)	
Penman	0.907 (34)	0.951 (34)	0.956 (37)	0.904 (39)	0.931 (42)	1 (48)

Table 9.4 gives monthly sums of evapotranspiration of the lysimeters, bog evapotranspiration derived by weighting the estimated fraction of the catchment area (Fig. 9.2) occupied by the species involved, Penman E_0 sums of the Clara Bog station, Birr and Mullingar and precipitation sums of Clara Bog.

No clear differences were found between the evapotranspiration sums of the two sets of *Calluna* lysimeters. Their LAI values were almost equal (1.75 vs. 1.72 in August 1992 and 1.15 vs. 1.14 in November 1992). Apart from the expected conclusion that no differences existed between evapotranspiration of *Calluna vulgaris* at different soil conditions, this result suggests that in general the lysimeter results were reasonably reliable. The *Eriophorum* lysimeters gave slightly larger results than the ones with *Calluna*. In this respect there was no difference with the results of Raheenmore Bog shown in Table 9.2. The totals of the *Eriophorum* lysimeters exceeded those of the *Sphagnum* types during the months November and December, but contrary to the results of Raheenmore Bog, not in all winter months. The *Sphagnum* lysimeters had a considerably larger evapotranspiration than on Raheenmore Bog, although the Penman results of the Met Éireann stations were lower over the measuring period on Clara Bog. The surface fraction of vegetation with living *Sphagnum* capitula on the lysimeters was 1 at all times. The species in the Clara Bog lysimeters were mainly *S. magellanicum* and *S. capillifolium*. As mentioned, their capitula are more resistant to temporary low phreatic levels than *S. papillosum*. However, as a result of the wet spring, such low levels did not occur on Clara Bog during the growing season of 1993. This explains the larger *Sphagnum* evapotranspiration than measured in the lysimeter experiment on Raheenmore Bog.

Table 9.4. Monthly sums of lysimeter evapotranspiration (mm) per species, weighted overall sums of evapotranspiration and excess precipitation (mm) on *Clara Bog* over 29^{th} July 1992 through 28^{th} July 1993. *Monthly sums of calculated Penman open water evaporation E_0 (mm), from the* stations Clara Bog, Birr and Mullingar. As for the data of Clara Bog, July is the sum of 29^{th} through 31^{st} July 1992 and 1^{st} through 28^{th} July 1993. As for the data of Birr and Mullingar, July is July 1993.

	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul		
Species	Lysimeter evapotranspiration												Sum	Weight
Calluna, burnt	58	31	26	15	15	23	24	38	58	78	67	83	516	0.03
Calluna, wet	56	28	24	13	15	23	25	37	58	84	72	83	518	0.12
Sphagnum	71	34	23	14	15	20	26	48	67	107	95	92	612	0.45
Eriophorum	61	31	21	13	16	19	23	40	57	92	80	77	530	0.35
Molinia	83	40	30	18	20	28	34	55	75	102	102	117	704	0.05
Weighted sums	66	32	23	14	15	21	25	44	62	98	86	87	573	1.00
	Precipitation												Sum	
	100	87	40	100	59	92	11	41	116	103	105	58	912	
	Excess precipitation												Sum	
	34	55	17	86	44	79	-14	-3	54	5	19	-29	347	
Station	Penman E_0												Sum	
Clara Bog	59	42	19	5	3	9	12	31	55	80	79	75	469	
Birr	76	41	16	7	-3	1	12	33	59	89	79	82	492	
Mullingar	88	44	16	3	0	12	12	35	63	96	89	92	550	

The largest evapotranspiration was measured in the *Molinia* lysimeters. This should in part be attributed to interception on dead stalks and leaves that still formed about 50% of the 'leaf' surface in the first week of May 1993. Another cause may have been the trampled vegetation and soil around the lysimeters. This situation may have caused additional evapotranspiration because of exposure to wind. Spieksma *et al.* (1997) indeed found a relatively large dependence on vapour pressure deficit and thus on the aerodynamic term of the Penman (in their case Penman-Monteith) equation of the evapotranspiration of *Molinia caerulea* in a bog in the eastern part of the Netherlands. Interception on the approximately 40 cm tall stalks and dead leaves may be a (partial) explanation. However, because of the rather small fraction of the catchment area that is dominated by *Molinia*, the effect of possible errors in the measurement on the final result is small.

9.4.3. Discussion

In both 'lysimeter years', the bog evapotranspiration exceeded that of grassland as calculated from meteorological data using Eq. (9.5). In the Raheenmore Bog experiment, the difference was 80 mm with the nearest station, Mullingar. Most of the difference was caused by the *Sphagnum* lysimeters, even though the lysimeters with *S. papillosum* almost certainly had a reduced evapotranspiration as a result of a precipitation deficit in the late spring and summer and subsequent dying of capitula. Such effects may be much more extreme in real dry summers, as was shown by Phersson and Pettersson (1997) who found reductions of up to 60% relative to calculated Penman E_0 during dry summer conditions in a raised bog near Uppsala, Sweden.

The evapotranspiration in the Clara Bog lysimeter experiment was larger than during the one on Raheenmore Bog in the preceding year, even though the Penman evaporation of the Met Éireann stations was smaller in the 'Clara' year than in the 'Raheenmore' year. A small part of this result is related to the inclusion of *Molinia* tussocks and the exclusion of *Narthecium* lawns in the Clara Bog experiment, because some parts of the Clara Bog catchment, particularly near Shanley's Lough, are dominated by *Molinia*. *Narthecium* lawns are less common in the Clara Bog catchment than on Raheenmore Bog. Because of the small fraction of the areas covered by both vegetation elements, the difference cannot be ascribed solely to this difference in composition of the vegetation. The other vegetation component with a significantly higher evapotranspiration was *Sphagnum*. There may have been some reduction of *Sphagnum* evapotranspiration in August and September 1992 after an approximately average summer in terms of precipitation. However, the wet spring of 1993 ensured that any reduction of evapotranspiration during April to July 1993 as a result of a water deficit is most unlikely to have occurred. This may explain the large *Sphagnum* evapotranspiration as found in the Clara Bog lysimeter experiment.

The overall results show that in both bogs and in the years involved, evapotranspiration considerably exceeded potential evapotranspiration values for grassland as estimated from Eq. (9.5) and even open water evaporation in the case of Clara Bog. On Clara Bog, the evapotranspiration of *Calluna vulgaris* and *Eriophorum vaginatum* approximately followed the 'classic' Penman open water equation, except in the winter months when their actual evapotranspiration was 10-15 mm per month larger. This difference was found for all lysimeters.

The highest evapotranspiration was measured in the *Molinia* lysimeters. It probably included an interception component related to the presence of tall dead leaves and stalks and hence is only in part evapotranspiration from living plants.

The explanation of the differences between *Sphagnum* evapotranspiration and Penman results is more difficult. Because the net available radiation energy is reasonably well defined (although some variation may be caused by the changing albedo of drying *Sphagnum* capitula), the difference must be attributed mainly to the aerodynamic term $\frac{\gamma E_a}{\Delta + \gamma}$ rather than to the radiation term of Eq. (9.3). This may be illustrated by results obtained by Kim and Verma (1996) in a poor *Sphagnum* dominated fen in northern Minnesota. They defined E_a by

$$E_a = 2.7(1 + 0.864u_2)(e_s(T_2) - e_2) \tag{9.7}$$

where E_a is expressed in kg m^{-2} d^{-1} and all other quantities in the same units as before. They found an approximately 1:1 ratio between calculated and measured evapotranspiration from a *Sphagnum* dominated plant cover. Unfortunately, the authors mentioned neither the *Sphagnum* species nor the measuring method of *ET*.

When applied to the data of the Clara Bog weather station, replacing E_a from Eq. (9.4) by E_a from Eq. (9.7) in Eq.(9.3), yields an evapotranspiration that is on average 0.25 mm d^{-1} higher, even during the winter. This would bring the calculated *Sphagnum* evapotranspiration, including the radiation component, to a level of 560 mm over the period August 1992 through July 1993, much closer to the measured value than the classic Penman approach, but still smaller. The differences between measured winter evapotranspiration of the lysimeters and the Penman result would almost disappear.

A problem in judging the results obtained is that in literature on evapotranspiration from bogs and other wetlands sometimes larger and sometimes smaller evapotranspiration values than 'potential' ones are claimed (Ingram, 1983). Ingram concluded that on treeless bogs in relatively snow-free zones, the evapotranspiration during the winter is probably larger than calculated E_0 and smaller in the summer when low phreatic levels and an increased albedo of *Sphagnum* with dead capitula cause conversion of a larger proportion of the incoming radiation energy into sensible heat. This seems to be confirmed by the results obtained from the experiments on Clara and Raheenmore Bog, even though during the season 1992/93 summer conditions as described by Ingram did not occur on Clara Bog. The results show that actual evapotranspiration from raised bogs cannot be estimated reliably from meteorological data, because the evapotranspiration of *Sphagnum* species in particular is too sensitive to even minor fluctuations of the phreatic level. If no reduction of evapotranspiration from *Sphagnum* occurs as a result of a sufficiently high water table, the aerodynamic part of the evapotranspiration process is still a problematic component.

Interactions between different species (e.g. effects of shadowing) were not measured, because different vegetation elements were separated in different lysimeters. This might have caused some overestimation of the bog evapotranspiration. One element was not measured: the evaporation of the shallow open water in pools and hollows. This uncertainty could not be clarified, given the available time and means.

9.5. Release of water from storage

The release from storage of water, ΔS in Eq. (9.1), is related to storage in the unsaturated zone, the saturated zone and fluctuations of the surface level (*Mooratmung*).

Storage in the unsaturated zone could not be measured reliably on a regular basis, given the available means. Because the unsaturated zone in both Raheenmore and Clara Bog West was shallow and locally even non-existing, it was ignored and changes in storage were derived from fluctuations of the phreatic level and *Mooratmung*, measured on the available benchmarks.

For each bog an approximately representative set of dip wells inside the catchment areas and with measurement series that covered the entire period over which reliable discharge data were available was selected. For Raheenmore the set consisted of sites 206, 210, 328, 330 and 332 (positions shown in Fig. 3.7). For Clara Bog, the sites 53, 55, 56, 58 and 59 (positions shown in Fig. 3.12) were selected. The measured levels were averaged over the sites and differences in storage due to fluctuations of the phreatic level were found from successive differences Δh in the series and the storage coefficient μ:

$$\Delta S_h = \mu(h_0 - h_1) = \mu\Delta h \tag{9.8}$$

where

h_0, h_1 = phreatic level [L] at the beginning of two successive time intervals between measurements

ΔS_h = change in storage [L] due to a change in phreatic level

The value of μ was estimated at 0.5 to account for areas with poor and good acrotelm and with parts of open water.

The same approach was applied to calculate differences in storage ΔS_s due to *Mooratmung* from surface levels z_s:

$$\Delta S_s = (z_{s_0} - z_{s_1}) = \Delta z_s \tag{9.9}$$

Eq. (9.9) does not show μ because $\mu = 1$. Changes in surface level were derived from the levelling benchmarks (three on Raheenmore Bog, two on Clara Bog West). The total change in storage ΔS could then be calculated as the sum of both:

$$\Delta S = \Delta S_h + \Delta S_s \tag{9.10}$$

9.6. Water balances

9.6.1. Balances based on lysimeter evapotranspiration

Raheenmore Bog

Evapotranspirations are lysimeter values as shown in Table 9.2. The discharge as measured at the gauging sites was assumed to be all acrotelm discharge (Fig. 5.1). Lateral catotelm discharge was set to 1 mm a^{-1} (as inferred in 5.4.2). Exfiltration to underlying mineral strata was estimated at 12 mm a^{-1} as inferred in 5.5.3 and applied per month as a constant rate.

Table 9.5. Water balance in mm of Raheenmore Bog over the lysimeter period 7th April 1991 through 6th April 1992. Input into the bog system is positive, losses are negative. Positive values in the storage terms ΔS_h (storage by changing phreatic level) and ΔS_s (storage by fluctuation of the surface level, *Mooratmung*) imply release from storage. The estimated catchment size is 28 ha.

Balance term	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Year
Precipitation	91	12	96	56	33	61	108	97	70	77	57	99	857
Evapotranspiration	-52	-84	-67	-75	-63	-52	-27	-12	-14	-12	-28	-53	-539
Acrotelm discharge	-52	-10	-6	-9	-6	-2	-25	-62	-43	-50	-21	-38	-324
Exfiltration	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-12
Lateral catotelm discharge	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-1
ΔS_h	8	50	-33	10	25	-31	-22	-2	-4	3	-1	-6	-3
ΔS_s	22	21	-9	10	14	4	-18	-11	-2	-1	1	-4	27
Remainder	16	-12	-20	-9	2	-21	15	9	6	16	7	-3	5

The remaining unexplained sum over the one year period is 0.6% of the total input and negligible. The sums per month show relatively large remainders. This may be attributed to delay beween precipitation and discharge and probably to errors in estimated changes in storage. Because the sum of the storage terms is small, these errors are unlikely to have influenced the overall result to a considerable extent.

This overall result means that the values of the less certain elements in the balance - evapotranspiration and catchment size - are probably reasonably correct. A possible misestimate of the exfiltration sum by, for example, a factor of 2 or 3 has little effect on the result. Hence the balance is not necessarily a confirmation of the exact results of 5.5.3, but it does confirm that the exfiltration from Raheenmore Bog is not a substantial component of the flow system.

Clara Bog West

Table 9.6 gives the water balance over the lysimeter test period of Clara Bog West. Lateral catotelm discharge was assumed to be 1 mm a^{-1} (5.4.3). Exfiltration to the underlying mineral strata was assumed to be 8 mm a^{-1} as inferred in 5.5.3. Both were assumed to be constant in time. The discharge of April 1993 had to be estimated from the discharge of Raheenmore because of problems with the discharge recorders of Clara Bog. The technique was linear regression on one-month sums. The relationship was based on 29 pairs of values. Its correlation coefficient r was 0.950.

Table 9.6. Water balance in mm of *Clara Bog West* over the lysimeter test period 29th July 1992 through 28th July 1993. Input into the bog system is positive, losses are negative. Positive values in the storage terms ΔS_h (storage by changing phreatic level) and ΔS_s (storage by fluctuation of the surface level, *Mooratmung*) imply release from storage. The estimated catchment size is 98 ha.

Balance term	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Year
Precipitation	101	87	40	100	59	97	11	41	117	102	105	62	922
Evapotranspiration	-66	-32	-23	-14	-15	-21	-25	-44	-62	-98	-86	-87	-573
Acrotelm discharge	-4	-22	-9	-36	-48	-45	-16	-7	-53	-22	-56	-5	-323
Exfiltration	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-8
Lateral catotelm discharge	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-1
ΔS_h	-24	-9	-3	-17	14	-7	17	-4	-6	-9	18	6	-24
ΔS_s	-7	-6	0	-13	-9	-1	11	0	-9	-1	9	11	-15
Remainder	-1	17	4	19	0	22	-3	-15	-14	-29	-11	-14	-22

The remainder in the balance is negative and 2.4% of the precipitation input. This result seems acceptable because it is within the margins of uncertainty of the one-year sum of the largest individual quantities in Table 9.6. The monthly balances show relatively large deviations, similar to those for Raheenmore Bog in Table 9.5.

At extremely large discharge peaks, such as in mid-June 1993 after a rainfall of more than 70 mm in 3 days, some water was observed flowing out over the bog surface between the measuring weirs. This means that a small fraction of the outflow was not recorded and thus the negative remainder should even have been slightly larger than calculated in Table 9.6. Possible causes of the negative remainder are discussed briefly below.

- A wrongly estimated difference in storage between the beginning and the end of the period is a likely cause, particularly because ΔS_h could not be estimated reliably.
- Overestimation of the discharge might have contributed to the difference, but because the measuring weirs were properly installed and calibrated, an error of 8% seems rather unlikely.

- An underestimated catchment size is a possible source of error. A size of 105 ha instead of 98 would eliminate the remainder of 21 mm, but this difference seems too much to account for the entire remainder in the balance.
- Overestimated evapotranspiration, related to wrong weighting factors for the different vegetation elements, might have caused an error.
- The situation immediately around and between the lysimeters may also have been a source of error. As a result of the wet conditions during the autumn and the winter of 1992/93, the surface became strongly trampled because of the activities associated with the weekly weighing. Advection effects of a dried out peat surface could theoretically have played a role during the spring and summer of 1993. However, because of the weather conditions, the surface hardly ever got dry during these months, so large errors resulting from conversion of radiation energy into sensible heat are unlikely to have occurred.
- Estimating errors in the exfiltration sum cannot have played a major role because of its small value.
- A small measuring error in the precipitation is another likely partial cause. Rain gauge measurements tend to underestimate the real precipitation (De Bruin, 1977). However, an error of 2.4% in the given conditions (3 gauges) seems rather much to account for the entire difference.

Hence it seems unlikely that the remainder may be attributed to one single balance term.

9.6.2. Water balances over the entire observation period

In section 9.4, considerable differences were found between evapotranspirations of the bogs and Penman E_0 of some meteorological stations of Met Éireann. The probability of reduction of evapotranspiration as a result of drying of the peat surface and of *Sphagnum* dominated vegetations in particular, was discussed. A problem in comparing the water balances of Raheenmore Bog and Clara Bog is that they cover different periods. Because both yield acceptably small remainders, it seems possible to compare both bogs by estimating evapotranspiration from the other terms of the balances. The monthly remainders in Table 9.5 and Table 9.6 often exceed the annual values. This shows that monthly balances derived in this way are unreliable, probably mainly because of storage effects that were estimated inaccurately. Therefore the balance periods should be considerably longer than a month, preferably a full year. Three periods with lengths of approximately a year were eventually distinguished. They are

Period 1: 18th September 1990 through August 1991
Period 2: 1st September 1991 through August 1992
Period 3: 1st September 1992 through 28th July 1993 (19th July for Raheenmore Bog)

The first two periods contain a full summer season, the last period lacks August and a few days of July. Some simplifications and adaptations to changed conditions are necessary. Remainders are assumed to be zero, *i.e.* Eq. (9.1) is supposed to apply to the unadjusted balances.

Table 9.7. Water balance (mm) and inferred evapotranspiration ET_{bog} (mm) of the catchments of Raheenmore Bog and Clara Bog West with Penman open water evaporation E_o of the meteorological stations Birr and Mullingar over three periods, covering 18th September 1990 to 19th July 1993 (Raheenmore) and 28th July 1993 (Clara). Penman E_o of the Clara Bog weather station was available over the last period only. Therefore the bog evapotranspiration ratios $f_b = \frac{ET_{bog}}{E_o}$ are based on data of Birr. Inputs are positive, outputs negative.

	Raheenmore Bog			Clara Bog West		
Period	18th Sept. 1990 - August 1991 (348 d)	September 1991- August 1992 (366 d)	September 1992 - 19th July 1993 (312 d)	18th Sept. 1990 - August 1991 (348 d)	September 1991- August 1992 (366 d)	September 1992 - 19th July 1993 (321d)
Term	Water balance			Water balance		
Precipitation	933	958	933	851	784	821
Discharge	-482	-325	-445	-320	-245	-319
Release from storage	68	-86	-13	25	-20	-8
Exfiltration	-11	-12	-10	-8	-8	-7
	ET_{bog} calculated from balance			ET_{bog} calculated from balance		
	-508	-535	-465	-548	-511	-487
	Penman E_o			Penman E_o		
Clara Bog weather stn.			-386			-410
Birr	-508	-574	-384	-508	-574	-408
f_b	1.00	0.93	1.20	1.08	0.89	1.19
Mullingar	-543	-620	-426	-543	-620	-453

As for Raheenmore Bog, ΔS_h after April 1992 could only be based on data of the groundwater recorder RHG1 (position shown in Fig. 3.13) because the dip wells were abandoned after this month. Data on ΔS_s of Raheenmore Bog were not available after April 1992 for the same reason, except two incidental measurements on 2nd August 1992 and 19th July 1993. Results are shown in Table 9.7. Table 9.7 also shows estimated evapotranspiration ratios $f_b = \frac{ET_{bog}}{E_o}$ for both bogs, based on the average Penman E_o of Birr only, because it almost equalled the value of Clara Bog during the period values of both stations were available. The Penman E_0-values of Mullingar seem too high to base a realistic f_b on.

With regard to Table 9.7, the following remarks are made.

- The high evapotranspiration of 573 mm as measured with the lysimeters (507 mm for the one month shorter period in Table 9.7) coincides with a large evapotranspiration sum on Raheenmore Bog that exceeds the Penman E_0 of the three nearest weather stations. It supports the conclusion based on the lysimeter results for Clara Bog West, that the evapotranspiration from this bog during the lysimeter test considerably exceeded the Penman E_0.
- The inferred evapotranspiration of Raheenmore Bog of the first period is smaller than for Clara Bog; in the second period the difference is reversed. The first period included a summer (1991) that was relatively dry on Raheenmore and approximately normal on Clara Bog (*cf.* Fig. 9.6). Another and probably additional explanation of the difference in 1991 is the position of the areas that contain most *Sphagnum* vegetations. In Raheenmore Bog they are in the central part of the bog and thus the upstream part of the catchment. In the Clara Bog catchment they are in the downstream part, the area of Shanley's Lough. Probably the latter part still obtained some recharge from upstream, whilst the upstream part of Raheenmore Bog only lost water.
- The second period included a spring and summer (1992) that were approximately normal in terms of precipitation on both bogs. Because Raheenmore Bog is the wetter one of both, this may explain the slightly larger evapotranspiration from this bog.
- During all periods, the actual evapotranspiration of the bogs exceeded the potential evapotranspiration of grassland ($0.75E_0$). The smallest value of f_b was 0.89.
- The conclusion drawn for Clara Bog that bog evapotranspiration can exceed E_0 if a summer is wet enough to prevent *Sphagnum* capitula to dry out is confirmed by the evapotranspiration result of Raheenmore Bog in the third period. It is almost exactly the same as for Clara Bog if the difference in period length of nine days in July is accounted for.

9.6.3. Conclusions

- The water balances of both Raheenmore Bog and Clara Bog West show a good fit of input (precipitation) and output (discharge, evapotranspiration, vertical seepage and lateral catotelm outflow). The balance of Raheenmore Bog fits almost perfectly, the one of Clara Bog shows a deficit of 2.3% of the input.
- The above results confirm that the exfiltration rates and lateral outflow through the catotelm are minor components in the hydrological system as inferred in 5.5, even though inevitable inaccuracies in the balances do not allow a confirmation of the exact results.

- The balances indicate that the lysimeter results are reasonably correct. Bog evapotranspiration ratios f_b were between 0.89 and 1.20, depending on the weather conditions between early spring and late summer. Continuously wet conditions coincided with large f_b. The results for Raheenmore Bog confirm the large evapotranspiration of the Clara Bog catchment during the 'lysimeter' year, because the f_b over this period was nearly the same for both bogs. This implies that small fluctuations of the phreatic level have a considerable impact on *Sphagnum* evapotranspiration and not only cause differences between dry and normal years, but even between normal and wet years, in spite of the humid Irish climate. Phreatic levels do not affect the evapotranspiration of other vegetation elements to this extent.
- It can be concluded rather safely that calculated potential evapotranspiration from data of a weather station such as the one on Clara Bog, even when positioned on the bog, is not suitable to estimate bog evapotranspiration. Effects of wet and dry summers on bog evapotranspiration are too large to be accounted for. The share of different *Sphagnum* species in a vegetation also affects evapotranspiration and the position of *Sphagnum* vegetations in the flow system may also have an effect. Differences between water balance results and calculated values may be 100 mm and more over a single year.
- Reliable methods to calculate evapotranspiration from meteorological data should be based on measurements on and above the vegetation studied and on different places on the bog. Hence, operating a single weather station on a bog is likely to yield inaccurate evapotranspiration results. Romanov's remark (Romanov, 1968b) that a reasonably accurate calculation of mire evapotranspiration requires tedious micrometeorological measurement procedures, implicitly confirms this.

9.7. Conclusions

- The sizes of the water balance catchments on Raheenmore Bog and Clara Bog as estimated from surface level gradients of the 100m x 100m OPW grid were 28 and 98 ha, respectively. The water balance studies gave no good reasons to adjust these values. Hence the applied technique was adequate.
- The precipitation sum of Raheenmore Bog from the meteorological summer of 1990 through the meteorological spring of 1993 exceeded the sum of Clara Bog by more than 13%. This difference should probably attributed to the average surface height of Raheenmore Bog, which exceeds the average of Clara Bog by about 45 m. The sums differed little from those of the nearest meteorological stations of Met Éireann, Birr (nearest to Clara Bog) and Mullingar (nearest to Raheenmore Bog).
- Most quarterly precipitation sums did not differ much from average values. Exceptions were the relatively dry winters of 1992 and 1993 and the extremely wet spring of 1993. The wet spring weather of 1993 continued during June 1993 when the sums

for Raheenmore Bog and Clara Bog were 137 and 105 mm respectively, against respective estimated normal values of 65 and 54 mm. On Raheenmore Bog, the summer of 1991 had a precipitation sum of about 80% of the estimated normal value, whilst the total of Clara Bog was approximately normal.

- The lysimeter evapotranspiration over April 1991 - March 1992 of Raheenmore Bog was approximately equal to the uncorrected Penman E_0 as calculated by Met Éireann. The lysimeter evapotranspiration measured on Clara Bog over August 1992 - July 1993 was even higher than Penman E_0 derived from the data of the local recording weather station and also exceeded the Penman values of Mullingar and the nearer station Birr. Most of this difference should be attributed to the evapotranspiration of *Sphagnum* and its dependence on phreatic levels. The summer of 1991 on Raheenmore Bog was relatively dry. This had an impact on *Sphagnum* evapotranspiration as was measured in the lysimeters with *Sphagnum papillosum*. The lysimeters with *S. magellanicum* were less affected, maybe not at all.
- During the Clara Bog lysimeter test, a slight reduction of *Sphagnum* evapotranspiration could have occurred during the autumn of 1992, but the extremely wet spring and early summer of 1993 probably ensured the maximum possible *Sphagnum* evapotranspiration during April-July 1993. The evapotranspiration of *Molinia caerulea* exceeded the *Sphagnum* evapotranspiration. The evapotranspiration sums of *Calluna vulgaris* and *Eriophorum vaginatum* were approximately the same during both tests. The main variable in bog evapotranspiration is *Sphagnum* evapotranspiration. It depends strongly on the phreatic level. This dependence varies between *Sphagnum* species. Because the phreatic level partly depends on the position in the flow system of the bog, the evapotranspiration of a *Sphagnum* vegetation may also be indirectly related to position.
- The most important unknown in *Sphagnum* evapotranspiration is the aerodynamic component of the evapotranspiration process. This is shown in particular by the large difference between bog evapotranspiration and Penman open water values during the spring and summer of 1993. Adequate estimates of bog evapotranspiration from meteorological data should be based on micro-meteorological measurements on a number of places on the bog with different vegetations.

10. SUMMARY AND CONCLUSIONS

10.1. The project and the bogs

This work is the result of the hydrological part of a field project that was carried out in the framework of the Irish-Dutch Raised Bog Study from September 1989 to the end of July 1993. The objectives of the project were to exchange experience on bog conservation and restoration techniques and knowledge on the ecosystem of living raised bogs between Ireland and The Netherlands. The field project was meant to enhance knowledge of bog ecosystems. The work was done in two Irish Midland bogs, Raheenmore Bog and Clara Bog, both in Co. Offaly.

The morphology of the landscape the bogs are embedded in is largely determined by geological processes related to the Midlandian land ice cover. The bogs have both formed in glacial basins and show a common transition from different types of fen peat in the lower peat strata to bog peat in the upper layers. The altitudes are approximately 105 m OD (Ordnance Datum) on Raheenmore Bog and 60 m OD on Clara Bog. Peat depths are up to about 14 m in Raheenmore Bog and up to 10.50 m in Clara Bog. The climate is cool and humid with relatively small seasonal variations. Mean temperatures are approximately 14.5 °C (July), 4 °C (January) and 9.0 °C (annual average). Average annual rainfall varies between 800 and 1000 mm, average annual evapotranspiration of grassland lies around 450 mm.

10.2. Research questions

Research questions addressed were to quantify hydrological properties of and processes in raised bogs, their relationships and interactions in both their relatively healthy and damaged parts.

This implies the development of the elements for a conceptual model of the hydrology of raised bogs. The diplotelmic approach, *i.e.* the concept of acrotelm/catotelm (*cf.* Fig. 2.4 and Fig. 5.1) is followed throughout this work.

The elementary questions as to processes concern both general questions on bog hydrology and specific questions related to the hydrological system of Raheenmore and Clara Bog.

<u>The general questions as to bog hydrology concern</u>

- The extent to which the cross-sectional shape of a raised bog be explained by the horizontal flow component in the catotelm; *i.e.* the applicability and extendibility of the Groundwater Mound Theory as formulated by Ingram (1982) .
- Vertical seepage or exfiltration to underlying strata and dependence on groundwater levels in the surroundings.

- The influence of drainage in the near surroundings and the kind of mineral substratum on the above process.
- The influence of drainage and subsidence on the shape of a bog surface
- Consequences of the shape of a bog surface on acrotelm conditions as reflected in acrotelm depth, transmissivity and storage coefficient
- The influence of acrotelm and catotelm properties on the fluctuation of the water table
- Effects of the acrotelm as a non-linear aquifer on bog discharge
- The extent to which the acrotelm, being a product of subtle balance of production and decay of organic matter, is self-regulating as to the above processes and self-healing after a disturbance has occurred.
- Effects of vegetation and weather conditions on evapotranspiration

Specific questions as to the hydrology of Raheenmore Bog and Clara Bog concern

- The effect of the old drains on Raheenmore Bog on the hydrology of the bog
- The effects of external drainage, often marginal drains around the bogs, on a bog's hydrological system
- The effect of the Clara-Rahan road that bisects Clara Bog on the hydrological system of Clara Bog
- The effects of the superficial drainage on Clara East on acrotelm conditions and subsidence
- The water balance of Clara Bog and Raheenmore Bog.

10.3. Measuring methods

As a tool in the fieldwork needed to answer the above questions, some measuring methods had to be developed or to be modified to be applicable in peat soils. They include a field method for measuring acrotelm transmissivity T_a and a modification of the piezometer method to measure saturated hydraulic conductivity k in the catotelm. To estimate k and catotelm transmissivity T_c, statistical relationships between humification, bulk density (expressed as volume fraction of solid matter ϕ_b) and k had to be found.

The measuring method for T_a is novel. It is a field method and consists of a small single well pumping test in a spade-dug pit of about 30x30 cm^2 in horizontal cross-section that can be done in a few minutes. Two methods were applied: a semi-steady state method and a recovery method in which the rise of the water table after pumping was used to calculate T_a. Both gave comparable results. Differences were mostly attributed to flexibility of the acrotelm material, which led to variations in apparent T_a during tests. Application of the equation of the piezometer method gave unsatisfactory results as a result of storage effects.

The piezometer method had to be modified to yield reproducible k-values of the catotelm. Flexibility of the peat matrix constituted a main problem in applying the method. It caused large differences between k derived from data obtained during the first and last stages of a test. Falling head, rising head and constant head tests all yielded different values. Eventually the falling head test with a small initial rise (20 cm) was selected. The data analysis was done on the last stage of the test when the peat matrix had recovered from disturbance caused at the start of the test. Although the piezometer method measures horizontal k, it was assumed that the measurements also represented vertical k, *i.e.* isotropy was assumed at the vertical scale of the filter screen length (20 cm). Eventually, this assumption appeared to be incorrect (*cf.* 10.4.2). No good reasons were found to assume non-Darcyan flow in catotelm peat during the tests.

Humification H was estimated using the Von Post method. Contrary to what is commonly found in peat literature, no statistically significant relationship of H and k was found. Theoretically, this might be partly related to sampling, because measurements of k and samplings for humification at each site were done at horizontal distances of a few metres and H was found to vary strongly over such small distances. However, this effect cannot have obscured the entire relationship. Also the likely smaller lateral variation of k indicates a poor relationship. A statistically strong relationship was found between k and ϕ_b. Although its predictive power for individual data pairs is small, the relationship was found useful to estimate catotelm transmissivity T_c and to a lesser extent the vertical resistance C_c of the catotelm. No direct relationship of the main peat strata (Fresh *Sphagnum* Peat, Strongly Humified *Sphagnum* Peat and Fen Peat) and k was found.

An effort was made to reconstruct pre-subsidence surface levels from a comparison of ϕ_b in "unsubsided" reference profiles and in subsided profiles.

Storage coefficients μ were measured together with evapotranspiration ET in lysimeters and by comparing one-hour rainfall sums with one-hour recordings of phreatic levels. Other quantities such as rainfall and phreatic levels were measured with usual methods.

Acrotelm depth D_a was defined as the depth to which the degree of humification did not exceed a value of 3 in Von Post's classification.

10.4. General points on raised bog hydrology

10.4.1. Bogs as groundwater mounds

The groundwater mound theory as published by Ingram (1982) is not applicable to Clara and Raheenmore bog and it is doubtful whether it is applicable to any bog in its original form.

The postulated elliptical cross-sectional shape of bogs is unproven, because the steepest part of the ellipse usually does not exist and an ellipse can often be fitted easily through the points in the less curved part of the dome, even though the shape is not elliptic but just convex.

The assumption of a spatially constant k was found not to be valid in both Clara Bog and Raheenmore Bog. Vertically k decreased by about two orders of magnitude between a depth of about 50 cm and the bottom of the catotelm and horizontally by a similar amount between centre and margin. The difference in the horizontal direction was not only caused by compaction caused by drainage at margins, but also by natural differences in volume fraction of solid matter ϕ_0 and in k between the central part and the bog margin. The latter indicates that the assumption of a spatially constant k is not valid in any raised bog. *Thus, in assessing catotelm flow from the shape of a bog, the concept of transmissivity T_c should replace k.*

As for Raheenmore Bog, a spatially constant infiltration of water from into the catotelm from the acrotelm should probably be rejected. The best fit of an ellipse was found in the most disturbed area where the catotelm transmissivity was about 1 $m^2 d^{-1}$ in the centre and 0.03 $m^2 d^{-1}$ at the bog margin. Although raised bogs are groundwater mounds by definition, *the results indicate that Ingram's steady-state hydrological explanation of their shape does not hold.* More dynamic processes such as fluctuations of phreatic levels, related soil mechanical processes and differences between ecological conditions in the centre and near the margin of a bog lead to differences in peat composition and thus to differences in k.

As for Clara Bog, its present shape differs so much from the "normal" convex shape that fitting a convex curve of whatever kind is impossible.

For both bogs, an average lateral discharge through the catotelm of 1 mm a^{-1} or less was inferred.

10.4.2. Vertical seepage

Vertical seepage v_e or exfiltration from the catotelm was inferred from C_c and differences between the hydraulic heads h at different depths. C_c as calculated from measured k and k estimated from ϕ_0 appeared to be far too small in the upper half of the catotelm. It often yielded extremely large v_e that could impossibly be explained from the water balance. When calculated for the deepest peat layers, v_e was extremely small.

The piezometer method as applied basically yields horizontal k. Apparently, horizontal k in the upper peat layers strongly exceeds vertical k. Hence these results are evidence of a strong anisotropy of k in the upper peat layers that decreases downwards. This decrease can be explained as an effect of the continuing process of decay in the catotelm. The layering of the peat is predominantly horizontal. This results in anisotropy with larger horizontal than vertical k. *As the process of decay continues, anisotropy decreases gradually. This explains the apparent decrease of v_e with depth.*

The estimated v_e of Clara Bog was between 5 and 10 mm a^{-1}. On Raheenmore Bog v_e was 10 to 15 mm a^{-1}. Both values are small compared to values from other bogs, but may probably be explained by the large peat depth.

The difference between the exfiltration of Clara Bog and Raheenmore Bog is caused by the mineral substratum. In Clara Bog, it consists of highly impervious glacio-lacustrine clay with a vertical *k* of approximately 25 mm a^{-1}. In Raheeenmore Bog the underlying clay is often more gritty. Although measurements of *k* in the underlying clay of Raheenmore bog are lacking, its much coarser granular composition indicates that its *k* must be at least an order of magnitude larger than in the clay underneath Clara Bog. The deepest peat of Raheenmore Bog has probably adjusted to the larger *k* of its mineral substratum. As the peat dome of Raheenmore Bog rose above its surroundings, the pore pressure of its lower strata became relatively low because of its hydraulic contact with the subjacent mineral aquifer. As a result, the deepest peat became compacted, thus creating a sealing layer at the bottom of the catotelm. In the centre of the bog, the hydraulic head in the underlying glacial till is 3 to 4 m below the bog's surface level. This is probably a self-sealing mechanism that may occur in any bog with a relatively permeable mineral substratum. In Clara Bog with its subjacent lacustro-glacial clay this phenomenon was not found, except near bog margins where the basin was too shallow for the clay to form. In neither bog, signs of an illuvial layer at the bottom of the catotelm were found.

10.4.3. Effects of external drainage on bog hydrology

In view of the self-sealing process outlined above, it is unlikely that a raised bog is affected by drainage in its near surroundings, unless a process of self-sealing at its bottom never occurred, for example if the differences between bog surface level and *h* in the mineral substratum never were substantial. A sudden and extremely large change of *h* in the mineral substratum may also affect the hydrological conditions in a bog that has developed a dense peat layer at its bottom. If a lowering of *h* in the substratum is caused by a change in the drainage of the surroundings of a bog, a sealing layer needs time to develop or to adjust itself to the new conditions. Initially it may cause an increased exfiltration that results in a measurable surface subsidence as a result of compaction of the deepest peat. In fact the subsidence is a sign that the process of self-sealing has begun.

If a raised bog is surrounded by a marginal drain, as for example Raheenmore Bog, the drainage may be expected to have a negligible direct effect on hydrological conditions in the bog itself.

10.4.4. Internal drainage and subsidence

Subsidence of bogs is caused by shrinkage of peat due to irreversible water loss from the peat matrix. If the water loss is caused by superficial drainage such as on Clara East, almost all the subsidence will occur in the upper metre of peat. If the water loss is caused by turf cutting along a bog margin, it can be proven that the direct effect on catotelm conditions is restricted to a few m from the margin, given the catotelm transmissivity values inferred from measurements of k and volume fraction of solid matter ϕ_b. However, the effect expands into the bog as a result of the increased surface slope which in turn causes an increased superficial drainage of the bog. *Thus a zone of increasing width becomes affected by the subsidence that started on the margin.* Because natural margin peat is more compact than peat in the centre of a bog, it may shrink less than peat in the more central part, where the original peat profile often is also deeper than near a margin. This may eventually cause parts of a bog to become concave instead of convex and watersheds to move towards the margin. This process has occurred at a large scale on Clara West. At a much smaller scale it can also be observed along the southern margin of Raheenmore Bog and on Clara East. Where margin peat has (almost) entirely been cut away, a bog remnant probably develops a new but lower convex cross-sectional shape.

Shallow drains on the bog cause a subsidence over the drained area of a few dm in less than 10 years. Long term effects are not clear, but the shape of Raheenmore Bog suggests that eventual subsidence may be larger.

10.4.5. Surface shape and acrotelm transmissivity

An acrotelm is a transmissivity-controlled aquifer, because its hydraulic gradient is determined by the shape of the catotelm and thus virtually constant in time. The average transmissivity T_a of the acrotelm adjusts itself to the surface level gradient I and discharge, *i.e.* the length of the upstream flow path. This mechanism is accomplished by the process of decay of freshly formed acrotelm material. The more this material is exposed to the atmosphere, the faster is the decay. If it remains submerged for most of the time, the process is slow. Fresh acrotelm material has a high k, which decreases as the material decays and loses its fibre strength. Thus the acrotelm adjusts itself to the average T_a that is required for the discharge of the average flux that comes from the upstream bog area, given the surface slope. Thus steep surface slopes and/or small upstream bog areas lead to small T_a and vice versa.

An immediate consequence of this process is the destruction of the acrotelm as a result of superficial drainage of a bog, such as the *Vorentwässerung*, applied on German bogs as the first stage of reclamation, or the similar drainage of Clara East.

Another consequence is the destruction of the acrotelm after an increase of the surface slope induced by turf cutting along a bog margin. The loss of regulation of the discharge by the acrotelm (*cf.* 10.4.7) may even speed up the process of subsidence. These effects can be observed in a broad zone along the margins of both Clara and Raheenmore Bog. A change in surface shape to concave as mentioned in the previous section may eventually cause opposite effects where the upstream flow path becomes long and the slope of the bog surface small. Examples are the deep acrotelm near Shanley's Lough, in the south-western part of Clara West (Fig. 6.24) and near the southern margin of Raheenmore Bog (Fig. 6.23).

10.4.6. Acrotelm properties and phreatic level fluctuations

Acrotelm transmissivity T_a is determined by a relationship with the phreatic level h. Whenever h increases as a result of precipitation, T_a increases sharply and so does the discharge from the bog. When h decreases again, the opposite process occurs until the outflow stops almost or entirely. The difference between h at top discharges and at the virtual cessation of discharge is up to a few dm. This is one of the two processes that prevents a bog from drying out and that limits the fluctuation of the phreatic level.

The second process is storage of water in the acrotelm. The storage coefficient μ in a healthy acrotelm was found to be approximately 0.4. Where pools and/or hollows occurred, μ could increase to 0.8 or even more at high phreatic levels. These high values prevent the phreatic level from fluctuating strongly. Consequently, seasonal fluctuations of more than 20 cm were hardly found in areas with a healthy acrotelm, both on Raheenmore and Clara Bog.

In areas with a poor acrotelm, the winter fluctuations of the phreatic level resembled those in places with a good acrotelm, but in the summer, when the phreatic level fluctuated in the decayed peat where μ is 0.20 or less, the fluctuations increased strongly (Fig. 8.2 and Fig. 8.3). Not only a positive correlation was found between depth of the phreatic level and its fluctuation, but also between surface slope and fluctuation. Apart from a direct effect of increased drainage, the effect of surface slope on acrotelm conditions is probably the underlying process of the latter relationship.

10.4.7. The acrotelm as a regulator of bog discharge

Acrotelm transmissivity T_a is controlled by the phreatic level h. The fibrous character of fresh acrotelm material or even the lower part of the living vegetation and the loss of strength during decay causes a rapid decrease of k with increasing depth. Thus a relationship of k, T_a and h exists. Consequently, h controls T_a, given the general acrotelm conditions as imposed by surface slope I and size of the upstream catchment A_u.

For specific discharges v_a up to about 1.5 mm d^{-1} an almost linear relationship was found with T_a. Above this rate, the relative increase of v_a exceeded the relative increase of T_a (Fig. 6.16).

The underlying mechanism is that above a certain h hollows and pools become interconnected and an increasing part of the water flows off as surface water. In areas with a poor acrotelm or on haplotelmic bog areas, sheet flow may occur under such conditions.

Point measurements of T_a in unflooded acrotelm parts then provide an inadequate estimate of the effective T_a at a scale of hectares.

10.4.8. The acrotelm as a self-regulating and self-healing system

Self-regulation of acrotelm properties is described in the above sections. T_a and to a lesser extent μ are the result of imposed conditions (climate, upstream catchment size and surface slope) and so is acrotelm depth D_a. Large D_a coincide with large T_a. However, no relationship was found for the deepest acrotelms of more than 20-25 cm deep. The relationship of μ with depth also depends on D_a. Thus a deep acrotelm is a more effective regulator of hydrological conditions than a shallow one.

It was found that in large parts of Clara Bog and Raheenmore Bog the acrotelm had been disturbed and the question was, whether these disturbances are permanent or temporary. T_a of an undisturbed acrotelm can be derived from v_a, I, flow pattern and upstream area. The system is self-perpetuating until it is disturbed. Examples are internal drainage, repeated burning and subsidence. If the acrotelm is disturbed, the groundwater level regime changes in that fluctuations become larger and the average level may become lower. Thus the conditions that determine the self-perpetuation of the acrotelm may not exist anymore and the question may be asked whether such a process is reversible. A final answer cannot be given, but both the simple model of acrotelm growth developed in 6.5 and field observations on Raheenmore Bog and Clara East suggest *that a healing process of the acrotelm may eventually develop if the hydrological change is not extremely large*. In the case of internal drainage, the drains have to fill in first. This is a process that may take 50-100 years under the climatic conditions of the Irish Midlands as can be inferred from developments on Clara West and Raheenmore Bog. Even though ingrown drains still transport water, they eventually become sufficiently ineffective to allow acrotelm growth as is demonstrated by acrotelm development in the area of ingrown drains on Raheenmore Bog. Blocking the discharge by damming is an adequate measure to speed up the process of acrotelm recovery if the dams are made at sufficiently small intervals of the surface level (about 10 cm).

Recovery from burning is a more rapid process, since the drainage conditions on the bog are much less affected. Nonetheless, the Raheenmore Bog experience shows that even this process may take 2-3 decades. *This shows that a full process of acrotelm recovery from damage inflicted by internal drainage may take more than a century to complete.*

10.4.9. Evapotranspiration

The lysimeter experiments demonstrated that the evapotranspiration rate *ET* of raised bogs under Midland conditions is considerably larger than calculated grassland evapotranspiration. It is also dependent on rainfall conditions in spring and summer. The most extreme variable is *Sphagnum ET*. This is caused by the specific mechanism of water transport to the surface in *Sphagnum* vegetations which is based on capillary rise rather than active transport through the plant. If *Sphagnum* capitula dry out and die, evapotranspiration is reduced considerably. This phenomenon is known from literature and was confirmed in the tests. The depth of the phreatic level at which this drying begins, depends on the *Sphagnum* species. In summers that are sufficiently wet to prevent capitula from drying out, the evapotranspiration of a *Sphagnum* surface and the bogs may exceed the Penman open water evaporation rate E_0. The inadequate part of the Penman equation is its aerodynamic term. Winter *ET* from the bogs was found to always exceed E_0.

10.5. Specific points on the hydrology of Clara Bog and Raheenmore Bog

10.5.1. Hydrological effects of the old drains on Raheenmore Bog

The drains on Raheenmore Bog, which are probably more than 100 years old, have caused subsidence in the north-eastern part of the bog. Their direct hydrological effect was found to have become very small and the drain blocks that were made in 1989 probably caused a further decrease of the remaining effect.

Because an acrotelm is already developing in the higher parts of the area and the flow path towards the drained area has probably become longer as a result of subsidence, the prospects of acrotelm recovery in the area seem to be good. The change in flow path probably caused the highest point of Raheenmore Bog to move westwards and may have reduced the flow towards the western margin. This may have led to the shallow acrotelms that were found there in 1991.

The surface levelling data of 1948 and 1990 show no signs that subsidence in the drained part between these years has been any larger than on other parts of Raheenmore Bog. The small subsidence found can be attributed to the natural process of decay that occurs in any catotelm and that was not compensated for by acrotelm growth. The small acrotelm growth outside the drained area can be explained as a result of damage inflicted by burning in years before the early 1970's.

10.5.2. Effects of external drainage on the hydrological conditions on the bogs

The marginal drain around Raheenmore Bog is often blamed for recent ecological changes on Raheenmore Bog, such as the disappearance of bog pools and hummock-hollow systems since the 1970's (e.g. Gill and Johnston, 1999). In view of the small exfiltration rate of 10-15 mm a^{-1} and its existence during 200 years (Gill and Johnston, 1999), such an effect is most unlikely, even though it was deepened in the 1980's. Generally speaking, the hydrology of a raised bog is highly independent of surrounding conditions. Temporary effects may occur as a result of large and sudden changes of the hydraulic head h in the near surroundings. Such changes are likely to induce shrinkage of the deepest peat (*cf.* 10.4.3), which eventually develops into a sealing layer of dense peat at the bottom of the catotelm as observed in Raheenmore Bog. A marginal drain around a bog is likely to cause a rather evenly divided subsidence with few consequences on surface slope and thus on acrotelm conditions. Local sudden and large lowerings of h, however, may cause local subsidence effects that do affect the surface slope I and acrotelm conditions.

10.5.3. The Clara-Rahan road

The construction of the Clara-Rahan with its associated drains across the centre Clara Bog around 1840 has had a dramatic effect on the hydrological conditions over the entire bog. It has caused the disappearance of the former dome shape of Clara Bog. The soak system of Shanley's Lough is the result of local subsidence that was a combined effect of the road and the till mound to the west of Shanley's Lough and rewetting caused by ingrowth of the drain system.

The present converging flow system of Clara West is the result of this subsidence process that caused the watersheds to move towards the margins where the peat did not subside as much because of the distance to the road and of its larger density, compared to peat in the centre of the bog.

The total subsidence of the bog surface along the road, including effects of peat losses by cutting and burning long the road is estimated at about 8 m. The surface in the centre of Clara West has subsided by at least 2 m, but 4 m is not an unlikely value. The rate of subsidence is still about 1.5 cm a^{-1}. Along the present north-western margin and along the Clara-Rahan road the rate of subsidence between 1982 and 1991 was about twice as large.

10.5.4. The drainage system on Clara East

The subsidence in Clara East between 1982 and 1991 has been larger than on Clara West. The difference is the effect of the drainage system that was installed in 1983. It is additional to the subsidence effect of the Clara-Rahan road. The average subsidence on Clara East between 1982 and 1991 has been about 4 cm a^{-1}. In view of the subsidence on Clara West, the effect of the drains may be estimated at 2-3 cm a^{-1}. It has at least contributed to a shift of 100-200 m of the watershed towards the northern margin. The provisional blocking of the drains in 1989 has stopped the subsidence in the flat central part, but in the more sloping areas it continued, albeit at a much lower rate of less than 1 cm a^{-1}.

The acrotelm of Clara East has deteriorated considerably as a result of the drains. Flow paths have been cut off and a well developed acrotelm is only found in a few isolated areas with local converging discharge and in Lough Roe, where a floating mat of bog vegetation has developed.

The blocking of the drains in 1989 may have prevented the acrotelm of the flatter central parts of the bog from further decay, but was inadequate to protect the more sloping parts. The blocking of 1995/96 has probably been more effective, but information on the effects is lacking.

10.5.5. The water balance of the two bogs

The water balances of both bogs from 18th September 1990 through 19th July 1993 as shown in Table 9.7 show that the precipitation P on Raheenmore Bog was about 15% larger than on Clara Bog. The evapotranspiration ET on Clara Bog was 2.5% larger than on Raheenmore Bog. The difference in P may be attributed to the difference in altitude of about 45 m. The discharges differ accordingly. The difference in ET might be attributed to the same cause, but it is so small that it could also have resulted from measuring errors. The largest loss term is evapotranspiration, but in Raheenmore Bog with relatively large precipitation sums, the discharge Q_a is not much smaller. *The average bog evapotranspiration ratio f_b was approximately 1, versus a crop factor f_g for grassland of 0.75.* Over three periods with an average length of 11.3 months, f_b varied from about 0.9 to 1.2, depending on rainfall conditions in spring and summer.

11. SAMENVATTING EN CONCLUSIES

11.1. Het project en de venen

Dit werk is het resultaat van het hydrologische deel van een veldproject in het kader van het Iers-Nederlandse project genaamd "Ecohydrology and Conservation of Bogs" dat duurde van september 1989 tot eind juli 1993. De doelstellingen waren het uitwisselen van ervaringen tussen Ierland en Nederland op het gebied van conservering en restauratie van hoogvenen en kennis van de ecosystemen van levende hoogvenen. Het veldproject was bedoeld om de kennis van hoogveen-ecosystemen te vergroten. Het werd uitgevoerd in twee hoogvenen in de Ierse Midlands, Raheenmore Bog en Clara Bog, beide in Co. Offaly.

De morfologie van het landschap waarin beide venen liggen, is in hoge mate bepaald door geologische processen die samenhangen met de landijsbedekking in het Weichselien (in Ierland Midlandian genoemd). De venen zijn gevormd in glaciale bekkens en vertonen beide een overgang van verschillende vormen van laagveen in hun diepere lagen naar hoogveen in hun bovenste deel. De hoogteligging is ongeveer 105 m (Raheenmore Bog) en 60 m (Clara Bog) boven de zeespiegel. De grootste veendiepten zijn ca. 14 m op Raheenmore Bog en ca. 10.50 m of Clara Bog. Het klimaat is koel en humide met betrekkelijk geringe seizoensschommelingen. De gemiddelde temperatuur bedraagt ca. 14.5 °C in juli, 4 °C in januari bij een jaargemiddelde van ca. 9.0 °C. De gemiddelde jaarlijkse neerslag ligt tussen 800 en 1000 mm, terwijl de gemiddelde jaarlijkse evapotranspiratie van grasland rond de 450 mm ligt.

11.2. Onderzoeksvragen

Het onderzoek had tot doel, te komen tot kwantitatieve uitspraken met betrekking tot hydrologische eigenschappen van en processen in hoogvenen, hun betrekkingen en interacties in zowel relatief gezonde als in aangetaste delen.

Dit houdt in het ontwikkelen van elementen van een conceptueel model van de hydrologie van hoogvenen. De zg. diplotelmische benadering, d.w.z. het concept van acrotelm/catotelm (zie Fig. 2.4 en Fig. 5.1) wordt in dit werk aangehouden.

Elementaire vragen ten aanzien van processen behelzen zowel algemene vraagstukken op het gebied van hoogveenhydrologie als specifieke zaken met betrekking tot de hydrologische systemen van Raheenmore Bog en Clara Bog.

<u>Algemene vraagstukken zijn</u>

- De mate waarin de horizontale dwarsdoorsnede van een hoogveen kan worden verklaard uit de horizontale stromingscomponent in de catotelm, d.w.z. de toepasbaarheid van de Groundwater Mound Theory, opgesteld door Ingram (1982).

- De wegzijging naar onderliggende lagen en de afhankelijkheid van grondwaterstanden in de omgeving
- De invloed van ontwatering in de nabije omgeving en de aard van het onderliggende minerale substraat op het hiervoor genoemde proces
- Het effect van ontwatering en zetting op de vorm van het veenoppervlak
- Gevolgen van de vorm van het veenoppervlak op omstandigheden in de acrotelm zoals blijkt uit dikte, doorlaatvermogen en de bergingscoefficiënt van de acrotelm.
- De invloed van de eigenschappen van acrotelm en catotelm op grondwaterstandsschommelingen
- De uitwerking van de acrotelm als een niet-lineaire aquifer op het afvoergedrag van een hoogveen
- De mate waarin de acrotelm als een produkt van de subtiele balans van produktie en afbraak van organische stof zelfregulerend is ten aanzien van bovengenoemde processen en zelfherstellend na verstoring
- Effecten van vegetatie en weersomstandigheden op de evapotranspiratie van hoogveen.

Specifieke vragen met betrekking tot de hydrologie van Raheenmore Bog en Clara Bog betreffen

- De invloed van een stelsel van oude greppels op Raheenmore Bog op de hydrologie van het veen
- De invloed van externe ontwatering, meestal in de vorm van watergangen direct rondom het veen, op het hydrologische systeem van het veen zelf
- De uitwerking van de weg van Clara naar Rahan, die Clara Bog in tweeën deelt, op het hydrologische systeem van Clara Bog
- De uitwerking van ondiepe ontwatering op het oostelijk deel van Clara Bog op eigenschappen van de acrotelm en zetting
- De waterbalans van Clara Bog en Raheenmore Bog.

11.3. Meetmethoden

Ter beantwoording van een deel van de onderzoeksvragen moesten meetmethoden worden ontwikkeld, c.q. worden aangepast om toepasbaar te zijn in veengronden. Daaronder viel een veldmethode voor het meten van het doorlaatvermogen T_a van de acrotelm en het modificeren van de piëzometermethode voor het meten van de verzadigde doorlatendheid k in de catotelm. Om k en het doorlaatvermogen T_c van de catotelm te kunnen schatten, moesten statistische verbanden tussen humificatie, bulk density (uitgedrukt als de volumefractie organische stof ϕ_o) en k worden vastgesteld.

De meetmethode voor T_a is voorzover bekend nieuw. Het is een veldmethode die bestaat uit een pompproef in een enkel "boorgat" dat bestaat uit een met de schop gemaakt gat met een horizontale doorsnede van ca. 30x30 cm^2. De bepaling kan in enkele minuten worden gedaan. Twee methoden werden toegepast: een semi-stationaire methode en één waarbij de snelheid van de stijging van de waterspiegel in het "boorgat" na afpompen werd gebruikt om T_a te berekenen. Beide methoden leverden vergelijkbare uitkomsten. Verschillen konden voornamelijk worden herleid tot effecten van de geringe stevigheid van het materiaal van de acrotelm die leidden tot verschillen in schijnbare T_a gedurende de meting.

De piëzometermethode moest worden aangepast om reproduceerbare k-waarden van de catotelm te verkrijgen. De geringe stevigheid van het veen leverde problemen bij de toepassing, omdat grote verschillen bleken te bestaan tussen k-waarden afgeleid van gegevens van het eerste, resp. het laatste stadium van de meting. Metingen met toevoeging en verwijderen van water of met een constante verhoging van de waterspiegel in de piëzometer gaven verschillende uitkomsten. Uiteindelijk werd besloten tot standaardisering op een methode met een vrij geringe initiële verhoging met ca. 20 cm van de waterspiegel in de piëzometer. De uitwerking was gebaseerd op de laatste fase van het herstel van de oorspronkelijke waterspiegel, waarbij de bodemmatrix zich weer (nagenoeg) had hersteld van de verstoring, teweeggebracht bij het begin van de meting. Hoewel in feite met de piëzometermethode horizontale k-waarden worden gemeten, is noodgedwongen uitgegaan van de aanname dat op de afstandsschaal van een filterlengte van 20 cm k isotroop zou zijn. Dit bleek uiteindelijk niet het geval (zie11.4.2). Er werden geen aanwijzingen gevonden, waaruit een niet voldoen van de stroming aan de wet van Darcy zou kunnen blijken.

De humificatiegraad H werd geschat aan de hand van de methode van Von Post (1922). In tegenstelling tot wat doorgaans in veenliteratuur wordt gemeld, werd geen statistisch betrouwbaar verband gevonden tussen H en k. In theorie zou dit kunnen worden toegeschreven aan de afstand tussen het punt voor k-meting en dat voor bemonstering t.b.v. de bepaling van H. De afstand tussen de punten was steeds enkele meters. H bleek over dergelijke korte afstanden al sterk te kunnen variëren. Dit effect kan echter moeilijk een statisch verband hebben versluierd. Ook de waarschijnlijk veel geringere laterale variabiliteit van k wijst eerder op de afwezigheid van een verband. Tussen k en ϕ_0 werd een statistisch betrouwbaar verband vastgesteld. Hoewel het voorspellend vermogen voor afzonderlijke gegevensparen niet groot is, bleek de betrekking nuttig te zijn bij het schatten van T_c en in mindere mate van de verticale weerstand C_c van de catotelm. Tussen k en de samenstelling van de belangrijkste veenlagen (Fresh *Sphagnum* Peat, Strongly Humified *Sphagnum* Peat and Fen Peat) werd geen rechtstreeks verband gevonden.

Getracht werd het veenoppervlak vóór zetting te reconstrueren door middel van een vergelijking met ϕ_0 in referentieprofielen, waarvan werd aangenomen dat geen zetting had plaatsgevonden.

Bergingscoëfficiënten μ werden bepaald in lysimeters, tegelijk met de evapotranspiratie *ET* en door middel van vergelijking van neerslagsommen van één uur en uurregistraties van de grondwaterstand. Voor het meten van andere grootheden zoals neerslag en grondwaterstanden werden gebruikelijke methoden toegepast.

De dikte van de acrotelm werd gedefinieerd als de diepte tot waar $H \leq 3$.

11.4. Algemene vraagstukken met betrekking tot de hydrologie van hoogvenen

11.4.1. Hoogvenen als grondwaterheuvels

De *Groundwater Mound Theory* zoals gepubliceerd door Ingram (1982) is niet toepasbaar op Clara en Raheenmore Bog en het valt te betwijfelen of de theorie in zijn oorspronkelijke vorm toepasbaar is op welk hoogveen ook.

Het postulaat van de elliptische dwarsdoorsnede van venen blijft onbewezen, omdat het steilste deel van de ellips meestal niet bestaat en punten in het minder gekromde deel van de doorsnede doorgaans gemakkelijk te vereffenen zijn op een ellips, ook als de vorm niet elliptisch doch alleen maar bol is.

De aanname van een ruimtelijk constante k bleek voor Clara Bog noch voor Raheenmore Bog op te gaan. Verticaal nam k met ongeveer twee orden van grootte af tussen een diepte van 50 cm en de onderkant van de catotelm. In horizontale richting werd een soortgelijke afname gevonden van het midden naar de rand van het veen. Het verschil tussen midden en rand was niet alleen toe te schrijven aan zetting op de rand als gevolg van ontwatering, maar ook door natuurlijke verschillen in ϕ_0 en k tussen midden en rand. Dit laatste betekent dat de aanname van een ruimtelijk constante k voor welk veen dan ook onjuist is. *Daarom moet bij het bepalen van horizontale stroming in de catotelm worden uitgegaan van het doorlaatvermogen T_c en niet van k.*

Voor wat betreft Raheenmore Bog moet de veronderstelling van een ruimtelijk constante infiltratie van water vanuit de acrotelm in de catotelm waarschijnlijk worden verworpen. De beste vereffening op een ellips werd gevonden in het meest verstoorde deel van het veen, waar T_c in het midden een waarde had van ca. 1 m^2d^{-1} en aan de rand één van 0.03 m^2d^{-1}. Hoewel hoogvenen per definitie grondwaterheuvels zijn, *geven de uitkomsten aan dat Ingram's stationaire hydrologische benadering niet klopt.* Dynamischer processen als grondwaterstandsschommelingen, daarmee samenhangende grondmechanische processen en verschillen tussen ecologische omstandigheden in het midden en langs de veenrand leiden tot verschillen in veensamenstelling en daarmee tot verschillen in k.

Op Clara Bog verschilt de dwarsdoorsnede zo sterk van de "normale" bolle doorsnede, dat vereffenen op wat voor bolle curve ook onmogelijk is.

Voor beide venen werd een gemiddelde zijdelingse afstroming via de catotelm van hoogstens 1 mm a^{-1} *afgeleid.*

11.4.2. Wegzijging

Wegzijging v_e naar de minerale ondergrond werd afgeleid uit C_c en verschillen in stijghoogte op verschillende diepten. C_c, berekend uit gemeten k en met op basis van ϕ_b geschatte k, bleek in de bovenste helft van de catotelm veel te klein. Daaruit werden vaak extreem grote waarden van v_e afgeleid die onmogelijk uit de waterbalans te verklaren waren. Indien berekend voor de diepste veenlagen, bleek v_e daarentegen buitengewoon klein.

Met de piezometermethode wordt in beginsel k in horizontale richting bepaald. Blijkbaar is in de bovenste veenlagen de horizontale k veel groter dan de verticale. Daarom zijn deze uitkomsten een bewijs voor een sterke anisotropie van k in de bovenste veenlagen die naar beneden toe afneemt. De verklaring voor deze afname is het proces van langzame afbraak in de catotelm. De gelaagdheid van veen is overwegend horizontaal. Dat leidt tot anisotropie met grotere horizontale dan verticale k. *Bij het voortschrijden van het afbraakproces neemt de anisotropie geleidelijk af. Dit verklaart de schijnbare afname van* v_e *met de diepte.*

De geschatte wegzijging v_e *voor Clara Bog was 5 tot 10 mm* a^{-1}. *Voor Raheenmore Bog bedroeg deze 10-15 mm* a^{-1}. Beide waarden zijn gering in vergelijking met waarden, bepaald voor andere venen. Dit verschil is waarschijnlijk grotendeels te verklaren uit de relatief grote veendikte.

Het verschil in wegzijging tussen Clara Bog en Raheenmore Bog is te verklaren uit het verschil in minerale ondergrond. Onder Clara Bog ligt een zeer slecht doorlatende lacustroglaciale kleilaag met een verticale k van ongeveer 25 mm a^{-1}. De klei onder Raheenmore Bog bevat vaak grover materiaal. Hoewel doorlatendheidsmetingen ontbreken, mag op grond van het verschil in korrelgrootte worden aangenomen dat de doorlatendheid ervan zeker een orde van grootte hoger ligt dan die van de klei onder Clara Bog.

Het diepste veen in de catotelm van Raheenmore Bog heeft zich waarschijnlijk aangepast aan de hogere k van de minerale ondergrond. Toen de grondwaterspiegel in het veen boven die in de omgeving uitgroeide, werd geleidelijk de poriëndruk in het onderste veen relatief laag ten opzichte van die in het bovenste veen als gevolg van het hydraulisch contact met de relatief doorlatende minerale ondergrond. Daardoor werd het onderste veen samengedrukt en ontstond een afsluitende laag aan de onderkant van de catotelm. In het midden van Raheenmore Bog ligt de stijghoogte in het onderliggende minerale materiaal 3-4 m onder het niveau van het veenoppervlak. Dit is vermoedelijk een zelf-afsluitend mechanisme dat kan voorkomen in elk veen met een relatief doorlatende ondergrond. In Clara Bog met zijn onderliggende lacustroglaciale klei werd dit verschijnsel niet aangetroffen, behalve langs de randen waar het bekken zo ondiep is dat geen klei is afgezet. In geen van beide venen werden tekenen van een inspoelingslaag aan de basis van het veen aangetroffen.

11.4.3. Uitwerking van externe ontwatering op de hydrologie van hoogvenen

Gezien het proces van zelf-afsluiting als hierboven aangegeven, is het onwaarschijnlijk dat de waterhuishouding van een hoogveen in belangrijke mate wordt beïnvloed door ontwatering in zijn naaste omgeving, tenzij het proces van zelf-afsluiting nooit is opgetreden, bijvoorbeeld als het verschil tussen de hoogte van het veenoppervlak en de stijghoogte h in de minerale ondergrond altijd gering is geweest. Een plotselinge en zeer grote verandering van h in de minerale ondergrond kan ook van invloed zijn op de hydrologische omstandigheden in een veen met een verdichte laag aan zijn basis. Als een verlaging van h in de ondergrond wordt veroorzaakt door een verandering in de ontwatering van de omgeving, heeft een afsluitende laag tijd nodig om zich te ontwikkelen of zich aan te passen aan de nieuwe omstandigheden. Aanvankelijk kan een vergrote wegzijging ontstaan die een meetbare zetting tot gevolg heeft als gevolg van samendrukking van het diepste veen. In feite is dit een teken dat het proces van zelf-afsluiting is begonnen.

Als een veen is omringd door een randsloot, zoals bijvoorbeeld Raheenmore Bog, dan zal dit type ontwatering naar verwachting geen grote invloed hebben op de hydrologische omstandigheden op het veen zelf.

11.4.4. Interne ontwatering en zetting.

Zetting van venen wordt veroorzaakt door krimpen van het veen door een grotendeels irreversibel verlies van water uit de veenmatrix. Als het verlies wordt veroorzaakt door oppervlakkige ontwatering, zoals op Clara Oost, dan zal nagenoeg alle zetting plaatsvinden in de bovenste meter van het veen. Van waterverlies veroorzaakt door turfsteken langs de veenrand, kan worden bewezen dat de onmiddellijke invloed op de omstandigheden in de catotelm beperkt is tot enkele meters vanaf de rand. Het bewijs is gebaseerd op de doorlaatvermogens van de catotelm, berekend uit metingen van k en ϕ_b. De zetting breidt zich vervolgens uit in het veen als gevolg van de toegenomen maaiveldshelling. Deze bewerkstelligt een intensivering van de oppervlakkige ontwatering van het veen. *Zo raakt een steeds bredere zone beïnvloed door de zetting die zijn oorsprong op de veenrand heeft.* Omdat veen dat aan de rand is ontstaan van nature compacter is dan veen uit het midden, zal het bij gelijke ontwatering minder krimpen dan veen uit het midden. In het midden is ook het totale veenprofiel vaak het diepst. Dit kan er uiteindelijk toe leiden dat een veen een holle in plaats van een bolle dwarsdoorsnede krijgt, waarbij waterscheidingen zich in de richting van de rand verplaatsen. Dit proces heeft zich op grote schaal voorgedaan op Clara West. Op een veel kleinere schaal kan het ook worden waargenomen op Raheenmore Bog en Clara Oost. Waar randveen nagenoeg geheel is verdwenen, zal een hoogveenrestant op termijn vermoedelijk een nieuwe maar lagere bolle dwarsdoorsnede aannemen.

Ontwateringsgreppels op het veen veroorzaken zetting in het gehele ontwaterde gebied van enkele decimeters in minder dan 10 jaar. De effecten op lange termijn zijn onzeker, maar de oost-west doorsnede van Raheenmore Bog geeft aan dat de uiteindelijke zetting vermoedelijk aanzienlijk groter is.

11.4.5. De vorm van het veenoppervlak en het doorlaatvermogen van de acrotelm

Een acrotelm is een watervoerende laag waarin het doorlaatvermogen de variabele is die de waterstroming bepaalt, omdat de stijghoogtegradiënt door de maaiveldshelling wordt bepaald en dus nagenoeg constant in de tijd is. Het gemiddelde doorlaatvermogen T_a van de acrotelm past zich aan aan de maaiveldshelling I en de afvoer, d.w.z. de stroomopwaartse afstand tot de waterscheiding langs een baan die samenvalt met de stroming. Dit mechanisme is gebaseerd op de snelheid van het afbraakproces van nieuw gevormd acrotelmmateriaal. Hoe meer dit materiaal aan de atmosfeer wordt blootgesteld, des te sneller is de afbraak. Als het materiaal meestentijds onder water ligt, is het afbraakproces langzaam. Jong acrotelmmateriaal heeft een hoge k, die afneemt naarmate het materiaal wordt afgebroken en de vezelstructuur zijn stevigheid verliest. Op die manier past een acrotelm zich aan de gemiddelde T_a aan, die bij de gegeven maaiveldshelling nodig is voor de afvoer van de gemiddelde flux, afkomstig is uit het bovenstroomse gebied.

Een direct gevolg van dit proces is de vernietiging van de acrotelm na oppervlakkige ontwatering van een veen, zoals de *Vorentwässerung* die op Duitse hoogvenen werd toegepast als eerste stadium van ontginning of de soortgelijke ontwatering van Clara Oost.

Een ander gevolg is het verdwijnen van de acrotelm na een toename van de maaiveldshelling als gevolg van het steken van turf langs de veenrand. Het verlies van het vermogen tot reguleren van de afvoer via de acrotelm kan het zettingsproces versnellen. Dergelijke effecten zijn waar te nemen in een brede zone langs de randen van zowel Clara Bog als Raheenmore Bog. Een omslag van een bol naar een hol veenoppervlak zoals hierboven genoemd, kan uiteindelijk een tegenovergestelde uitwerking hebben als de bovenstroomse stromingsroute lang wordt en de helling van het veenoppervlak gering. Voorbeelden zijn de diepe acrotelm in de omgeving van

Shanley's Lough, in het zuidwestelijk deel van Clara West (Fig. 6.24) en het zuiden van Raheenmore Bog (Fig. 6.23).

11.4.6. Acrotelmeigenschappen en grondwaterstandsschommelingen

Het doorlaatvermogen T_a van de acrotelm wordt bepaald door een relatie met de grondwaterstand *h*. Als de grondwaterspiegel stijgt als gevolg van neerslag, neemt T_a sterk toe en daarmee ook de afvoer. Als de grondwaterspiegel vervolgens daalt, treedt het omgekeerde proces op, tot de afvoer nagenoeg of zelfs geheel ophoudt. Het verschil in *h* bij topafvoer en het stoppen van de afvoer bedraagt hooguit enkele decimeters. Dit is één van de twee processen die de schommeling van de grondwaterstand beperken en zo een hoogveen behoeden voor uitdrogen.

Het tweede proces is de berging van water in de acrotelm. Voor een goed ontwikkelde acrotelm werd een bergingscoëfficient μ van ongeveer 0.4 gevonden. Waar slenken voorkomen, kan μ bij hoge grondwaterstanden oplopen naar 0.8 of nog hoger. Deze hoge waarden voorkomen sterke schommelingen van de grondwaterstand. Daardoor kwamen grotere seizoensschommelingen dan 20 cm niet voor in gebieden op Raheenmore Bog of Clara Bog met een goed functionerende acrotelm.

In gedeelten met een slecht werkende acrotelm vertoonde de schommeling van *h* in de winter weinig verschil met die in gebieden met een goed functionerende acrotelm. In de zomer daarentegen, als de grondwaterspiegel zich bevond in veen met een μ van 0.20 of minder, namen de schommelingen sterk toe (Fig. 8.2 en Fig. 8.3). Er werd een positieve correlatie gevonden voor zowel diepte en fluctuatie van *h* als maaiveldshelling *I* en fluctuatie van *h*. Afgezien van een directe invloed van versterkte ontwatering is waarschijnlijk ook de invloed van de helling op de kwaliteit van de acrotelm een proces dat laatstgenoemde relatie beïnvloedt.

11.4.7. De acrotelm als regulator van de afvoer van hoogvenen

Het doorlaatvermogen T_a van de acrotelm wordt bepaald door de grondwaterstand *h*. Het vezelgehalte van jong acrotelmmateriaal en het onderste deel van de vegetatie alsmede het verlies aan sterkte bij afbraak veroorzaakt een snelle afname van de doorlatendheid *k* met de diepte. Daardoor bestaat een verband tussen *k*, T_a en *h* en wordt T_a bepaald door *h* bij acrotelm-omstandigheden, bepaald door de helling *I* van het oppervlak en de grootte A_u van het bovenstroomse vanggebied. Voor specifieke afvoeren v_a tot ongeveer 1.5 mm d^{-1} werd een vrijwel lineair verband gevonden met T_a. Daarboven was de relatieve toename van v_a groter dan die van T_a (Fig. 6.16).

Het achterliggende mechanisme is dat bij een grondwaterstand h boven een zeker niveau de slenken verbinding met elkaar krijgen en een toenemend deel van de afvoer via het oppervlaktewater verloopt. In delen met een slecht ontwikkelde of ontbrekende acrotelm kan afstroming direct over het veenoppervlak optreden. Puntmetingen van T_a

in niet overstroomde gedeelten geven dan op een schaal van hectares een te lage schatting van de effectieve T_a.

11.4.8. De acrotelm als zelfregulerend en zelfherstellend systeem

In het voorgaande is zelfregulering van acrotelmeigenschappen aan de orde geweest. T_a en in mindere mate μ worden bepaald door omstandigheden (klimaat, bovenstrooms vanggebied en maaiveldshelling). Dat geldt ook voor de acrotelmdikte D_a. Hoge waarden van D_a plegen samen te vallen met hoge T_a. Er kon echter geen relatie met T_a worden vastgesteld voor D_a boven 20-25 cm. Het verband tussen μ en diepte hangt ook af van D_a. Daardoor is een dikke acrotelm een doeltreffender regelsysteem van hydrologische omstandigheden dan een dunne.

Omdat in grote delen van zowel Raheenmore Bog als Clara Bog een verstoorde acrotelm voorkwam, deed zich de vraag voor of die verstoringen blijvend of tijdelijk waren. Bij een ongestoorde acrotelm hangt T_a af van v_a, I, stromingspatroon en grootte van het bovenstroomse gebied. Het systeem houdt zichzelf in stand tot er een verstoring optreedt. Voorbeelden zijn interne ontwatering, herhaald afbranden en zetting. Als de acrotelm wordt verstoord, leidt dat tot een verandering van het grondwaterstandsregime in de zin dat de fluctuatie toeneemt en dat het gemiddelde niveau daalt. Daarmee kunnen de omstandigheden die het op eigen kracht voortbestaan van de acrotelm mogelijk maken, worden tenietgedaan. Dat leidt tot de vraag, of dit proces omkeerbaar is. Een definitief antwoord daarop kan niet worden gegeven. Het eenvoudige model voor acrotelmgroei, ontwikkeld in hoofdstuk 6.5 en veldwaarnemingen op Clara Oost en Raheenmore Bog doen vermoeden dat *een herstelproces van de acrotelm zich uiteindelijk kan ontwikkelen als de hydrologische veranderingen niet te extreem zijn.* Bij interne drainage zal eerst een verlandingsproces in de greppels moeten optreden. Dit proces kan in de klimaatsomstandigheden van Midden-Ierland zo'n 50-100 jaar in beslag nemen, zoals valt af te leiden uit ontwikkelingen op Raheenmore Bog en Clara West. Hoewel verlande greppels nog steeds water afvoeren, worden ze uiteindelijk zo weinig werkzaam dat acrotelmgroei kan optreden. Dit is aangetoond door de acrotelmgroei in het gebied van de verlande greppels op Raheenmore Bog. Het blokkeren van de afvoer met dammen is een doelmatige maatregel om het proces van herstel van de acrotelm te versnellen, indien de dammen zodanig worden gelegd dat het verval in maaiveldshoogte tussen opeenvolgende dammen klein genoeg (ca. 10 cm) is.

Herstel van de gevolgen van brand is een sneller proces, omdat het afvoerproces van water minder wordt beïnvloed. Niettemin toont de ervaring op Raheenmore Bog aan, dat ook dit proces 2-3 decennia kan duren. *Dit alles geeft aan dat een volledig herstel van ontwateringsschade meer dan een eeuw kan duren.*

11.4.9. Evapotranspiratie

De uitkomsten van de lysimeterproeven gaven aan dat de evapotranspiratie *ET* van hoogvenen onder omstandigheden van Midden-Ierland aanzienlijk hoger ligt dan de berekende potentiële graslandverdamping. *ET* hangt ook af van de neerslag(verdeling) in voorjaar en zomer. De belangrijkste variabele is de *ET* van *Sphagnum*. De oorzaak hiervan is het bijzondere mechanisme van watertransport naar het oppervlak van *Sphagnum*vegetaties, dat is gebaseerd op capillaire opstijging in plaats van actief transport door de plant. Als de capitula van *Sphagnum* uitdrogen en afsterven, wordt de evapotranspiratie aanmerkelijk geringer. Dit verschijnsel was bekend uit de literatuur en werd bij de proeven bevestigd. De grondwaterstand waarbij dit uitdrogen begint, verschilt per *Sphagnum*soort. In zomers die nat genoeg zijn om uitdroging van capitula te voorkomen, kan *ET* van een *Sphagnum*oppervlak en van de venen hoger liggen dan de Penman open water verdamping E_0. Het zwakke punt van de Penman-vergelijking is de aerodynamische term. *ET* van de venen lag in de winter altijd hoger dan E_0.

11.5. Specifieke punten met betrekking tot de hydrologie van Clara Bog en Raheenmore Bog.

11.5.1. Hydrologische effecten van de greppels op Raheenmore Bog

De greppels op Raheenmore Bog zijn vermoedelijk minstens 100 jaar oud. Ze hebben geleid tot zetting in het noordoostelijke deel van het veen. Vastgesteld werd dat hun directe invloed op het hydrologische systeem zeer gering is geworden. De in 1989 aangebrachte dammen hebben waarschijnlijk geleid tot een verdere vermindering van hun invloed.

Omdat in de hogere delen van het begreppelde deel zich een acrotelm aan het ontwikkelen is en de afstand tussen waterscheiding en het begreppelde deel door zetting vermoedelijk langer is geworden, lijken de vooruitzichten voor acrotelmontwikkeling in het gebied goed. De verplaatsing van de waterscheiding heeft waarschijnlijk wel geleid tot een verminderde toestroming naar het westelijk deel van het veen. Dit kan (mede) de oorzaak zijn van de ondiepe acrotelm die daar in 1991 werd aangetroffen.

Een vergelijking van waterpassingen van het veenoppervlak gedaan in 1948 en 1990 leidt tot de slotsom dat de zetting in die periode in het begreppelde deel niet groter was dan elders op Raheenmore Bog. De geringe zetting die uit de gegevens bleek, kan worden toegeschreven aan het natuurlijke proces van afbraak dat in elke catotelm optreedt en niet wordt gecompenseerd door acrotelmgroei. De geringe acrotelmgroei buiten het begreppelde deel kan worden verklaard uit schade als gevolg van afbranden vóór de jaren 1970.

11.5.2. De invloed van externe ontwatering op de hydrologische omstandigheden in de venen

De randsloot om Raheenmore Bog wordt dikwijls gezien als de oorzaak van de recente veranderingen in het ecosysteem van Raheenmore Bog, zoals het verdwijnen van veenpoelen en bult-slenksystemen sinds de jaren 1970 (bv. Bellamy, 1986 en Gill en Johnston, 1999). Gelet op de geringe wegzijging van 10-15 mm a^{-1} en het bestaan van de randsloot gedurende ca. 200 jaar (Gill en Johnston, 1999) is een dergelijk effect onwaarschijnlijk, ook al werd de sloot verdiept in de jaren 1980. In het algemeen is de waterhuishouding van een hoogveen weinig afhankelijk van de hydrologische omstandigheden in zijn naaste omgeving. Tijdelijke effecten van grote en plotselinge veranderingen in de stijghoogte h in de nabije omgeving op het veen zijn denkbaar. Dergelijke veranderingen kunnen zetting veroorzaken in de diepste lagen van het veen (zie 11.4.3), waardoor uiteindelijk een afsluitende laag van verdicht veen aan de onderkant van de catotelm ontstaat, zoals daadwerkelijk waargenomen op Raheenmore Bog. Een randsloot rondom een veen zal eerder een vrij gelijkmatige zetting veroorzaken, waardoor de maaiveldshelling niet zoveel zal veranderen en dus ook niet de omstandigheden in de acrotelm.

Plaatselijke, plotselinge en grote veranderingen van h kunnen eventueel plaatselijk zetting veroorzaken waardoor de maaiveldshelling I en de omstandigheden in de acrotelm wel worden beïnvloed.

11.5.3. De weg van Clara naar Rahan

De aanleg van de weg van Clara naar Rahan rond 1840 met daarmee samenhangende ontwateringssloten dwars over het midden van Clara Bog heeft een dramatische uitwerking gehad op de hydrologische omstandigheden van het hele veen. Dit heeft geleid tot het verdwijnen van de bolle vorm van Clara Bog. Het zeer natte gebied rond Shanley's Lough is het gevolg van lokale zetting die weer een gevolg was van zowel de weg, het bestaan van een opduiking van de grondmoraine ten westen van Shanley's Lough als de verlanding van het slotenstelsel.

Het huidige convergerende stromingsstelsel van Clara West is het gevolg van dit zettingsproces, waardoor de waterscheidingen zich verplaatsten naar de rand van het veen waar de zetting minder was. Dit was een gevolg van zowel de grotere afstand tot de weg als de grotere natuurlijke dichtheid van het veenmateriaal.

De totale zetting in het veen langs de weg, met inbegrip van verliezen door turfwinning en afbranden wordt geschat op circa 8 m. Het veenoppervlak in het midden van Clara West is tenminste 2 en mogelijk 4 m gezakt. De zaksnelheid is nog steeds ongeveer 1.5 cm a^{-1}. Langs de tegenwoordige noordwestelijke rand van Clara Bog en langs de weg was de zaksnelheid tussen 1982 en 1991 ongeveer twee keer zo groot.

11.5.4. Het ontwateringsstelsel van Clara Oost.

De zetting op Clara Oost is tussen 1982 en 1991 groter geweest dan op Clara West. Het verschil is terug te voeren op het in 1983 aangelegde ontwateringsstelsel en komt bovenop de door de weg veroorzaakte zetting. De gemiddelde zetting van Clara Oost in de genoemde periode lag rond 4 cm a^{-1}. Gezien de zetting op Clara West mag de door de ontwatering veroorzaakte extra zetting worden geschat op gemiddeld 2 à 3 cm a^{-1}. Deze extra zetting heeft op zijn minst bijgedragen aan de verplaatsing van de waterscheiding met 100-200 m in de richting van de noordelijke veenrand. De voorlopige afdamming van 1989 heeft de zetting in het vlakke middendeel een halt toegeroepen, maar in de meer hellende delen ging de zetting door, zij het in een veel lager tempo: minder dan 1 cm a^{-1}.

De acrotelm van Clara Oost is door de ontwatering sterk achteruitgegaan. Stromingsroutes zijn afgesneden, zodat een goed ontwikkelde acrotelm nog slechts wordt aangetroffen op geïsoleerde plekken met lokale convergerende stroming en in Lough Roe, waarin zich een kragge met typische hoogveenvegetatie heeft ontwikkeld.

De dammen van 1989 hebben vermoedelijk een verder verval van de acrotelm in het middendeel van Clara Oost voorkomen, maar waren onvoldoende om de hellende delen te beschermen. De afdamming van 1995/96 is waarschijnlijk effectiever geweest, maar goede informatie ontbreekt.

11.5.5. De waterbalans van beide venen

De waterbalansen van beide hoogvenen over de periode 18 september 1990 tot en met 19 juli 1993 zoals weergegeven in Tabel 9.7 geven aan dat de gemiddelde neerslag P op Raheenmore Bog ongeveer 15% hoger lag dan die op Clara Bog. Dit verschil is waarschijnlijk te verklaren door het verschil in hoogteligging van omstreeks 45 m. De evapotranspiratie ET van Clara Bog was ongeveer 2.5% hoger dan die van Raheenmore Bog. Dit verschil is wellicht op dezelfde grond te verklaren, maar zou ook kunnen worden teruggevoerd op onnauwkeurigheid van de metingen. De afvoeren Q_a van beide venen verschillen ongeveer overeenkomstig het verschil in neerslaghoeveelheid. De grootste verliesterm in de waterbalans is ET, maar op Raheenmore Bog met zijn hogere neerslag ligt Q_a maar weinig lager. De gemiddelde verdampingsverhouding $f_b = \frac{ET_{bog}}{E_o}$ voor de venen lag op ongeveer 1, tegen een gewasfactor voor grasland f_g=0.75. Over drie perioden met een gemiddelde lengte van 11.3 maanden varieerde f_b, afhankelijk van de neerslag in voorjaar en zomer, van ongeveer 0.9 tot 1.2.

REFERENCES

Aldén, L. and S. Forsberg, 1987. Waterbinding and dewatering of peat. *Proc. Symp. '87 Wetlands/Peatlands, Edmonton, 1987,* pp. 39-44, Ottawa.

Amoozegar, A. and A.W. Warrick, 1986. Hydraulic conductivity of Saturated Soils: Field Methods. In: Klute, A., Editor. Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods. 2nd Ed., pp. 735-798. *Series Agronomy* 9(1). *Am. Soc. Agron., Soil Sci. Soc. Am.* Madison, Wis.

Aue, B., 1991. Über die moorhydrologische Schutzfunktion des sekundären Randgehänges im Dosenmoor bei Neumünster (Schleswig-Holstein). *Telma* 21:157-174.

Aue, B., 1992. Hydrologische Untersuchungen an vernässten Hochmoorstandorten im Dosenmoor bei Neumünster. 201 pp. *Schriftenreihe Inst. für Wasserwirtschaft und Landschaftsökologie der Christian-Albrechts-Universität Kiel.* Heft 17.

Averdieck, F.-R. and S. Schneider, 1977. Anthropogen beeinflußte Moorprofile. *Telma* 7:15-26.

Baden, W. and R. Eggelsmann, 1963a. Zur Durchlässigkeit der Moorböden. *Zeitschr. für Kulturtechnik u. Flurbereinigung* 4(4):226-254.

Baden, W. and R. Eggelsmann, 1963b. Wechselwirkung zwischen Oberflächen- und Grundwasser im Moor. *Symp. Surface Waters Berkeley 19-8 - 31-8 1963. IASH Publ.* 63:469-478.

Baden, W. and R. Eggelsmann, 1964. Der Wasserkreislauf eines nordwestdeutschen Hochmoores. Eine hydrologische Studie über den Einfluß von Entwässerung und Kultivierung auf den Wasserhaushalt des Königsmoores b. Tostedt/Han. *Schriftenreihe des Kuratoriums für Kulturbauwesen,* Heft 12. 156 pp. *Verlag Wasser und Boden,* Hamburg.

Bakker, T.W.M., 1992. The shape of bogs from a hydrological point of view. *Int. Peat J.* 4:47-54.

Balyasova Ye. L., 1974. Variations in the level regime of highmoor bogs in the European USSR. *Soviet Hydrology: Selected Papers* 13(5):281-285. (English translation of an article in *"Transactions of the State Hydrologic Institute" (Trudy GGI)*, 22:3-20, 1974).

Balyasova, Ye.L. (1979); Methods for estimating the reliability of experimentally determined major hydrologic characteristics of bogs. *Soviet Hydrology: selected papers* 18(2):117-123. (English translation of an article in "Transactions of the State Hydrologic Institute" (Trudy GGI), 261:96-101,1979).

Barber, K.E., 1981. Peat Stratigraphy and Climatic Change. *Balkema*, Rotterdam.

Barry, T.A., 1954. Some considerations affecting the classification of the bogs of Ireland and their peats. *Int. Peat Symp., Dublin, 1954*, Section B.2.:1-19.

Barry, T.A., M.L. Carey and R.F. Hammond, 1973. A survey of cutover peats and underlying mineral soils. Bord na Móna, Cnoc Dioluin Group. *Soil Survey Bull.* 30. *Bord na Móna/An Foras Talúntais*, Dublin.

Bay, R.R., 1969. Runoff from small peatland watersheds. *J. Hydrol.* 9:90-102.

Bell, J., 1991. A study of the environmental effects of a bog road, Clara, Co. Offaly, Ireland. M.Sc. thesis, *Dept. of Civil Engineering, Imperial College*, London.

Bellamy, D., 1986. The Wild Boglands. Bellamy's Ireland. 178 pp. *Facts on File Publications.*

Bennett, J.R. and P.M. Johnston, 1996. Monitoring the hydrogeological and geotechnical performance of peat dams at Raheenmore Bog, Co. Offaly. Final Report I. Presentation of Fieldwork Information for the Monitoring Period April 1995, to April 1996. *Irish-Dutch Raised Bog Study. Geohydrology and Ecology. Univ. of Dublin, Dept. of Civil, Structural & Environmental Engineering.*

Bloetjes, O.A.J. and J.J.M. van der Meer, 1992. A Preliminary Stratigraphical description of peat development on Clara Bog. 27 pp +appendices. *Irish-Dutch Peatland Study. Fysisch Geografisch en Bodemkundig Laboratorium, Universiteit van Amsterdam.*

Boelter, D.H., 1964. Water storage characteristics of several peats in situ. *Soil Sci. Soc. Amer. Proc.* 28:433-435.

Boelter, D.H., 1965. Hydraulic conductivity of peats. *Soil Science* 100(4):227-231.

Boelter, D.H. , 1969. Physical Properties of Peats as Related to Degree of Decomposition. *Soil Sci. Soc. Am. Proc.* 33:606-609.

Boiten, W., 1985. De Rossum-stuw. *Polytechnisch Tijdschrift/Civiele Techniek* 40(2):1-8.

Borger, G.J., 1990. Peatland exploitation in the Low Countries. In: M.G.C. Schouten and M.J. Nooren (Eds.). Peatlands, Economy and Conservation, pp. 15-21. *SPB Academic Publishing*, The Hague, Netherlands.

Bouwer, H. and R.C. Rice, 1983. The Pit Bailing Method for Hydraulic Conductivity Measurement of Isotropic or Anisotropic Soil. *Trans. ASAE*-1983:1435-1439.

Bragg, O.M., P.D. Hulme, H.A.P. Ingram and R.A. Robertson. Peatland Ecosystems and Man: An Impact Assessment. 406 pp. *Dept. of Biol. Sci.Univ. of Dundee / Int. Peat Soc.*, Jyväskylä, Finland.

Bragg. O.M., 1995. Towards an Ecohydrological basis for Raised Mire Restoration. In: Wheeler, B.D., S.C. Shaw, W.J. Fojt and R.A. Robertson (Eds.). Restoration of temperate wetlands: 305-314. *Wiley.*

Burington, R.S. (1973). Handbook of Mathematical Tables and Formulas. 5th Ed. 500 pp. *McGraw-Hill.*

Burt, T.P., A.L. Heathwaite and J.C. Labadz (1990). Runoff production in peat covered catchments. In: Anderson, M.G. and T.P. Burt (Eds). Process Studies in Hillslope Hydrology. *Wiley & Sons.*

Casparie, W.A., 1969. Bult- und Schlenkenbildung in Hochmoortorf. (Zur Frage des Moorwachstums-Mechanismus). *Vegetatio* 19:146-180.

Casparie, W.A., 1972. Bog development in South-eastern Drenthe (The Netherlands). Thesis, Univ. Groningen. *Uitgeverij Dr. W. Junk*, The Hague.

Chason, D.B. and D.I. Siegel, 1986. Hydraulic conductivity and related physical properties of peat, Lost River Peatland, Northern Minnesota. *Soil Science* 142(2):91-99.

Clymo, R.S., 1983. Peat. In: Gore, A.J.P. (Ed.), 1983. Ecosystems of the world. 4A. Mires: Swamp, Bog, Fen and Moor. General Studies. pp. 159-224. *Elsevier.*

Clymo, R.S., 1984. The limits to peat bog growth. *Phil. Trans. R. Soc. London* B303:605-654.

Clymo, R.S., 1992. Productivity and decomposition of peatland ecosystems. In: O.M. Bragg, P.D. Hulme, H.A.P. Ingram and R.A. Robertson (Eds). Peatland Ecosystems and Man: An Impact Assessment. pp. 3-16. *Dept. of Biological Sciences, University of Dundee* and *The International Peat Society*, Jyväskylä.

Clymo, R.S., 1997. The Roles of *Sphagnum* in Peatlands. In: L. Parkyn, R.E. Stoneman, and H.A.P. Ingram (Eds). Conserving Peatlands, pp. 95-102. *CAB International*, Wallingford.

Clymo, R.S., 1998. *Sphagnum*, the peatland carbon economy, and climate change. In: J.W. Bates, N.W. Ashton and J.G. Duckett, 1998. Bryology fot the Twenty-first Century. *Maney Publishing & the British Ecological Society.*

Connaughton, M.J. 1967. Global Solar Radiation, Potential Evapotranspiration and Potential Water Deficit in Ireland. *Technical Note 31, Meteorological Service*, Dublin.

Cross, J.R., 1989. Peatlands. Wastelands or heritage? An introduction to bogs and fens. 28 pp. *Wildlife Series 1 No. 1. Wildlife Service Ireland. Stationery Office*, Dublin.

Dai, T.S. and J.H. Sparling, 1973. Measurement of hydraulic conductivity of peats. *Can. J. Soil Science* 53:21-26.

Daly, D. and P. Johnston, 1994. The hydrodynamics of raised bogs: an issue for conservation. In: Keane, T. and E. Daly. The Balance of Water - Present and Future. *Proc. Agmet Conference, Dublin, September 7-9, 1994*: 105-21.

De Bruin, H.A.R., 1977. The accuracy of measuring areal precipitation with a rain gauge network. In: Committee for Hydrological Research TNO, Precipitation and measurements of precipitation, *Proc. Techn. Meeting* 33:17-46.

De Zeeuw, J.W., 1976. Peat and the Dutch Golden Age. The historical meaning of energy-attainability. *A.A.G. Bijdragen* 21:3-31.

Deij, L.J.L., 1968. Enige opmerkinegn over de neerslagmeting en de neerslagverdeling naar tijd en plaats in ons land. In: Committee for hydrological research T.N.O. Precipitation data. *Proc. Techn. Meeting* 22:71-85.

Draper, N.R. and H. Smith, 1981. Applied Regression Analysis. 2nd Ed. 709 pp. *John Wiley & Sons.*

Edelman, J.H. 1972. Groundwater hydraulics of extensive aquifers. 216 pp. *Int. Inst. for Land Recl. and Impr./ILRI,* Wageningen.

Edom, F. and A.A. Golubcov, 1996. Prognose einer potentiell natürlichen Ökotopzonierung für Mittelgebirgsregenmoore durch berechnung hydrologischer Parameter. In: Festschrift anläßlich des 60. Geburtstages von Prof. Dr. Gerd Peschke. Wasser im System Boden-Pflanze-Atmosphäre. *IHI-Schriften* 2:103-111, Zittau.

Eggelsmann, R., 1960. Über den unterirdischen Abfluß aus Mooren. *Die Wasserwirtschaft* 50:149-154.

Eggelsmann, R., 1963. Die potentielle und aktuelle Evaporation eines Seeklima-Hoochmoores. *IAHS Publ.* 62:88-97.

Eggelsmann, R., 1967. Oberflächengefälle und Abflußregime der Hochmoore. *Wasser und Boden* 19(8):247-252.

Eggelsmann, R., 1987. Ökotechnische Aspekte der Hochmoor-Regeneration. *Telma* 17:59-94.

Eggelsmann, R., 1990a. Moor und Wasser. In: Göttlich, Kh., Moor- und Torfkunde. 3rd Ed., pp. 288-320. *E. Schweizerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller),* Stuttgart.

Eggelsmann, R., 1990b. Wasserregelung im Moor. In: Göttlich, Kh., Moor- und Torfkunde. 3rd Ed., pp. 321-349. *E. Schweizerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller),* Stuttgart.

Eshuis, J.A. and H. Kruitbosch, 1942. Ontginning van veengronden. In: J. van de Mortel (Ed). Het veen en zijn ontginning. Voordrachten gehouden op de 11de wetenschappelijke bijeenkomst van de sectie Nederland der Internationale Bodemkundige Vereniging 24 en 25 October 1941 te Utrecht, pp. 47-80. *Nederlandsche Heidemaatschappij,* Arnhem.

Feddes, R.A. and K.J. Lenselink, 1994. Evapotranspiration. In: H.P. Ritzema (Ed.), Drainage Principles and Applications, pp. 145-173. *Int. Inst. Land Recl. Impr.,* Wageningen

Feldmeyer-Christe, E. and G. Mulhauser, 1994. A moving mire - the burst bog of la Vraconnaz. In: Grünig, A., (ed.) Mires and Man. Mire Conservation in a Densely Populated Country -The Swiss Experience. *Swiss Fed. Inst. for Forest, Snow and Landscape Research,* Birmensdorf.

Flynn, R., 1993. The hydrology of Clara Bog and the surrounding area. Unpublished report, 163 pp. *Geol. Survey of Ireland.*

Franzén, 1992. Can earth afford to lose the wetlands in the battle against the increasing greenhouse effect? *Proc. 9th Int. Peat Congress, Uppsala 22-26 June 1992.* Vol. I:1-18.

Früh, J., 1897. Über Moorausbrüche. *Vierteljahrsschrift d. Naturf. Gesellsch. Zürich* XLII:202-237.

Galvin, L.F., 1976. Physical properties of Irish peats. *Irish J. Agric. Res.* 15:207-221.

Galvin, L.F. and E.T. Hanrahan, 1967. Steady state drainage flow in peat. *Highway Research Record 203:77-86. Highway Research Board, Nat. Academy of Sciences,* Washington DC.

Gill, M. and P. Johnston, 1999. Raheenmore Bog Subsidence Study 1948-1994. 5pp. & app. *Trinity College,* Dublin.

Gloudemans, E., 1990. Hydrological report on Irish bogs. Field work on Clara Bog and Raheenmore Bog. 36 pp. *Irish-Dutch Raised Bog Study. Wageningen Agric. Univ., Dept. of Hydrology, Soil Physics & Hydraulics.*

Gore, A.J.P., 1983. Introduction. In: Gore, A.J.P. (Ed.), 1983. Ecosystems of the world. 4A. Mires: Swamp, Bog, Fen and Moor. General Studies. pp. 1-34. *Elsevier.*

Granlund, E., 1932. De svenska högmossarnas geologi. Deras bindningsbetingelser, utvecklingshistoria och utbredning jämte sambandet mellan högmossbildning och försumpning. *Sveriges Geologiska Undersökning. Ser. C. Avhandlingar och uppsatser. Årsbok 26,* N:o 1. 193 pp. *P.A. Norstedt & Söner,* Stockholm.

Grosse-Brauckmann, G., 1990. Ablagerungen der Moore. In: Göttlich, Kh., Moor- und Torfkunde. 3rd Ed., pp. 175-236. *E. Schweizerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller),* Stuttgart.

Grosse-Brauckmann, G., 1996. German Peatlands and Peatland research -Past and Present-. In: G.W. Lüttig (Ed). 10th International Peat congress. Peatlands Use - Present, Past and Future. Vol. 4:1-21. *Schweitzerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller),* Stuttgart.

Grünig, A., 1993. Introduction to Switzerland. In: A. Grünig (Ed.), Mires and Man. Mire Conservation in a Densely Populated Country – The Swiss Experience. *Swiss Fed. Inst. for Forest, Snow and Landscape Research,* Birmensdorf.

Hallakorpi, I.A., 1936. Om sättning av torvmarkerna. *Svenska Mosskulturför. Tidskrift* 30(2):101-107.

Hammond, R.F., 1978. Peatland Map of Ireland. Scale 1:575,000. *National Soil Survey, An Foras Talúntais,* Dublin.

Hammond, R.F., 1981. The Peatlands of Ireland. To accompany Peatland Map of Ireland, 1978. *Soil Survey Bulletin* 35, 59 pp. *An Foras Talúntais,* Dublin.

Hammond, R.F., 1984. The classification of Irish peats as surveyed by the National Soil Survey of Ireland. *Proc. 7th Int. Peat Congress Dublin, June 18-23 1984,* Vol 1:168-187. *The International Peat Society*, Helsinki, Finland.

Hahn, G.J., 1989. Statistical intervals. In: Wadsworth, H.M. (Ed.), 1989. Handbook of statistical methods for engineers and scientists. *McGraw-Hill Publishing Co.*

Hanrahan, E.T., 1954. An investigation of some physical properties of peat. *Géotechnique* 4:108-123.

Hanrahan, E.T., 1964. A road failure on peat. *Géotechnique* 14:185-202.

Hänninen, P., 1987. Comparison between the Von Post degree of humification and fibre content method and physical and chemical properties of different grain sizes of peat. *Proc. Symp. '87 Wetlands/Peatlands Edmonton*, pp. 71-75, Ottawa.

Hayward, P.M. and R.S. Clymo, 1982. Profiles of water content and pore size in *Sphagnum* and peat, and their relation to peat bog ecology. *Proc. Royal Soc. of London* B 215:299-325.

Hemond, H.F. and J.C. Goldman, 1985. On non-Darcyan water flow in peat. *J. Ecol.* 73:579-584.

Hill, R., 1992. The origin and dynamics of the birch wood on Clara Bog, Co. Offaly. BA thesis, *School of Botany, Trinity College*, Dublin.

Hobbs, N.B., 1986. Mire morphology and the properties and behaviour of some British and foreign peats. *Quart. J. Eng. Geol.* 19:7-80.

Huisman, D.F.M.J., 1991. Hydrological field work on Clara and Raheemore Bogs. *Irish-Dutch Raised Bog Study.* 33 pp., 5 app. *Department of Hydrology, Soil Physics and Hydraulics, Wageningen Agricultural University.*

Hulme, P.D., 1986. The origin and development of wet hollows and pools on Craigeazle mire, south-west Scotland. *Int. Peat J.* 1:15-28.

Ingram, H.A.P., 1978. Soil layers in mires: function and terminology. *J. Soil Sci.* 29(2):224-227.

Ingram, H.A.P., 1982. Size and shape in raised mire ecosystems: a geophysical model. *Nature* 297:300-303.

Ingram, H.A.P., 1983. Hydrology. In: Gore, A.J.P. (Ed.), 1983. Ecosystems of the world. 4A. Mires: Swamp, Bog, Fen and Moor. General Studies. pp. 67-158. *Elsevier.*

Ingram, H.A.P., 1987. Ecohydrology of Scottish peatlands. *Trans. Royal Soc. Edinburgh: Earth Sciences* 78:287-296.

Ingram. H.A.P., D.W. Rycroft and D.J.A. Williams, 1974. Anomalous transmission of water through certain peats. *J. Hydrol.* 22:213-218.

Ingram, H.A.P. and O.M. Bragg, 1984. The diplotelmic mire: some hydrological consequences reviewed. *Proc. 7th Int. Peat Congress Dublin, June 18-23 1984*, Vol 1:220-234. *The International Peat Society*, Helsinki, Finland.

Ingram, H.A.P., W. Fojt and P.J. Smart, 1985. Die Durchlässigkeitsmerkmale des Niedermoortorfes im Upton Fen. *Telma* 15:67-74.

Isaaks, E.H. and R.M. Srivastava, 1989. Applied Geostatistics. 561 pp. *Oxford Univ. Press,* Oxford.

ISO, 1983. Measurement of liquid flow in open channels. ISO Standards Handbook 18, *ISO,* Geneva.

Ivanov, K.E., 1965. Fundamentals of the theory of swamp morphology and hydromorphological relationships. *Soviet Hydrology. Selected Papers* 4:224-258.

Ivanov, K.E., 1975. Hydrological stability criteria and preservation of bogs and bog/lake systems. In: Hydrology of Marsh-ridden Areas. Proc. Minsk Symp. June 1972, pp. 343-353. *The Unesco Press*, Paris.

Ivanov, K.E., 1981. Water Movement in Mirelands. 276 pp. *Academic Press.* (English translation of "Vodoobmen v bolotnykh landshaftakh", *Gidrometeoizdat*, Leningrad, 1975.)

Joosten, J.H., 1993. Denken wie ein Hochmoor. Hydrologische Selbstregulation von Hochmooren und deren Bedeutung für Wiedervernässung und Restauration. *Telma* 23:95-115.

Kac, N.J., 1971. The mires of the Earth. 295 pp., *Nauka,* Moscow (in Russian, publication not seen).

Karesniemi, K., 1972. Dependence of humification degree on certain properties of peat. *Proc. 4th Int. Peat Congr. Otaniemi, 1972*, 2:273-282.

Kelly, L. and M.G.C. Schouten, 1999. Ecology. In: Schouten, M.G.C. (Ed.), Ecohydrology and conservation of raised bogs. *Government Stationery Office*, Dublin.

Kendall, M.G., 1962. Rank correlation methods. 3rd Ed. *Charles Griffin*, London.

Kermack, K.A., and J.B.S. Haldane, 1950. Organic correlation and allometry. *Biometrika* 37:30-41.

Kim, J. and S.B. Verma, 1996. Surface exchange of water vapour between an open Sphagnum fen and the atmosphere. *Boundary-Layer Met.* 79:243-264.

Kirkham, D., 1945. Proposed method for field measurement of permeability of soil below the water table. *Proc. SSSA* 10:58-68.

Koorevaar, P., G. Menelik and C. Dirksen, 1983. Elements of Soil Physics. 230 pp. *Developments in Soil Science* 13, Elsevier.

Korpijaakko, M., 1988. Consideration of the factors affecting the hydraulic conductivity of peat as ground of both laboratory and field tests. *Proc. VIII. Int. Peat Congress, Leningrad 1988.* Vol. III:127-136., Leningrad.

Kulczynski, S. (1949). Peat bogs of Polesie. Mém. de 'l Académie Polonaise des Sciences et des Lettres. Série B:1-356. (English translation of work originally published in Polish in 1939).

Kuntze, H., 1972. Rekultivierung gealteter Moorkulturen. *Telma* 2:109-118.

Lappalainen, E., 1996. Global Peat resources. In: G.W. Lüttig (Ed). 10th International Peat congress. Peatlands Use - Present, Past and Future. Vol. 2:80-86. *Schweitzerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller)*, Stuttgart.

Leene G.J., and A.H.L.M. Tiebosch, 1993. Water balance study of Clara Bog, Ireland. *Irish-Dutch Raised Bog study.* MSc-thesis, *Wageningen Agric. Univ., Dept. of Water Resources.*

Lensen, H.A., 1991. Hydrology of Clara and Raheenmore Bogs. Catchment definition; acrotelm survey; determination of surface subsidence; quality check of groundwater data. Irish-Dutch Peatland Study. 47 pp. *Department of Hydrology, Soil Physics and Hydraulics, Wageningen Agricultural University.*

Linnaeus, C., 1751. Skånska Resa. På höga överhetens befallning förrättad år 1749 med rön och anmärkningar uti ekonomien, naturalier, antkviteter, seder, levnadssätt. Reprint 1982, *Wahlström & Widstrand,* Stockholm.

Luthin, J.N. and D. Kirkham, 1949. A piezometer method for measuring permeability of soil in situ below a water table. *Soil Science* 68:349- 358.

Lütt, S., 1992. Produktionsbiologische Untersuchungen zur Sukzession der Torfstichvegetation in Schleswig-Holstein. 250 pp + app. *Mitt. Arb. Gem. Geobot. Schleswig-Holstein u. Hamburg.* Heft 43. Kiel.

Lüttig, G., 1989. Hier irrten Alexander von Humboldt und andere. *Telma* 19:43-55.

Malmström, C., 1923. Degerö stormyr. En botanisk, hydrologisk och utvecklingshistorisk undersökning över ett nordsvenskt myrkomplex. *Medd. Statens Skogsförsöksanstalt* 20:1-206.

Malmström, C., 1939. Methoden zur Untersuchung der Wasserverhältnisse von Torfböden. In: E. Abderhalden, ed. Handbuch der biologischen Arbeitsmethoden. Abt. XI: Methoden der Erforschung der Leistungen des Pflanzenorganismus. Teil 4, 1. Hälfte, pp. 373-390. *Urban & Schwarzenberg,* Berlin/Vienna.

Masing, V., 1998. Multilevel approach in mire mapping, research and classification. Contribution to the IMCG Classification Workshop March 25-29 1998, Greifswald. (6 pp., unpublished).

Meteorological Service, 1989-1991. Agrometeorological Bulletin, Dublin. Monthly issues.

Meteorological Service, 1992-1993. Monthly Weather Bulletin, Dublin. Monthly issues.

Miller, R.L. and J.S. Kahn, 1962. Statistical Analysis in the Geological Sciences. 483 pp. *Wiley*, New York.

Mitchell, G.F., 1976. The Irish Landscape. 240 pp. *Collins*, London.

Moore, P.D., 1986. Hydrological changes in mires. In: B.E. Berglund (Ed.). Handbook of Holocene Palaeoecology and Palaeohydrology. *John Wiley & Sons.*

Moore, P.D. and D.J. Bellamy, 1974. Peatlands. 221 pp. *Elek Science*, London.

Naucke, W., 1990. Chemie von Moor und Torf. In: Göttlich, Kh., Moor- und Torfkunde. 3rd Ed., pp. 237-261. *E. Schweizerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller)*, Stuttgart.

Nichols, D.S. and J.M. Brown, 1980. Evaporation from a Sphagnum moss surface. *J. Hydrol.* 48:289-302.

Nicholson, I.A., R.A Robertson and M. Robinson, 1989. The effects of drainage on the hydrology of a peat bog. *Int. Peat J.* 3:59-83.

Nilsson, T. (1964). Standardpollendiagramme und ^{14}C-Datierungen aus dem Ageröds Mosse im mittleren Schonen. *Lunds Univ. Årsskr.* 59(7):1-52.

Nilsson, L.Y., 1982. Vad händer vid dikning och avvattning? Hydrologiska och kemiska konsekvenser. Miljökonsekvenser vid ökat torvutnyttjande. *Ingenjörsvetenskapsakademin Rapport* 227:23-34, Stockholm.

O'Donnell, T., 1996. Types and Global Distribution of Mires in Ireland. In: G.W. Lüttig (Ed). 10th International Peat congress. Peatlands Use - Present, Past and Future. Vol. 2:49-59. *Schweitzerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller)*, Stuttgart.

Overbeck, F., 1975. Botanisch-geologische Moorkunde unter besonderer Berücksichtigung der Moore Nordwestdeutchlands als Quellen zur Vegetations-, Klima- und Siedlungsgeschichte. 719 pp. *Karl Wachholtz Verlag*, Neumünster.

Päivänen, J., 1969. The bulk density of peat and its determination. *Silva Fennica* 3(1):1-19.

Päivänen, J., 1973. Hydraulic conductivity and water retention in peat soils. *Acta For. Fennica* 129:1-70.

Phersson, M. and O. Pettersson, 1997. Energy and Water Balances of a Bog in Central Sweden. *Nordic Hydrol.* 28(4/5):263-272.

Potonié, H., 1909. Das Auftreten zweier Grenzhorizonte innerhalb eines und desselben Moorprofils. *Jahrb. d. Königl. Preuß. Geol. Landesanst.* 19:398-409, Berlin.

Rodgers, M., 1993. Final Report. Preliminary site investigation, Clara Bog, Co. Offaly. Carried out for Geological Survey of Ireland. *Soil Mechanics Laboratory, University College*, Galway.

Romanov, V.V., 1968a. Hydrophysics of bogs. 299 pp. *Israel Program of Scientific Translations*, Jerusalem. (English translation of "Gidrofizika bolot", *Gimiz Gidrometeorologicheskoe Izdatel'stvo*, Leningrad, 1961)

Romanov, V.V., 1968b. Evaporation from bogs in the European territory of the USSR. 183 pp. *Israel Program of Scientific Translations*, Jerusalem. (English translation of "Isparenie bolot Evropeiskoi territorii SSSR", *Gimiz Gidrometeorologicheskoe Izdatel'stvo*, Leningrad, 1962).

Rycroft, D.W., D.J.A. Williams and H.A.P. Ingram, 1975a. The transmission of water through peat. I. Review. *J. Ecol.* 63:535-556.

Rycroft, D.W., D.J.A. Williams and H.A.P. Ingram, 1975b. The transmission of water through peat. II. Field experiments. *J. Ecol.* 63:557-568.

Sachs, L., 1982. Applied Statistics. A Handbook of Techniques. Translated by Zenon Reynarowich. *Springer-Verlag*.

Samuels, H., 1992. Drainage and subsidence on a raised bog. M.Sc. thesis. *Dept. of Civil Engineering, Imperial College*, London.

Schneebeli, M., 1991. Hydrologie und Dynamik der Hochmoorentwicklung. Diss. ETH Nr. 9366. 133 pp and 8 app. *ETH*, Zürich.

Schneider, S. and R. Schneider, 1990. Verteilung der Moore auf Erde. In: Göttlich, Kh., Moor- und Torfkunde. 3rd Ed., pp. 65-101. *E. Schweizerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller)*, Stuttgart.

Schothorst, C.J., 1982. Drainage and behaviour of peat soils. In: H. de Bakker and M.W. van den Berg (Eds). Proceedings of the symposium on peat lands below sea level. *ILRI Publication* 30:130-163. *Int. Inst. for Land Reclamation and Improvement*, Wageningen.

Schouwenaars, J.M., 1990. Problem-oriented studies on plant-soil-water relations. PhD-thesis, 175 pp. *Wageningen Agricultural University*.

Schouwenaars, J.M., 1993. Hydrological differences between bogs and bog-relicts and consequences for bog restoration. In: E.P.H. Best and J.P. Bakker (Eds), Netherlands-Wetlands. *Hydrobiologia* 265:217-224.

Schouwenaars, J.M., J. Blankenburg and G. Sterk, 1992. Hydrologische Feld- und Modellversuche in Hochmoor-Regenerationsflächen. *Telma* 22:37-52.

Schouwenaars, J.M., F. van Amerongen and M. Booltink, 1992. Hydraulic resistance of peat layers and downward seepage in bog relicts. *Int. Peat J.* 4:65-76.

Schouwenaars, J.M and J.P.M. Vink, 1992. Hydrophysical properties of peat relicts in a former bog and perspectives for Sphagnum regrowth. *Int. Peat Journal* 4:15-28.

Schouwenaars, J.M., 1993. De verdamping van pijpestrootje (*Molinia caerulea*) en veenmos (*Sphagnum papillosum*) in hoogveengebieden en haar betekenis voor het waterbeheer. *H2O* 26(14):376-382.

Schouwenaars, J.M., H. Esselink, L.P.M. Lamers and P.C. van der Molen, 1987. Hoogveenherstel in Nederland. Bestaande kennis en benodigd onderzoek. Preadvies hoogvenen. 122 pp. & app. *University of Groningen, Stichting Bargerveen, University of Nijmegen, Adviesbureau Groenholland.*

Segeberg, H., 1951. Der gegenwartige Stand des Problems der Moorsackung. *Wasser u. Boden* 3(1-2):28-33.

Segeberg, H., 1952. Ein Verfahren zur Beurteilung des Vertorfungsgrades von Hochmoortorfen mit Hilfe des Volumengewichtes. *Landwirtsch. Forschung* 3:144-155.

Segeberg, H., 1960. Moorsackungen durch Grundwasserabsenkung. *Zschr. F. Kulturtechnik* 1:145-161.

Sernander, R., 1910. De scanodaniska torfmossarnas stratigrafi. *Geol. Fören. i Stockholm Förh.* 31(6):423-448.

Sevruk, B., 1989a. Reliability of Precipitation Measurement. In: B. Sevruk (ed.). Precipitation Measurement. WMO/IAHS/ETH Workshop on Precipitation Measurement St. Moritz, 3-7 December 1989, 13-19. *ETH,* Zurich.

Sevruk, B., 1989b. Wind Induced Measurement Error for High-Intensity Rains. In: B. Sevruk (ed.). Precipitation Measurement. WMO/IAHS/ETH Workshop on Precipitation Measurement St. Moritz, 3-7 December 1989, 199-204. *ETH,* Zurich.

Sevruk, B. and S.W. Klemm, 1989. Types of standard precipitation gauges. In: B. Sevruk (ed.). Precipitation Measurement. WMO/IAHS/ETH Workshop on Precipitation Measurement St. Moritz, 3-7 December 1989, 227-232. *ETH,* Zurich.

Siegel, D.I., 1992. Groundwater Hydrology. In: Wright, H.E., B.A. Coffin and N.E. Aaseng, editors. The Patterned Peatlands of Minnesota, pp.163-172. *Univ. Minnesota Press,* Minneapolis.

Sijtsma, B.R. and A.A. Veldhuizen, 1992. Hydrology of Clara and Raheenmore Bog. Consolidation, Evapotranspiration, Storage Coefficients, Acrotelm Transmissivity, Piezometer Test, Groundwater dBase, Retention. 81 pp. & appendices. *Irish-Dutch Raised Bog Study. Wageningen Agric. Univ., Dept. of Water Resources.*

Skempton, A.W. and D.J. Petley, 1970. Ignition loss and other properties of peats and clays from Avonmouth, King's Lynn and Cranberry Moss. *Géotechnique* 20:343-356

Smiles, D.E. and E.G. Youngs, 1965. Hydraulic conductivity determination by several field methods in a sand tank. *Soil Science* 99:83-87.

Smyth, M., 1993. Quaternary Geology and Geophysical Studies of Clara and Raheenmore Bogs, Co. Offaly, Ireland. 254 pp. & appendices. PhD. Thesis, *Dept. of Geology & The Applied Geophysics Unit, University College,* Galway.

Snedecor, G.W. and W.G. Cochran, 1989. Statistical Methods. 8th Ed., 503 pp. *Iowa State University Press*, Ames.

Spieksma, J.F.M., E.J. Moors, A.J. Dolman and J.M. Schouwenaars, 1997. Modelling evaporation from a drained and rewetted peatland. *J. Hydrol.* 199:252-271.

Stanek, W. and T. Silc, 1977. Comparisons of four methods for determination of degree of peat humification (decomposition) with emphasis on the Von Post method. *Can. J. Soil Science* 57:109-117.

Streefkerk, J.G. and W.A. Casparie, 1989. The hydrology of bog ecosystems. 125 pp. *Staatsbosbeheer*, Utrecht.

Succow, M. and L. Jeschke, 1990. Moore in der Landschaft. 2nd Ed., 268 pp. *Verlag Harri Deutsch*, Thun and Frankfurt/M.

Tansley, A.G., 1939. The British Isles and their Vegetation. 2 vol., 930 pp. *Cambridge Univ. Press.*, Cambridge (reprint of 1953 seen).

Ten Dam, H.J. and J.F.M. Spieksma, 1993. Hydrology of Clara and Raheenmore Bog. Permeability of Raheenmore Bog. Subsidence study of Clara Bog West. 66 pp. *Irish-Dutch Raised Bog Study. Wageningen Agric. Univ., Dept. of Water Resources.*

Treacy, N., 1990. Closing address to the Peatlands in Perspective Symposium. In: M.G.C. Schouten and M.J. Nooren (Eds.). Peatlands, Economy and Conservation, pp. 101-104. *SPB Academic Publishing*, The Hague, Netherlands.

Uhden, O., 1951. Verschlechtert die Entwässerung und Kultivierung der Moore die Wasserverhältnisse der Unterlieger? *Wasser u. Boden* 3(8):180-182.

Uhden, O., 1956. Neue Erkentnisse über das Sacken und "Atmen" der Hochmoore. *Die Wasserwirtschaft* 46(10):261-265.

Uhden, O., 1960. Das Grosse Moor bei Ostenholz. Schriftenreihe des Kuratoriums für Kulturbauwesen. Heft 9. 159 pp. and appendices. *Verlag Wasser und Boden*, Hamburg.

Uhden, O., 1967. Niederschlags und Abflußbeobachtungen auf unberührten, vorentwässerten und kultivierten Teilen eines nordwestdeutschen Hochmoores, der Esterweger Dose am Küstenkanal bei Papenburg. *Schriftenreihe des Kuratoriums für Kulturbauwesen*, Heft 15(I). 99 pp. *Verlag Wasser und Boden*, Hamburg.

Uhden, O., 1972. Gebirgshochmoore und Wasserwirtschaft am Beispiel des Brockenfeldmoores im Oberharz. *Schriftenreihe des Kuratoriums für Kulturbauwesen.* Heft 21. 175 pp. *Verlag Wasser und Boden*, Hamburg.

Van Beers, W.F.J., 1963. The auger-hole method. A field measurement of the hydraulic conductivity of soil below the water table. *Int. Inst. Land Recl. Impr. ILRI Bull.* 1, 32 pp.

Van den Boogaard, M., 1993. Regional hydrogeology of Clara Bog; an Irish raised bog. *Irish-Dutch Raised Bog Study. Wageningen Agric. Univ., Dept. of Water Resources.* 62 pp.+app.

Van der Cruysen, J.H.G, A. Grent and R. van Wolfswinkel, 1993. Acrotelm Survey of Clara Bog. 78 pp and appendices. *Irish-Dutch Peatland Study. Wageningen Agric. Univ., Dept. of Water Resources.*

Van der Molen, P.C., M. Schalkoort and R. Smit, 1992. Hummock-hollow complexes on Clara Bog, Co. Offaly, Ireland. In: P.C. van der Molen. Hummock-hollow complexes on Irish raised bogs. A palaeo-actio ecological approach of environmental and climatic change, pp. 117-173. *PhD-thesis, Univ. of Amsterdam.*

Van der Molen, W.H., 1975. Subsidence of peat soils after drainage. In: Hydrology of Marsh-ridden areas. *Proceedings of the Minsk Symposium, June 1972*:183-186. *Unesco Press, IAHS*, Paris.

Van der Molen, W.H., 1981. Über die Breite hydrologischer Schutzzonen um Naturschutzgebiete in Mooren. *Telma* 11:213-220.

Van der Molen, W.H., L.J. Pons, S. van der Schaaf and J.M. Schouwenaars, 1992. Hydrology of natural raised bogs in Western Europe. *Proc. 9th Int. Peat Congress, Uppsala 22-26 June 1992.* Vol. III:219-220.

Van der Molen, W.H. and J. Wesseling, 1989. A solution in closed form and a series solution to replace the tables for the thickness of the equivalent layer in Hooghoudt's drain spacing formula. *Agric. Water Manag.* 19:1-16.

Van der Schaaf, S., 1984. Errors in level recorder data: prevention and detection. *J. Hydrol.* 73:373-382.

Van der Schaaf, S., 1996. Acrotelm conditions in two Irish Midlands raised bogs as affected by surface slope and superficial drainage. In: G.W. Lüttig (Ed). 10th International Peat congress. Peatlands Use - Present, Past and Future. Vol. 2:121-127. *Schweitzerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller)*, Stuttgart.

Van der Schaaf, S., 1998a. Self regulation of acrotelm transmissivity and discharge in two Irish Midland raised bogs. In: T. Malterer, K. Johnson and J. Stewart (eds.). Peatland restoration & Reclamation. Techniques and Regulatory Considerations. *Proc. Intern. Peat Symp.*, Duluth, Minnesota, USA, 14-18 July 1998, pp. 161-169.

Van der Schaaf, S., 1998b. Anisotropie und Selbstregulierung bei Versickerungsverlusten in Hochmooren. *Telma* 28:131-144.

Van der Schaaf, S., 1999. Bog hydrology. In: Schouten, M.G.C. (Ed.), Ecohydrology and conservation of raised bogs. *Government Stationery Office*, Dublin.

Van der Schaaf, S, J.W van 't Hullenaar, J.R. ten Kate and W.H. van der Molen, 1992. In situ measurement of acrotelm transmissivity. *Proc. 9th Int. Peat Congress* 3:227-228, Uppsala.

Van Gerven, M., 1990. Preliminary studies on the hydrology of Clara Bog and Raheenmore Bog. 34 pp. & app. *Irish-Dutch Raised Bog Study. Wageningen Agric. Univ., Dept. of Hydrology, Soil Physics and Hydraulics.*

Van 't Hullenaar, J.W. and J.R. ten Kate, 1991. Hydrology of Clara and Raheenmore Bogs. Evapotranspiration, storage coefficients, lateral flow in the acrotelm, catchment definition, test of the piezometer method for hydraulic conductivity. 51 pp and appendices. *Irish-Dutch Raised Bog Study. Wageningen Agric. Univ., Dept. of Hydrology, Soil Physics and Hydraulics.*

Van Tatenhove, F. and J. Van der Meer, 1990. The Quaternary Geology of Clara Bog and Raheenmore, Co. Offaly, Ireland. Preliminary mapping of surficial deposits. *Irish-Dutch Raised Bog Study. Fysisch Geografisch en Bodemkundig Laboratorium, Universiteit van Amsterdam.*

Van Walsum, P.E.V. and A.A. Veldhuizen, 1995. Modelstudie waterhuishouding Fochteloërveen en omgeving: simulatie van scenario's voor het waterbeheer met SIMGRO. *DLO-Staringcentrum. Rapport 399,* 179 pp. and appendices.

Vasander, H. and H. Roderfeld, 1996. Restoration of peatlands after harvesting. In: H. Vasander (Ed). Pealtlands in Finland, p. 143-147. *Finnish Peatland Society,* Helsinki.

Veldkamp, N.M. and R. Westein, 1993. Hydrology of Raheenmore Bog. A water balance study. 50 pp & app. *Irish-Dutch Raised Bog Study. Wageningen Agric. Univ., Dept. of Water Resources.*

Verry, E.S., 1984. Microtopography and water table fluctuation in a Sphagnum mire. *Proc. 7th Int. Peat Congress Dublin, June 18-23 1984.* Vol.2:11-31. *The International Peat Society,* Helsinki, Finland.

Verry, E.S. and D.H. Boelter, 1975. The influence of bogs on the distribution of streamflow from small bog-upland catchments. Hydrology of Marsh-ridden areas. *Proceedings of the Minsk Symposium, June 1972. Unesco Press, IAHS,* Paris.

Verry, E.S., K.N. Brooks and P.K. Barten, 1988. Streamflow response from an ombrotrophic mire. *Symposium on the Hydrology of Wetlands in the temperate and cold regions, Joensuu, Finland 6-8 June 1988.* Vol 1:52-59. *Publ. Acad. Finl.* 4/1988.

Von Post, L., 1922. Sveriges Geologiska Undersöknings torvinventering och några av dess hittils vunna resultat. *Svenska Mosskulturföreningens Tidskrift* 36:1-27.

Von Post, L. and E. Granlund, 1926. Södra Sveriges torvtillgångar. I. *Sveriges Geol. Unders., Ser. C,* nr. 335.

Vorobiev, P.K., 1963. Investigations of water yield of low lying swamps of Western Siberia. *Soviet Hydrology: Selected Papers* 2:226-252. (English translation of original paper published in "*Transactions of the State Hydrologic Institute" (Trudy GGI)* 105:45-79, 1963).

Waine, J., J.M.B. Brown and H.A.P. Ingram, 1985. Non-Darcyan transmission of water in certain humified peats. *J. Hydrol.* 82:327-339.

Walker, D. and P.M. Walker, 1961. Stratigraphic evidence of regeneration in some Irish bogs. *J. Ecol.* 49:169-185.

Weber, C.A., 1900. Ueber die Moore mit besonderer berücksichtigung der zwischen Unterweser und Unterelbe liegenden. *Jahresbericht der Männer vom Morgenstern* 3:3-23.

Weber, C.A., 1901. Über die Erhaltung von Mooren und Heiden Norddeutschlands im Naturzustande sowie über die Wiederherstellung von Naturwäldern. *Abh. naturwiss. Vereins Bremen* 15 (3):263-278, Bremen.

Weber, C.A., 1902. Vegetation und Entstehung des Hochmoors von Augstumal im Memeldelta mit vergleichenden Ausblicken auf andere Hochmoore der Erde. Eine formationsbiologisch-historische und geologische Studie. *Verlagsbuchhandlung Paul Parey,* Berlin.

Weber, C.A., 1907. Aufbau und Vegetation der Moore Norddeutschlands. *Beiblatt zu Englers Bot. Jahrb.* 90:19-34.

Weber, C.A., 1928. Grenzhorizont und Klimaschwankungen. *Abh. naturw. Ver. Bremen.* 26:98-106, Bremen.

Weber, C.A., 1930. Grenzhorizont und älterer Sphagnumtorf. *Abh. naturw. Ver. Bremen.* 28:57-65, Bremen.

Wheeler, B.D., S.C. Shaw, W.J. Fojt and R.A. Robertson (Eds.). Restoration of temperate wetlands. 562 pp., *Wiley.*

Wösten, J.H.M., G.J.Veerman, en J. Stolte, 1994. Waterretentie- en doorlatendheidskarakteristieken van boven- en ondergronden in Nederland: De Staringreeks. Vernieuwde uitgave 1994. *SC-DLO, Technisch Document* 18, Wageningen.

Youngs, E.G., 1968. Shape factors for Kirkham's piezometer method for determining the hydraulic conductivity of soil ***in situ*** for soils overlying an impermeable floor or infinitely permeable stratum. *Soil Science* 106:235-237.

Zijl, W. and M. Nawalany, 1993. Natural Groundwater Flow. 321 pp. *Lewis Publishers.*

APPENDICES

A. Humification and volume fraction of solid matter transects

A.1. Transect positions

As for Raheenmore Bog, two transects are available: N-S and C-E. As for Clara Bog West, three transects have been worked out: A'-A, N-SW and W-E. The transects include most sampling sites. Only the sites that did not fit well on the lines have been excluded. The positions of transects and included sites are shown in fig. A.1.

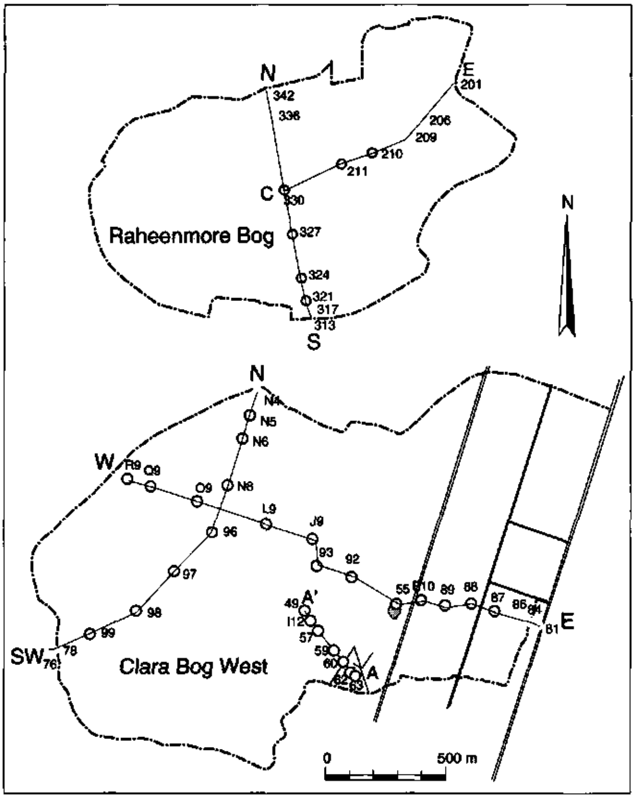

Fig. A.1. Positions of the transects.

A.2. Cross sections along the transects

A cross section along each transect is given in figs. A.2 through A.6. Each one shows the surface level and the level of the transition from peat to mineral subsoil. Because the transects are reasonably perpendicular to the surface level contours, they also give information on surface slopes.

On Raheenmore Bog, the bottom level of the FP at sites 204, 327, 330 and 333 was estimated from the depth to which the deepest piezometers could be pressed down into the peat. At sites

204 and 333, no sampling was done and therefore no information was available as to the depth of the transition from FSP to HSP and from HSP to FP.

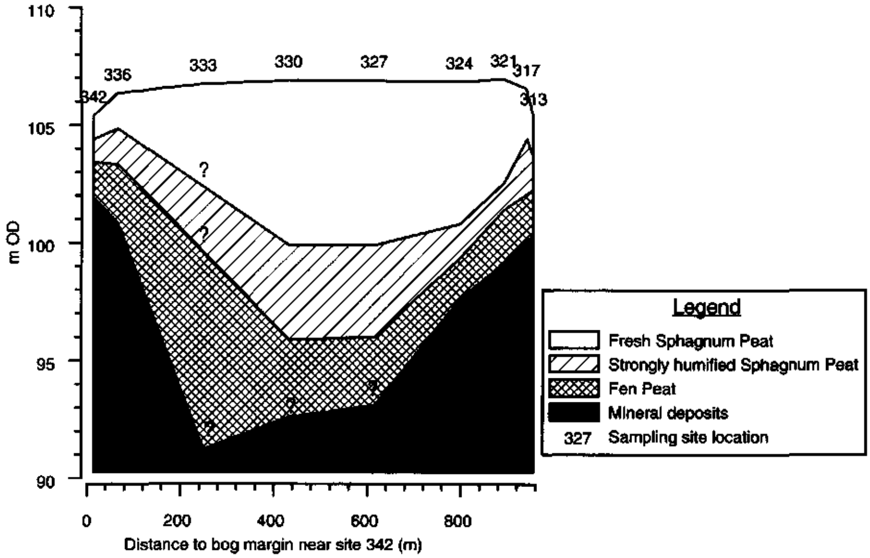

Fig. A.2. Cross section along transect N-S of *Raheenmore Bog*. Levels in metres above Ordnance Datum (m OD). Estimated levels are indicated by a "?".

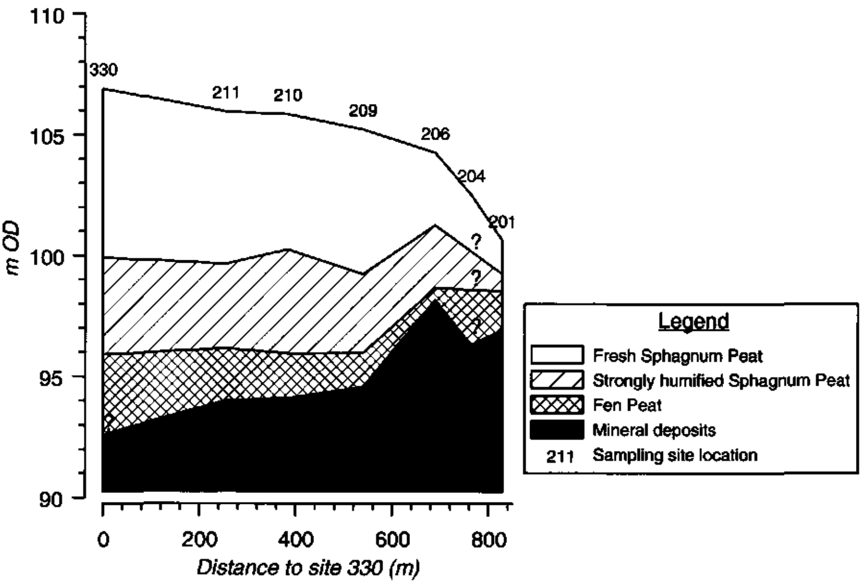

Fig. A.3. Cross section along transect C-E of *Raheenmore Bog*. Estimated levels are indicated by "?".

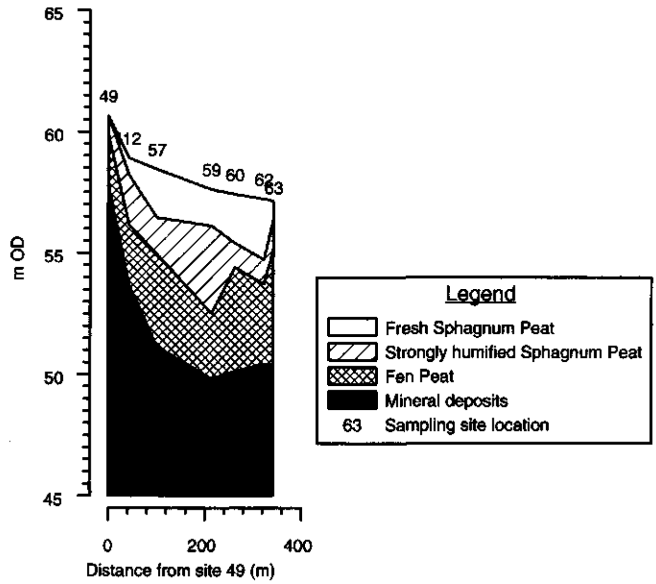

Fig. A.4. Cross section along transect A'-A of *Clara Bog West.*

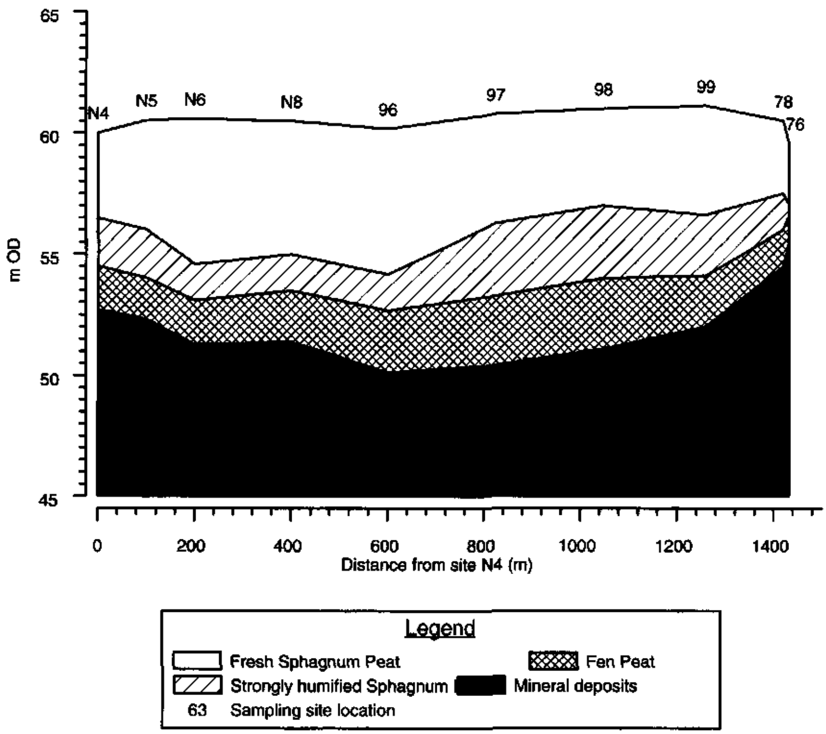

Fig. A.5. Cross section along transect N-SW of *Clara Bog West.*

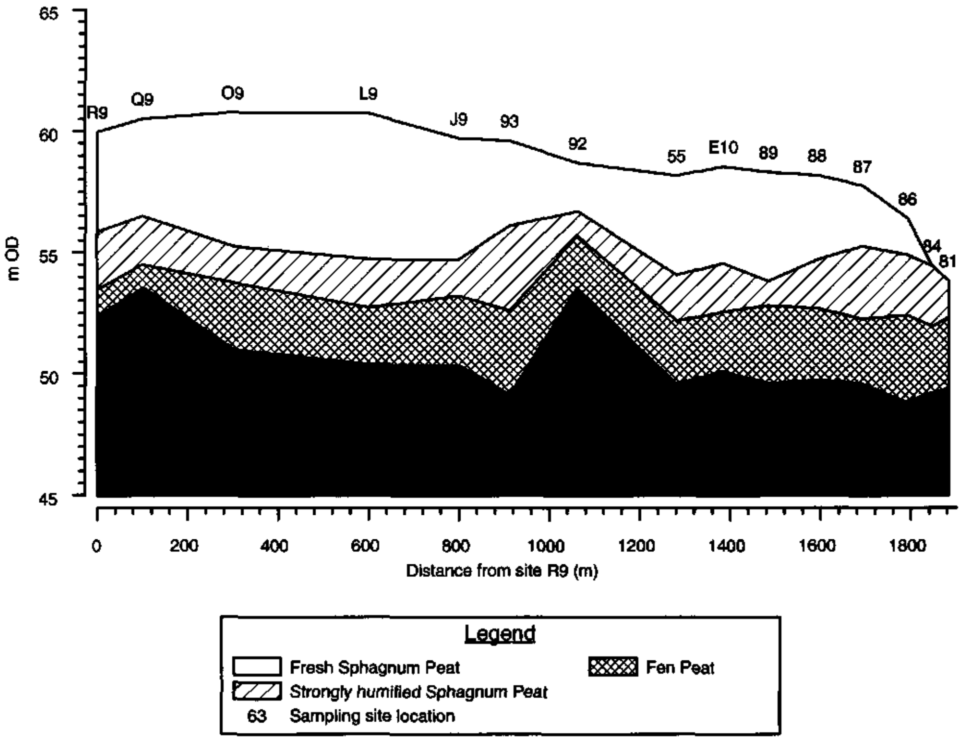

Fig. A.6. Cross section along transect W-E of *Clara Bog West.*

A.3. Humification profiles

The humification profiles show humification values according to Von Post at depth intervals of approximately 0.5 m and the transitions from FSP to HSP, HSP to FP and FP to underlying mineral deposits, which usually consist of lake marl, glacio-lacustrine clay deposits or till (Bloetjes and Van der Meer, 1992). They are given in figs. A.7 through A.11 in the same order as the cross sections in A.2.

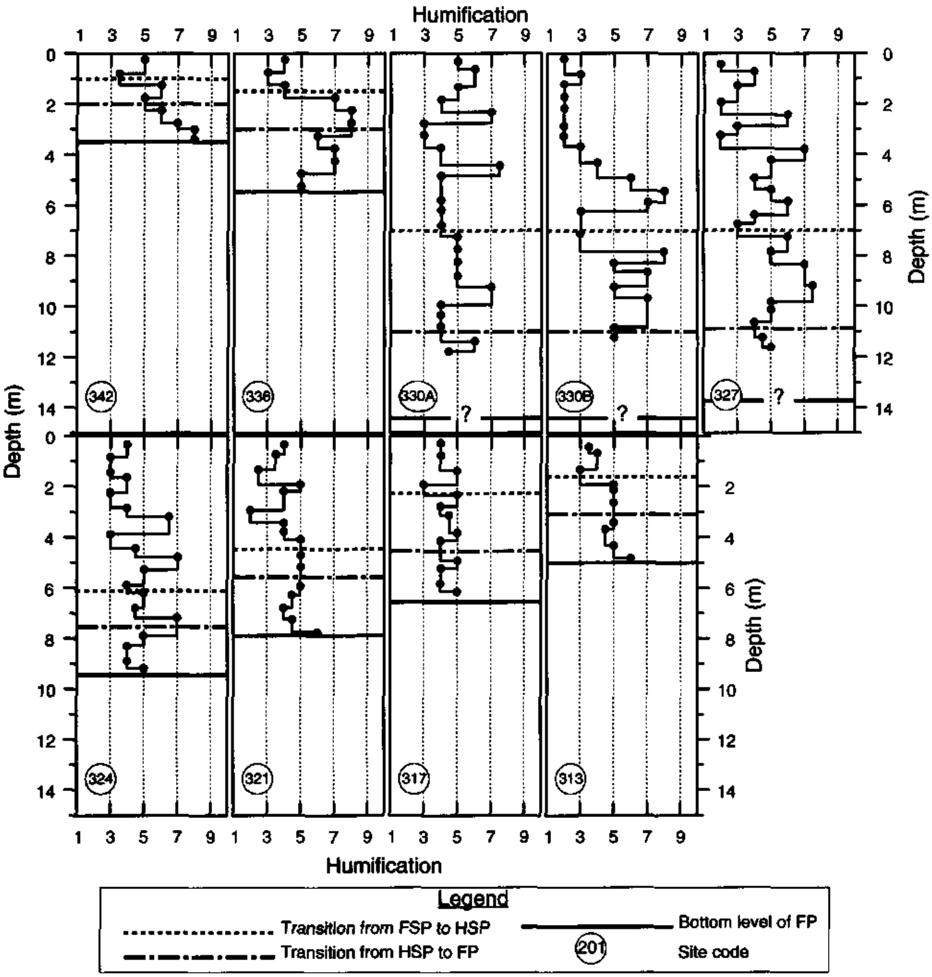

Fig. A.7. Profiles of humification *H* along transect N-S, *Raheenmore Bog*.

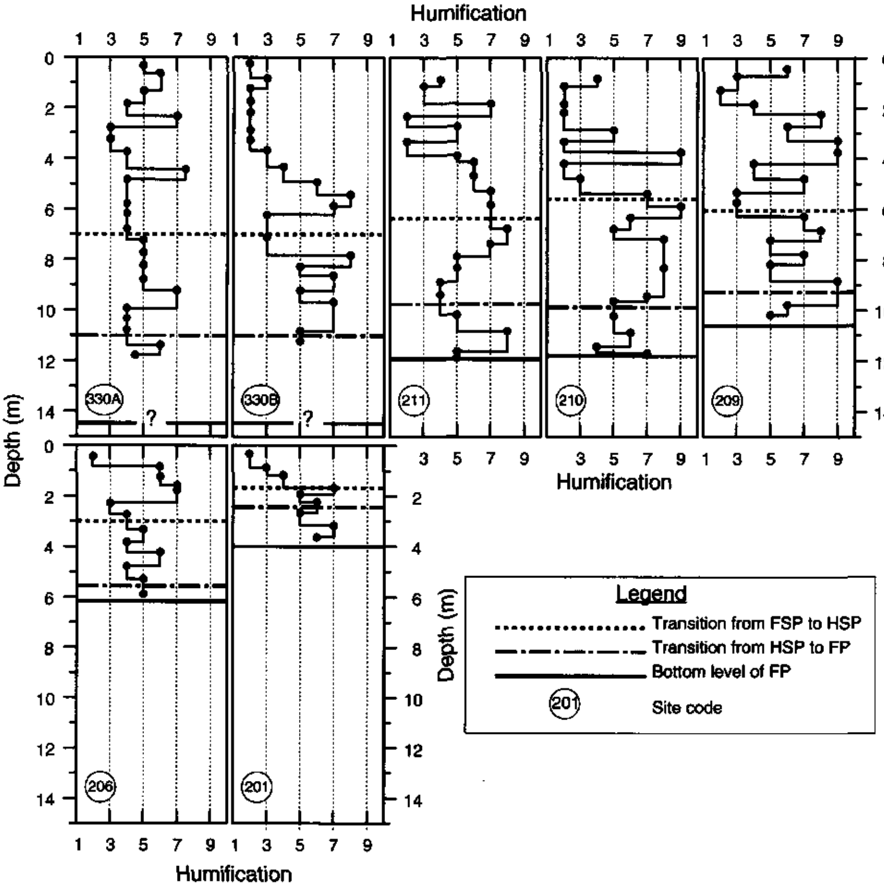

Fig. A.8. Profiles of humification *H* along transect C-E, *Raheenmore Bog*.

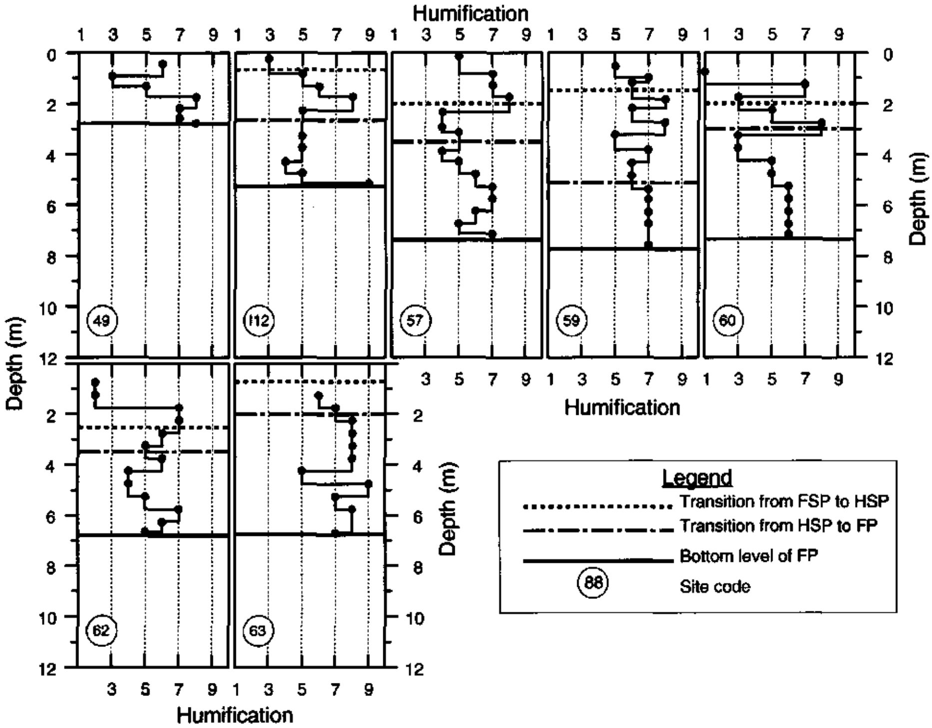

Fig. A.9. Profiles of humification *H* along transect A-A', *Clara Bog West.*

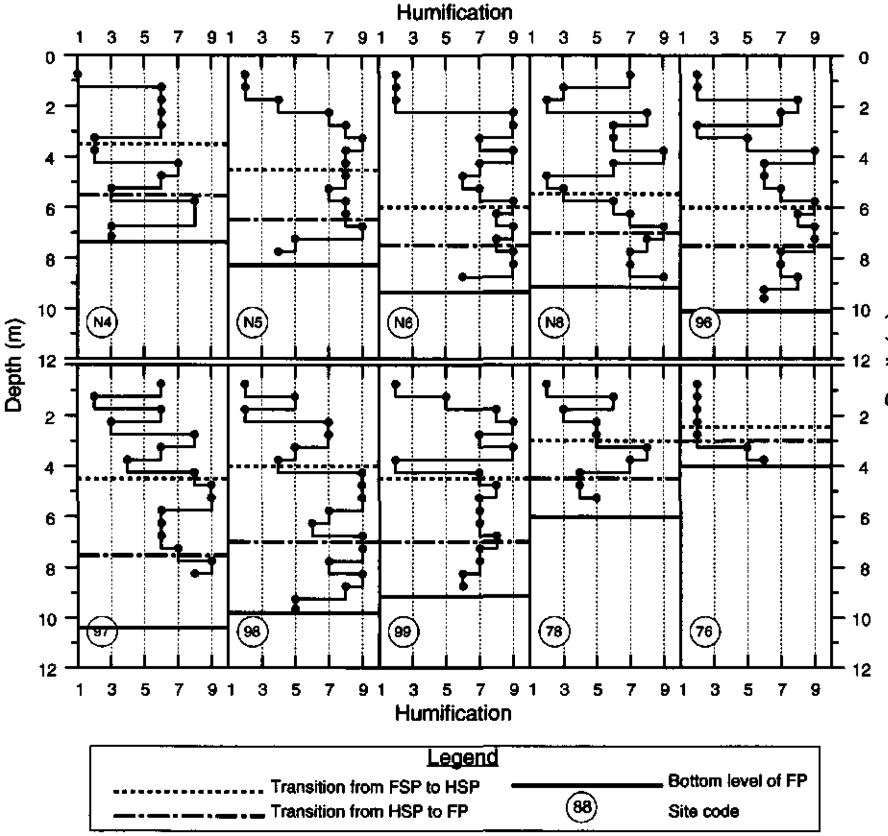

Fig A.10. Profiles of humification *H* along transect N-SW, *Clara Bog West*.

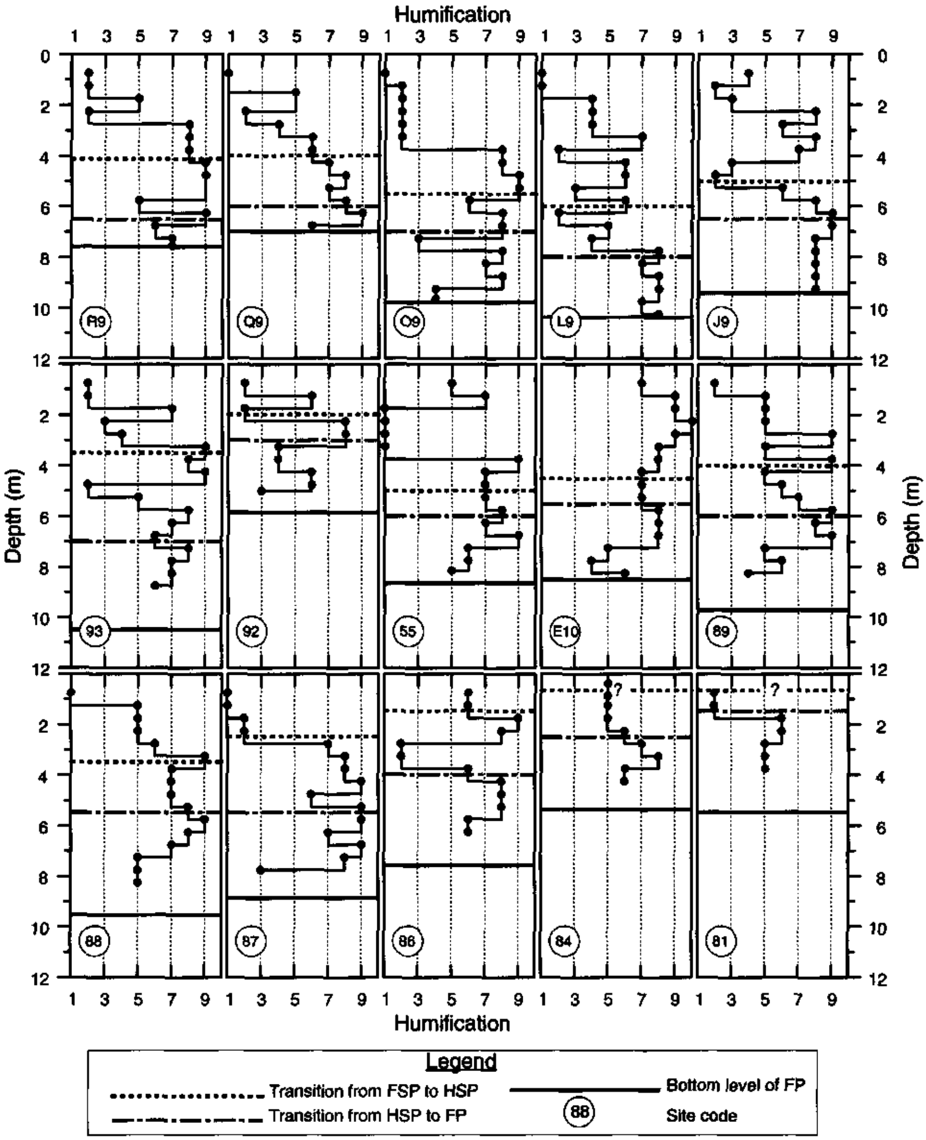

Fig. A.11. Profiles of humification *H* along transect W-E, *Clara Bog West*.

A.4. Profiles of volume fraction of solid matter

The profiles in figs. 12 through 16 show volume fractions of solid matter for the same profiles and mostly at the same depths as in the previous section. The transition depths from FSP to HSP, HSP to FP and FP to underlying mineral deposits are shown as in section A.2.

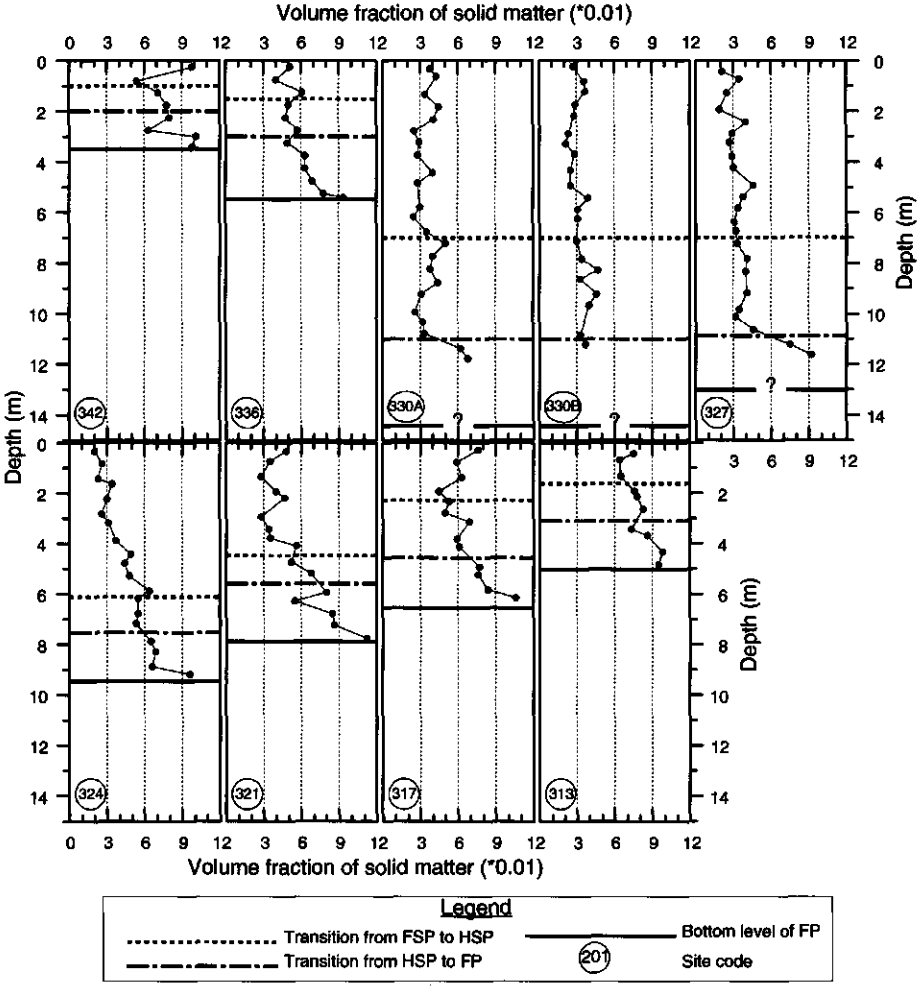

Fig. A.12. Volume fraction of solid matter ϕ_o along transect N-S, *Raheenmore Bog.*

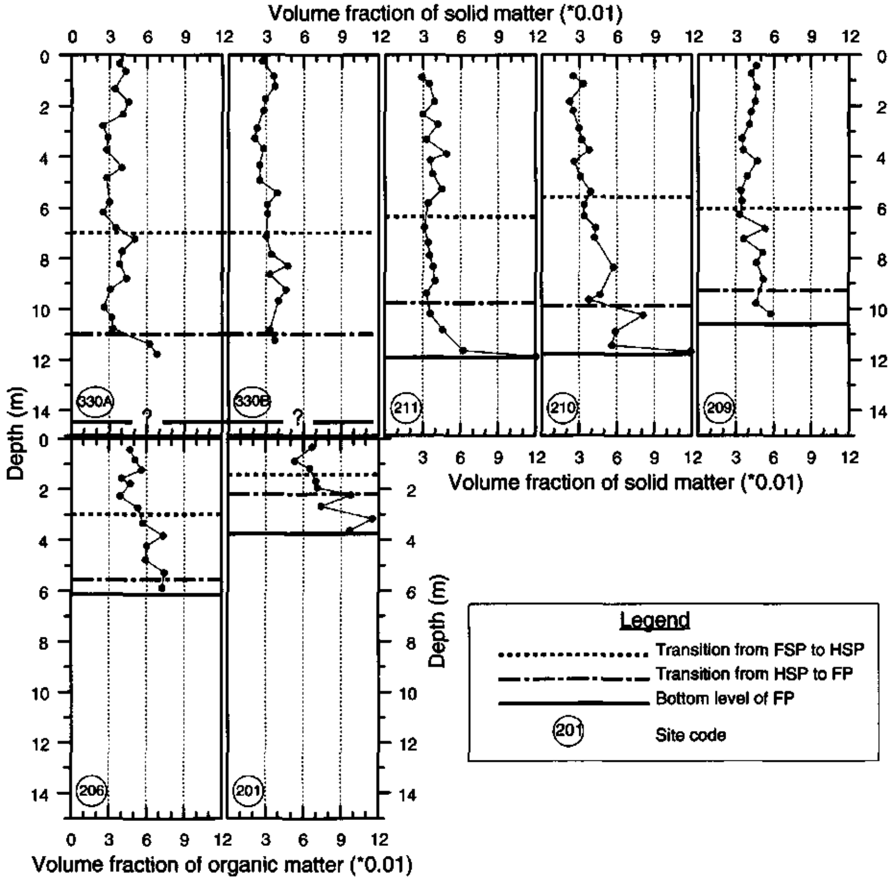

Fig. A.13. Volume fraction of solid matter ϕ_0 along transect C-E, *Raheenmore Bog*.

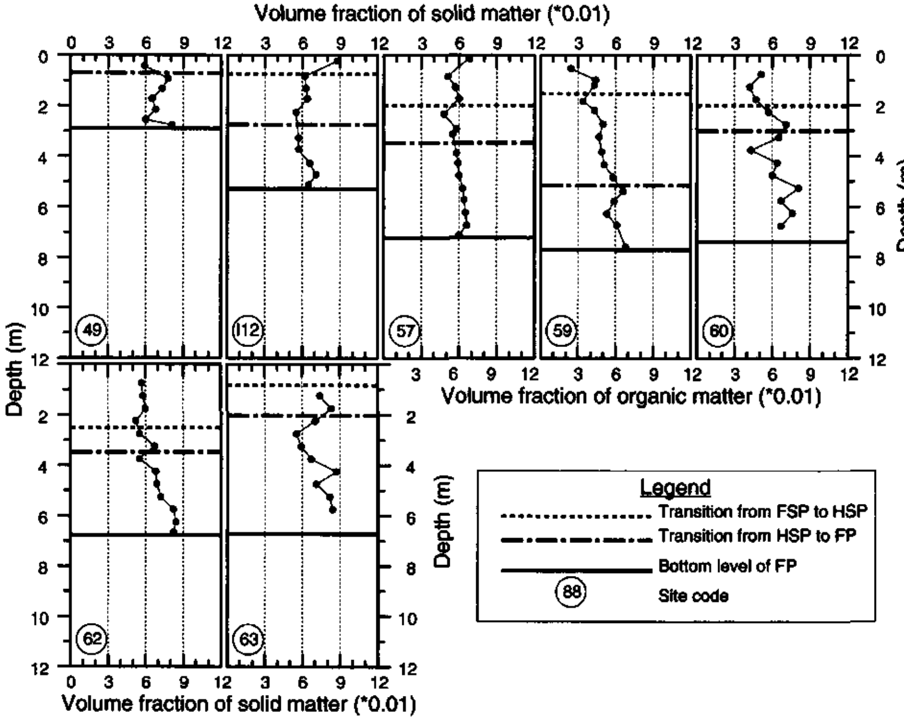

Fig. A.14. Volume fraction of solid matter ϕ_0 along transect A'-A, *Clara Bog West.*

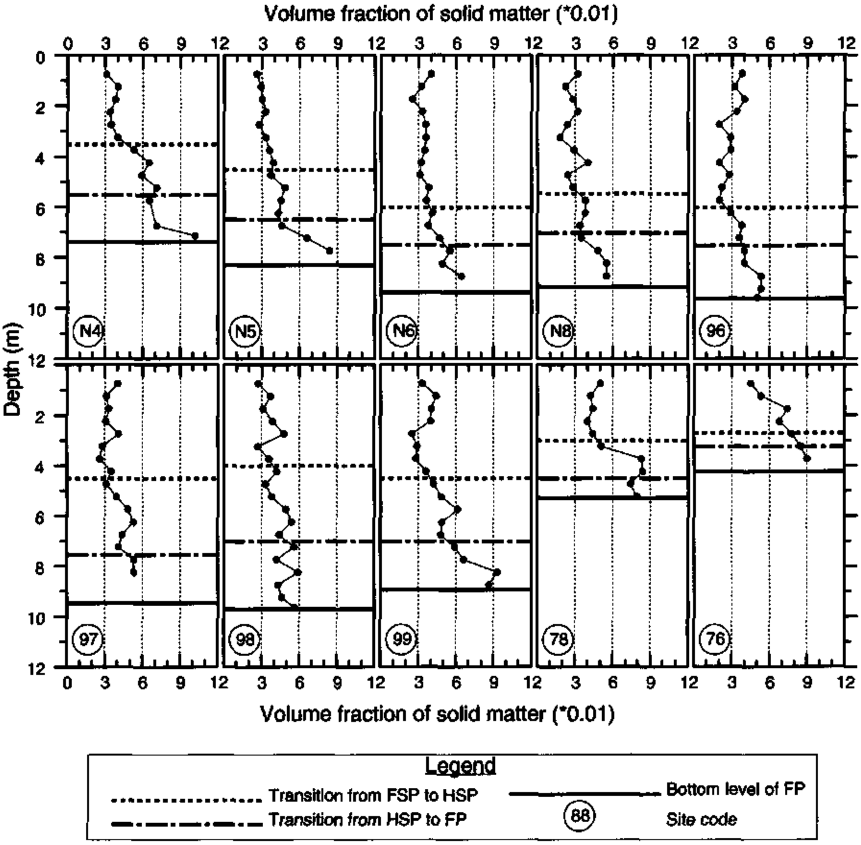

Fig. A.15. Volume fraction of solid matter ϕ_0 along transect N-SW, *Clara Bog West.*

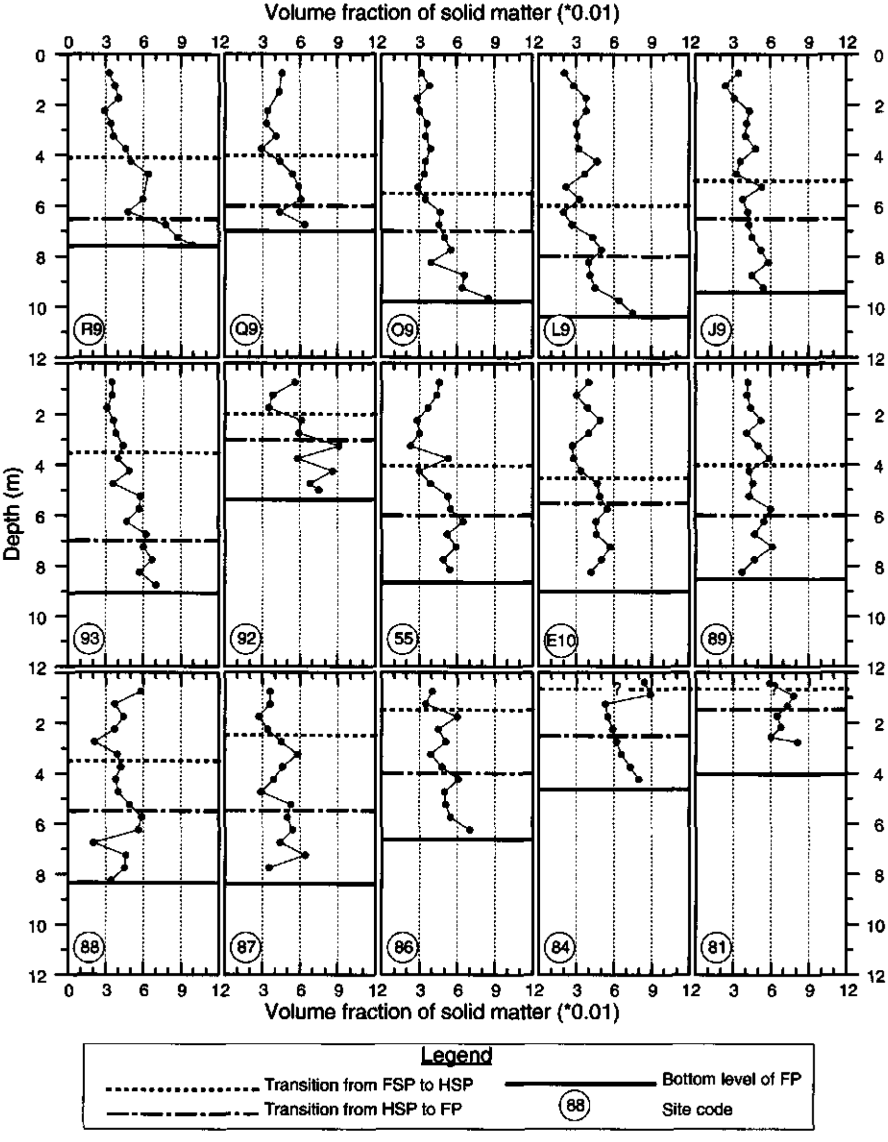

Fig. A.16. Volume fraction of solid matter ϕ_0 along transect W-E, *Clara Bog West*.

A.5. Average ϕ_0 and correlation of ϕ_0 and H with depth at individual sites

The tables have been arranged per transect. They show for each profile

- the site code;
- whether the site was classified as a margin site (M) or as one of the central area (C);
- the profile depth D in m;
- the number of samples n;
- Spearman's rank correlation coefficient $r_S(H,d)$ of H and depth, uncorrected for ties
- the average of ϕ_0 ($\bar{\phi}_o$);
- the correlation coefficient $r(\phi_0,d)$ of ϕ_0 and depth.

Table A.1. Average volume fraction of solid matter ϕ_o and correlation coefficient of ϕ_o and depth d for transect N-S, *Raheenmore Bog.*

Site	M or C	D	n	$r_S(H,d)$	$\bar{\phi}_o$	$r(\phi_0,d)$
342	M	3.50	8	0.90	0.080	0.29
336	M	5.50	12	0.18	0.060	0.80
330A	C	12.75?	23	-0.02	0.037	0.29
330B	C	12.75?	21	0.69	0.032	0.50
327	C	13.80?	23	0.42	0.038	0.66
324	C	9.25	19	0.47	0.047	0.93
321	C	7.80	16	0.62	0.056	0.83
317	M	6.50	13	0.18	0.068	0.62
313	M	5.00	10	0.77	0.079	0.84

Table A.2. Average volume fraction of solid matter ϕ_o and correlation coefficient of ϕ_o and depth d for transect C-E, *Raheenmore Bog.*

Site	M or C	D	n	$r_S(H,d)$	$\bar{\phi}_o$	$r(\phi_0,d)$
330A	C	12.75?	23	-0.02	0.037	0.29
330B	C	12.75?	21	0.69	0.032	0.50
211	C	11.95	21	0.16	0.042	0.49
210	C	11.75	21	0.49	0.043	0.76
209	M	10.65	20	0.18	0.043	0.35
206	M	6.10	13	-0.18	0.056	0.78
201	M	3.70	9	0.69	0.079	0.80

Table A.3. Average volume fraction of solid matter ϕ_o and correlation coefficient of ϕ_o and depth d for transect A'-A, SW of Shanley's Lough, *Clara Bog West*.

Site	M or C	D	n	$r_S(H,d)$	$\bar{\phi}_o$	$r(\phi_o,d)$
49	M	2.85	7	0.69	0.069	0.20
I12	M	5.20	10	0.19	0.065	-0.28
57	M	7.30	15	0.06	0.059	0.41
59	C	7.80	15	0.10	0.050	0.88
60	C	7.30	13	0.23	0.064	0.68
62	C	6.80	13	0.17	0.061	0.87
63	M	6.70	10	0.14	0.073	0.32

Table A.4. Average volume fraction of solid matter ϕ_o and correlation coefficient of ϕ_o and depth d for transect W-E, *Clara Bog West*.

Site	M or C	D	n	$r_S(H,d)$	$\bar{\phi}_o$	$r(\phi_o,d)$
R9	M	7.60	14	0.51	0.053	0.88
Q9	C	7.00	12	0.78	0.046	0.61
O9	C	9.80	19	0.54	0.043	0.79
L9	C	10.50	20	0.71	0.038	0.65
J9	C	9.40	18	0.52	0.042	0.71
93	C	9.30	17	0.32	0.048	0.90
92	M	5.20	10	0.15	0.063	0.67
55	C	8.65	16	0.39	0.045	0.61
E10	C	8.50	16	-0.64	0.042	0.54
89	C	8.75	16	0.33	0.048	0.23
88	C	8.60	16	0.17	0.042	0.01
87	C	8.20	15	0.62	0.043	0.47
86	M	7.60	12	-0.02	0.050	0.63
84	M	5.30	9	0.74	0.069	-0.08
81	M	4.50	7	0.26	0.074	-0.58

Table A.5. Average volume fraction of solid matter ϕ_o and correlation coefficient of ϕ_o and depth d for transect N-SW, *Clara Bog West*.

Site	M or C	D	n	$r_S(H,d)$	$\overline{\Phi}_o$	$r(\phi_o,d)$
N4	M	7.30	13	0.16	0.054	0.92
N5	C	8.20	15	0.35	0.041	0.86
N6	C	9.30	17	0.48	0.039	0.76
N8	C	9.10	17	0.42	0.034	0.76
96	C	10.05	19	0.33	0.034	0.54
97	C	10.35	16	0.51	0.039	0.69
98	C	9.90	19	0.40	0.042	0.70
99	C	9.10	17	-0.13	0.049	0.80
78	M	6.00	10	0.14	0.059	0.82
76	M	4.00	7	0.80	0.070	0.95

B. Hydraulic conductivity transects

B.1. Transect positions

For Raheenmore Bog, one transect was worked out. It consists of the C-E transect shown in fig. I.1 of Appendix I and the southern half of the N-S transect, shown in the same figure. For Clara Bog West, a transect from SW to E was composed of the southwestern half of the N-SW transect, the eastern part of the W-E transect and some connecting sites in between. A small transect, running from site 901, N of Shanley's Lough, to site 57 in transect A'-A, also shown in fig. B.1, lies approximately perpendicular to it. The positions of the transects and the sites included in them is shown if fig. B.1 below.

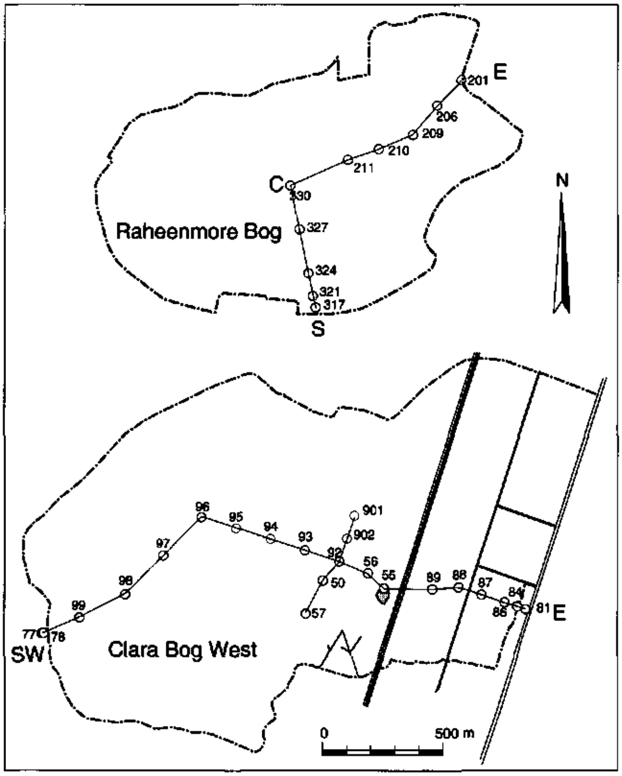

Fig. B.1. Positions of the *k*-transects.

B.2. *k*-profiles

The profiles show $\log_{10}\frac{k}{\mathrm{m\,d^{-1}}}$ versus depth below the surface. Fig. B.1 shows the Raheenmore transect, fig. B.2 the large SW-E transect of Clara Bog West and fig. B.3 the small transect 901-50 that is approximately perpendicular to it.

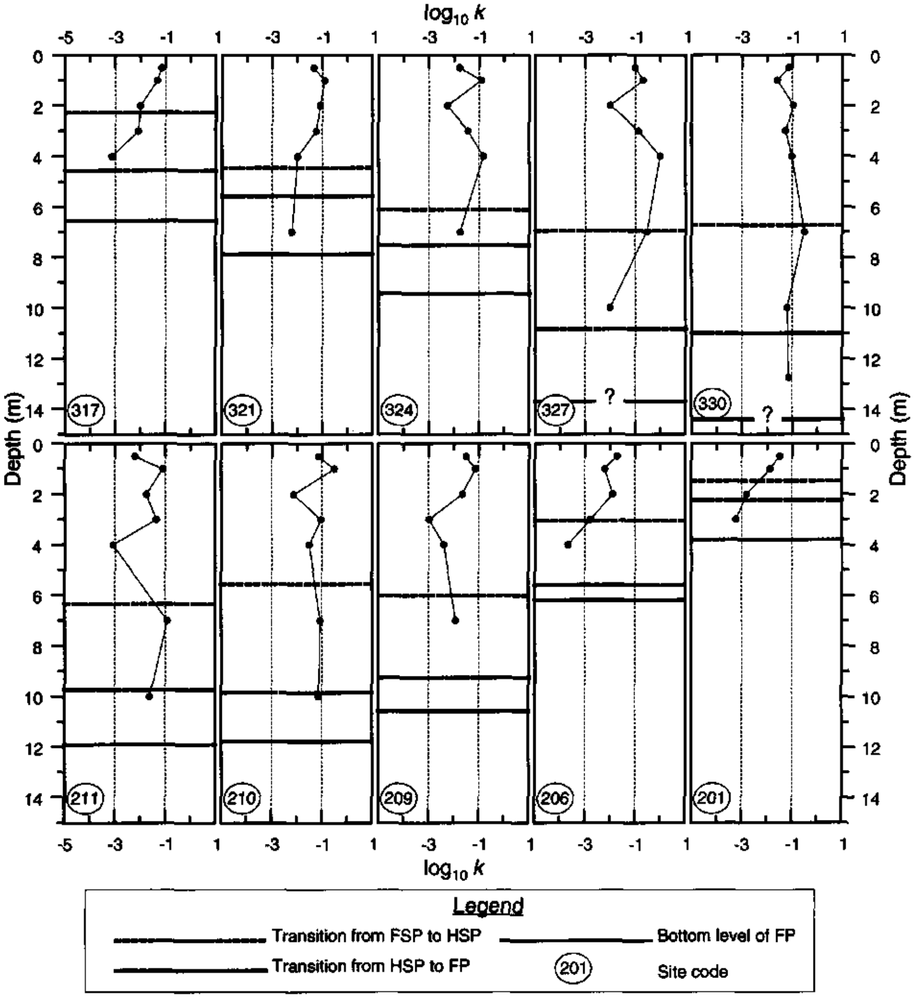

Fig. B.2. Profiles of hydraulic conductivity *k*, expressed as $\log_{10} k$ (*k* in m d^{-1}) along transect S-C-E, *Raheenmore Bog*.

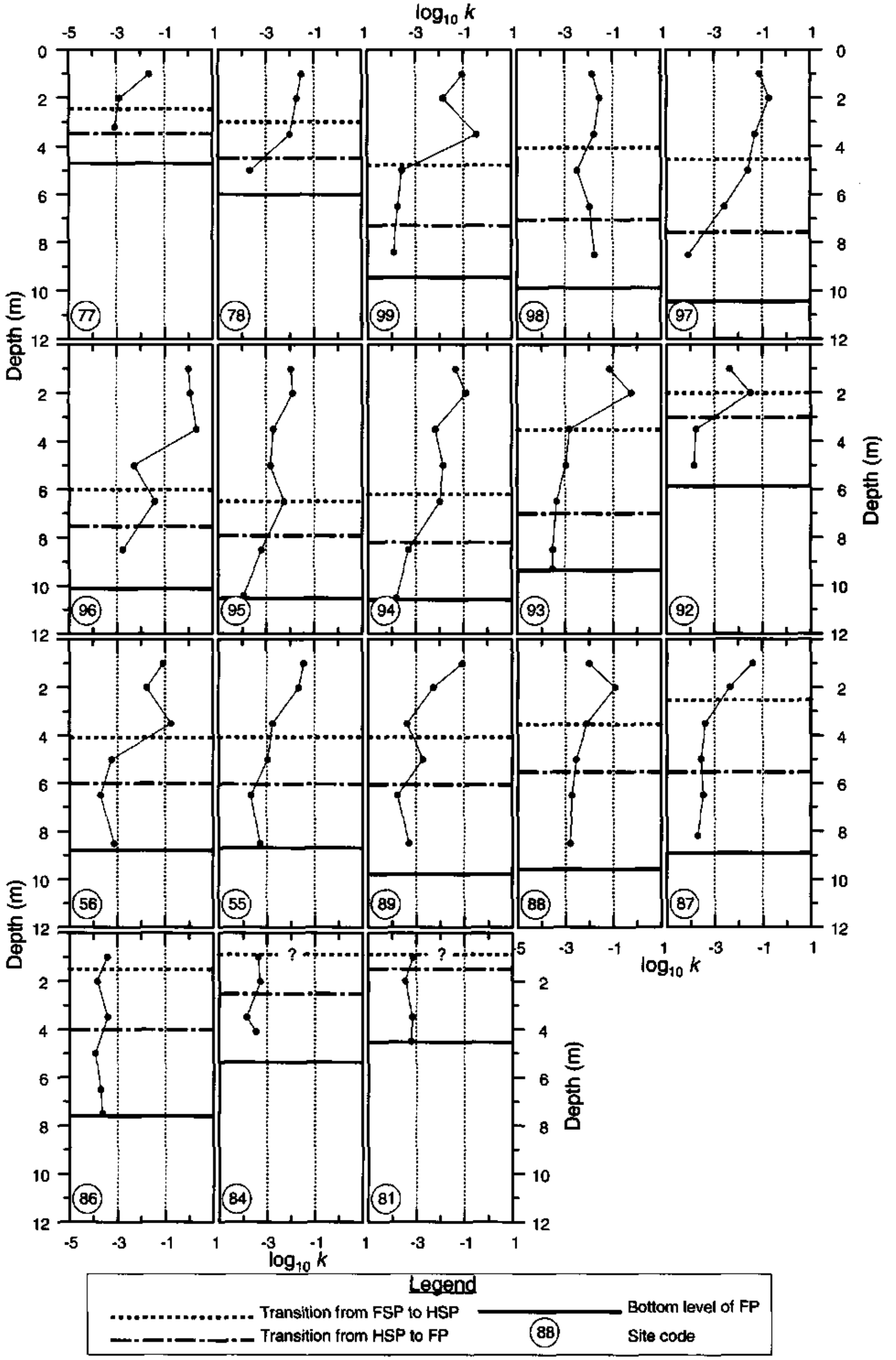

Fig. B.3. Profiles of hydraulic conductivity k, expressed as $\log_{10} k$ (k in m d^{-1}), along transect SW-E, *Clara West*.

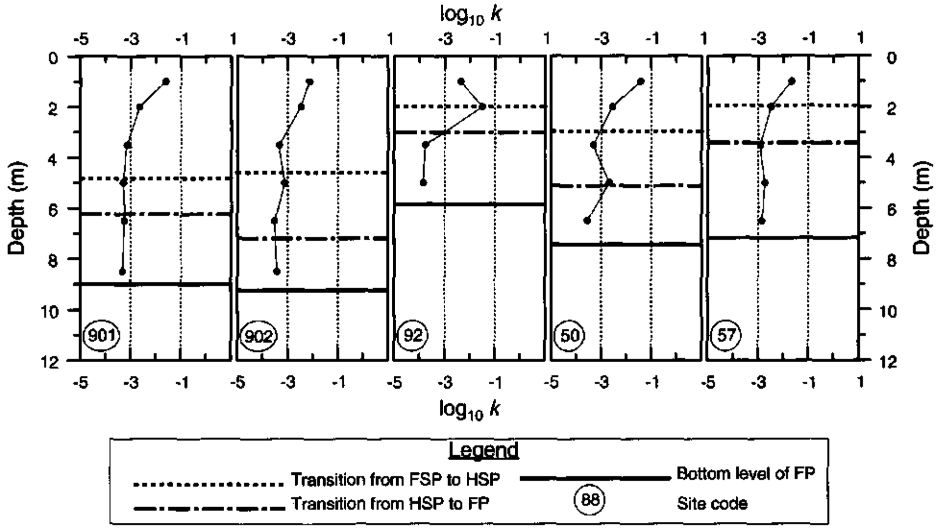

Fig. B.4. Profiles of hydraulic conductivity, expressed as $\log_{10} k$ (k in m d^{-1}) along transect 901-57, *Clara Bog West*.

B.3. Geometric mean of *k* and correlation of *k* with depth at individual sites

Tables B.1 through B.3 show for each individual profile

- site code;
- profile depth D in m;
- whether a profile is a margin or a centre site;
- number of tests per profile n;
- geometric mean of k in m d^{-1};
- correlation coefficient of $\log_{10} k$ and measuring depth d.

Table B.1. Geometric means of k, number of measurements n and correlation coefficient of $\log_{10} k$ (k expressed in m d^{-1}) and depth d for transect S-C-E, *Raheenmore Bog*.

Site	Margin or Centre	D	n	geometric mean of k (m d^{-1})	$r(\log_{10} k, d)$
317	Margin	6.50	5	$1.1*10^{-2}$	-0.97
321	Centre	7.80	6	$3.4*10^{-2}$	-0.86
324	Centre	9.25	6	$3.2*10^{-2}$	-0.02
327	Centre	13.80 (?)	7	$9.5*10^{-2}$	-0.24
330	Centre	12.75 (?)	7	$7.9*10^{-2}$	0.38
211	Centre	11.95	7	$1.9*10^{-2}$	0.16
210	Centre	11.75	7	$6.0*10^{-2}$	0.02
209	Margin	10.65	6	$1.2*10^{-2}$	-0.33
206	Margin	6.10	5	$3.5*10^{-3}$	-0.91
201	Margin	3.70	4	$4.5*10^{-3}$	-0.99

Table B.2. Geometric means of k, number of measurements n and correlation coefficient of $\log_{10} k$ (k expressed in m d^{-1}) and depth d for transect SW-E, *Clara Bog*.

Site	Margin or Centre	D	n	geometric mean of k (m d^{-1})	$r(\log_{10} k, d)$
77	Margin	5.00	3	$3.0*10^{-3}$	-0.90
78	Margin	6.00	4	$6.0*10^{-3}$	-0.91
99	Centre	9.10	6	$3.8*10^{-3}$	-0.82
98	Centre	9.90	6	$1.3*10^{-2}$	-0.25
97	Centre	10.35	6	$1.3*10^{-2}$	-0.93
96	Centre	10.05	6	$9.9*10^{-2}$	-0.86
95	Centre	10.40	7	$2.9*10^{-3}$	-0.88
94	Centre	10.50	7	$6.4*10^{-3}$	-0.93
93	Centre	9.30	7	$3.2*10^{-3}$	-0.85
92	Margin	5.20	4	$1.3*10^{-3}$	-0.80
56	Centre	8.65	6	$5.2*10^{-3}$	-0.79
55	Centre	8.65	6	$2.4*10^{-3}$	-0.89
89	Centre	8.75	6	$1.8*10^{-3}$	-0.78
88	Centre	8.60	6	$6.5*10^{-3}$	-0.77
87	Centre	8.20	6	$1.0*10^{-3}$	-0.86
86	Margin	7.65	6	$2.2*10^{-4}$	-0.28
84	Margin	5.35	4	$3.3*10^{-4}$	-0.58
81	Margin	4.50	4	$5.8*10^{-4}$	0.10

Table B.3. Geometric means of k, number of measurements n and correlation coefficient of $\log_{10} k$ (k expressed in m d^{-1}) and depth d for transect 901-57, *Clara Bog*.

Site	Margin or Centre	D	n	geometric mean of k (m d^{-1})	$r(\log_{10} k, d)$
901	Centre	9.00	6	$1.3*10^{-3}$	-0.80
902	Centre	9.15	6	$9.5*10^{-4}$	-0.85
92	Margin	5.20	4	$1.3*10^{-3}$	-0.80
50	Centre	7.40	5	$2.0*10^{-3}$	-0.81
57	Margin	7.30	5	$2.9*10^{-3}$	-0.77

C. Vertical resistance and vertical flow in the catotelm

C.1. Site positions

The vertical flow rate U_{vc} in the catotelm was calculated for individual sites where vertical resistance values from k-measurements, measurements of ϕ_0 or both were available. Fig. C.1 shows the positions on both bogs.

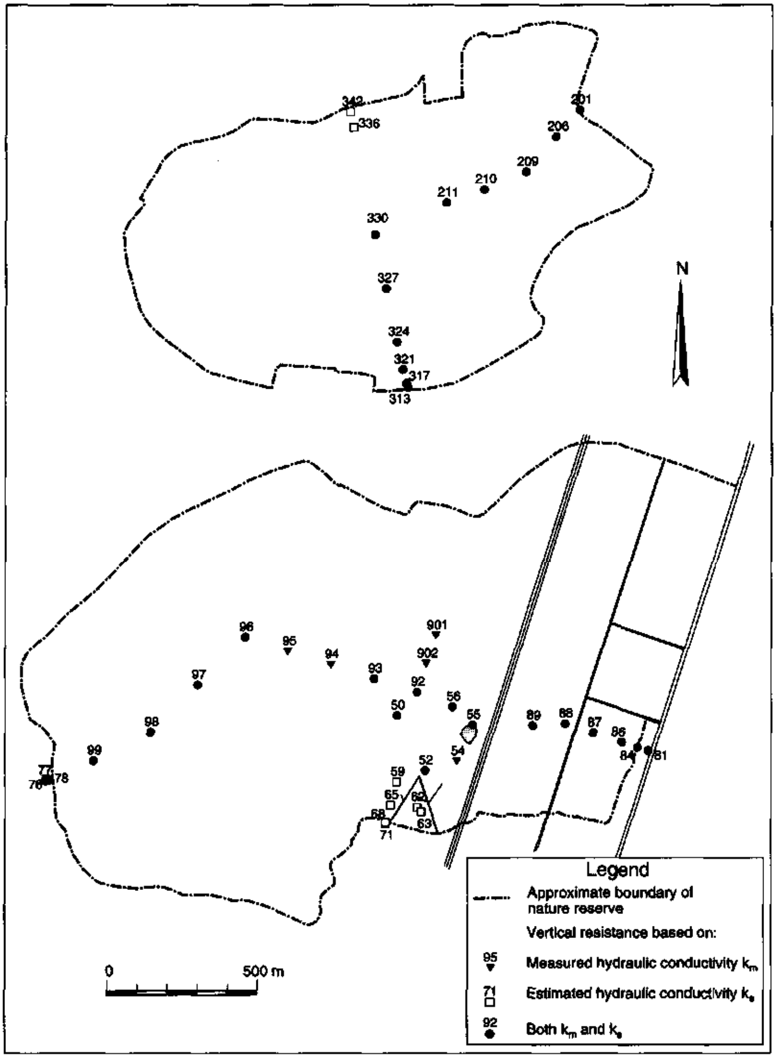

Fig. C.1. Positions of the sites for which vertical catotelm flow was calculated.

C.2. Results

The results are presented in two tables, C.1 and C.2. Table C.1 shows the results for Raheenmore Bog, Table C.2 for Clara Bog.

Table C. 1. Calculation of vertical flow rate U_{vc} through the catotelm of *Raheenmore Bog*, based on vertical resistance of the catotem C_c, calculated from volume fraction of solid matter ϕ_o and measured hydraulic conductivities k. Calculation of applied C_c from ϕ_o according to Eqs. (5.27) and (5.28). Negative values of U_{vc} indicate a loss (exfiltration into the subjacent mineral deposits).

Site	Surface level (m OD) & Total peat depth (m)	Filter depth (m)	Mean hydraulic head Jan. 1991-Jan. 1992 (m OD) n=27	C_c (days) between surface and filter, based on			C_c applied (days)	U_{vc} (mm a^{-1}), calculated over depth from	
				ϕ_o	k	ϕ_o and k		Surface	Next higher piezometer
201	100.34	phreatic	99.972						
		1.50	99.782			410	410	-170	
		3.00	99.119			7200	7200	-43	-35
	3.70	3.60	99.074			13000	13000	-24	-3
206	103.97	phreatic	103.904						
		3.00	103.810			500	500	-65	
		4.50	103.744			2900	2900	-20	-10
	6.10	6.00	103.748			4400	4400	-14	-3
209	104.95	phreatic	104.924						
		3.00	104.887			610	610	-22	
		4.50	104.858			760	760	-32	-72
		6.00	104.854			800	800	-32	-40
	10.65	13.70	104.740			1300	1300	-53	-86
210	105.57	phreatic	105.558						
		3.00	105.544			100	100	-50	
		4.50	105.546			140	140	-31	+21
	11.75	6.00	105.544			170	170	-30	-25
211	105.73	pheatic	105.781						
		3.00	105.759			190	190	-43	
		4.50	105.702			690	690	-41	-41
		6.00	105.659			760	760	-59	-260
	11.95	12.30	104.831			42000	42000	-8	-7
313	105.05	phreatic	104.385						
		2.00	104.277			1300	1300	-29	
		2.70	104.236			5100	5100	-11	-4
	5.00	3.75	104.217			18000	18000	-3	-1

Table C. 1. Calculation of vertical flow rate U_{vc} through the catotelm of ***Raheenmore Bog***, based on vertical resistance of the catotem C_c, calculated from volume fraction of solid matter ϕ_o and measured hydraulic conductivities k. Calculation of applied C_c from ϕ_o according to Eqs. (5.27) and (5.28). Negative values of U_{vc} indicate a loss (exfiltration into the subjacent mineral deposits).

Site	Surface level (m OD) & Total peat depth (m)	Filter depth (m)	Mean hydraulic head Jan. 1991-Jan. 1992 (m OD) n=27	C_c (days) between surface and filter, based on			Applied C_c (days)	U_e (mm a^{-1}), calculated over depth from	
				ϕ_o	k	ϕ_o and k		Surface	Next higher piezometer
317	105.94	phreatic	105.815						
		2.00	105.712			1100	1100	-34	
		3.40	105.479			1300	1300	-98	-540
	6.50	4.75	105.413			2700	2700	-54	-16
321	106.71	phreatic	106.572						
		2.00	106.544			50	50	-200	
		3.50	106.510			88	88	-260	-330
		5.00	106.186			420	420	-330	-350
	7.80	7.60	105.617			12000	12000	-28	-18
324	106.59	phreatic	106.599						
		1.80	106.560			56	56	-260	
		3.30	106.546			210	210	-94	-34
		4.80	106.399			270	272	-270	-820
	9.25	9.25	105.117			11000	11000	-49	-43
327	106.63	phreatic	106.647						
		2.00	106.634			72	72	-66	
		3.30	106.624			98	98	-84	-140
		5.00	106.614			150	150	-77	-65
	13.60?	13.60	103.573			70000	70000	-16	-16
330	106.65	phreatic	106.672						
		2.00	106.656			53	53	-59	
		3.50	106.653			89	89	-47	-28
		5.00	106.630			120	120	-110	-330
		12.00	105.895			1036	1036	-270	-290
	14.30?	14.30	104.084			1041	1041	-910	-135000
336	106.10	phreatic	106.029						
		2.00	105.983	320			390	-43	
		3.50	105.650	550			670	-210	-430
		4.90	105.432	1500			2000	-110	-61
	5.50	5.00	105.383	2000			2600	-90	-28
342	105.16	phreatic	105.066						
		2.00	104.971	11100			19000	-2	
	3.50	2.90	104.814	13000			21000	-5	-29

Table C. 2. Calculation vertical flow rate U_{vc} through the catotelm of *Clara Bog West*, based on vertical resistance of the catotem C_c, calculated from volume fraction of solid matter ϕ_0 and/or measured hydraulic conductivities k. Calculation of applied C_c according to Eqs. (5.31) through (5.33). Negative values of U_{vc} indicate a loss (seepage from the catotelm into the subjacent mineral deposits).

Site	Surface level (m OD) & Total peat depth (m)	Filter depth (m)	Mean hydraulic head Jan. 1992-Jan. 1993 (m OD) n=27	C_c (days) between surface and filter, based on			Applied C_c (days)	U_e (mm a^{-1}), calculated over depth from	
				ϕ_0	k	ϕ_0 and k		Surface	Next higher piezometer
50	58.47	phreatic	58.471						
	7.40	7.50	57.753			33000	33000	-8	
52	57.82	phreatic	57.833						
	8.10	9.57	57.451			10000	10000	-14	
54	57.81	phreatic	57.808						
		2.35	57.668		220		180	-290	
		4.35	57.426		850		1000	-140	-110
	8.65	8.65	57.350		14000		14000	-12	-2
55	58.19	phreatic	58.203						
	8.65	13.30	57.648			8100	8100	-25	
56	58.42	phreatic	58.446						
		4.50	58.254			600	600	-120	
	8.65	9.30	58.070			7900	7900	-18	-9
57	58.44	phreatic	58.352						
		3.00	58.192			6700	6700	-9	
		4.50	58.157			8800	8800	-8	-6
	7.30	5.75	58.142			12000	12000	-6	-2
59	57.61	phreatic	57.619						
		3.00	57.272	390			600	-210	
		4.50	57.103	930			1300	-140	-84
	7.85	6.00	57.036	5500			6600	-32	-5
63	57.13	phreatic	57.153						
		1.50	56.882	38000			29000	-3	
		3.00	56.485	100000			76000	-3	-3
	6.70	4.50	55.875	220000			160000	-3	-3
65	57.58	phreatic	57.324						
		3.00	56.793	4300			4800	-40	
		4.50	56.652	31000			29000	-9	-2
	6.10	5.70	56.550	70000			60000	-5	-1
68	57.46	phreatic	56.644						
		1.50	56.315	750			970	-120	
		2.90	54.999	8400			8700	-69	-62
	6.10	3.95	54.946	56000			47000	-13	-1

Table C. 2. Calculation vertical flow rate U_{vc} through the catotelm of *Clara Bog West*, based on vertical resistance of the catotem C_c, calculated from volume fraction of solid matter ϕ_o and/or measured hydraulic conductivities k. Calculation of applied C_c according to Eqs. (5.31) through (5.33). Negative values of U_{vc} indicate a loss (seepage from the catotelm into the subjacent mineral deposits).

Site	Surface level (m OD) & Total peat depth (m)	Filter depth (m)	Mean hydraulic head Jan. 1992-Jan. 1993 (m OD) n=27	C_c (days) between surface and filter, based on			Applied C_c (days)	U_e (mm a^{-1}), calculated over depth from	
				ϕ_o	k	ϕ_o and k		Surface	Next higher piezometer
71	75.38	phreatic	(unreliable)						
		1.50	55.413	56000			41000		
	5.00	3.00	54.640	930000			520000		-1
76	59.75	phreatic	58.940						
		1.50	58.700			600	600	-140	
	4.00	3.00	58.055			50800	50800	-6	-5
77	60.26	phreatic	59.670						
		1.50	59.488		400		500	-150	
	5.00	3.00	59.105		1800		3800	-55	-39
78	60.50	phreatic	60.261						
		1.50	60.084			400	400	-170	
	6.00	3.00	60.016			700	700	-120	-72
81	53.84	phreatic	53.140						
	4.50	5.25	53.171			86000	86000	+0.1	
84	54.46	phreatic	53.916						
		4.50	53.967			11000	11000	+2	
	5.35	5.10	53.972			15000	15000	+1	+0.4
86	56.42	phreatic	56.303						
		4.50	56.203			9400	9400	-4	
	7.65	7.45	56.055			25000	25000	-4	-3
87	57.77	phreatic	57.794						
		4.50	57.579			2100	2100	-37	
	8.20	8.65	57.430			9000	9000	-15	-8
88	58.20	phreatic	58.135						
		4.50	58.043			1500	1500	-22	
	8.60	9.40	57.984			4000	4000	-14	-9
89	58.33	phreatic	58.339						
		4.50	58.178			1700	1700	-35	
	8.75	9.60	58.037			9400	9400	-12	-7
92	58.72	phreatic	58.707						
		2.25	58.605			1100	1100	-35	
		4.50	57.710			300000	300000	-1	-1
	5.20	5.20	57.711			310000	310000	-1	0

Table C. 2. Calculation vertical flow rate U_{vc} through the catotelm of ***Clara Bog West***, based on vertical resistance of the catotem C_c, calculated from volume fraction of solid matter ϕ_o and/or measured hydraulic conductivities k. Calculation of applied C_c according to Eqs. (5.31) through (5.33). Negative values of U_{vc} indicate a loss (seepage from the catotelm into the subjacent mineral deposits).

Site	Surface level (m OD) & Total peat depth (m)	Filter depth (m)	Mean hydraulic head Jan. 1992-Jan. 1993 (m OD) n=27	C_c (days) between surface and filter, based on			Applied C_c (days)	U_e (mm a^{-1}), calculated over depth from	
				ϕ_o	k	ϕ_o and k		Surface	Next higher piezometer
93	59.62	phreatic	59.665						
		4.50	59.457			700	700	-120	
	9.30	10.78	58.592			10000	10000	-38	-33
94	60.12	phreatic	60.141						
		4.50	60.021		300		210	-210	
	10.50	11.20	59.144		11000		11000	-32	-28
95	60.53	phreatic	60.577						
		4.50	60.442		1000		1200	-40	
	10.40	11.35	59.804		14000		14000	-20	-18
96	60.71	phreatic	60.743						
		2.50	60.721			76	76	-100	
		4.50	60.720			87	87	-96	-51
	10.05	11.50	59.399			7300	7300	-68	-67
97	60.78	phreatic	60.735						
		4.50	60.650			180	180	-170	
	10.35	10.90	59.444			29000	29000	-17	-15
98	61.00	phreatic	60.973						
		4.50	60.896			360	360	-78	
	9.90	12.10	60.537			7200	7200	-22	-19
99	61.12	phreatic	61.079						
		4.50	60.990			120	120	-270	
	9.10	12.85	60.579			440000	440000	-0.4	-0.3
901	59.21	phreatic	59.219						
		2.25	59.187		400		430	-28	
		4.50	58.925		2700		5600	-19	-18
	9.00	6.00	58.690		12000		12000	-16	-14
902	59.01	phreatic	58.997						
		2.25	58.933		430		490	-50	
		4.50	58.593		3900		10000	-15	-14
	9.15	6.00	58.315		16000		16000	-15	-16

D. Fitted Parameters of acrotelm transmissivity models

D.1. Site positions

The positions of the sites with at least 5 measurements of the acrotelm transmissivity T_a are shown in Fig. D.1 (Raheenmore Bog) and Fig. D.2 (Clara Bog West).

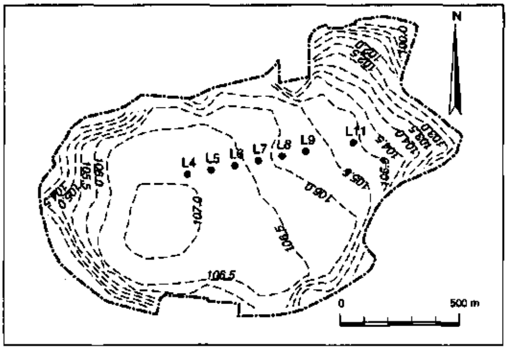

Fig. D.1. Positions of the sites on *Raheenmore Bog* where the acrotelm transmissivity was measured on 5 different dates from 13th April 1991 to 15th March 1992.

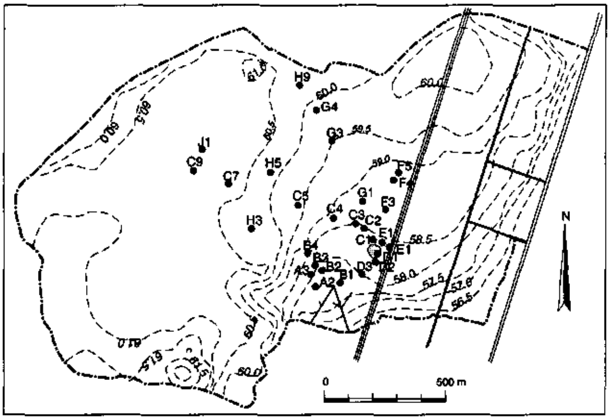

Fig. D.2. Positions of the sites on *Clara Bog* where the acrotelm transmissivity where the acrotelm transmissivity T_a was measured on at least five different dates between 4th November 1992 and 23rd March 1993.

D.2. Results

The results are presented in two tables, D.1 and D.2. Table D.1 shows the results for Raheenmore Bog, Table D.2 for Clara Bog.

Table D.1. Fitting results for the Ivanov model and the exponential model for sites with 5 measurements of the acrotelm transmissivity T_a on *Raheenmore Bog*. Measurements were done on five different dates during 1991/92.

Site	Range of phreatic level h (cm above surface)		Range of measured T_a (m^2d^{-1})		n	Ivanov model $\log_{10}\frac{T_a}{m^2d^{-1}} = \log_{10}\frac{8.64a_I(1-\frac{h}{cm})^{1-m_I}}{m_I-1}$			Exponential model $\log_{10}\frac{T_a}{m^2d^{-1}} = a_{exp} + b\frac{h}{cm}$		
	max.	min.	max.	min.		a_I	m_I	α_I	a_{exp}	b_{exp}	α_{exp}
L4	0	-11.0	21	0.4	5	3.9	2.43	0.0099	1.16	0.146	0.0089
L5	0	-11.0	930	43	5	58	2.53	0.15	2.45	0.194	0.079
L6	0	-6.3	69	7.0	5	5.3	1.82	0.10	1.73	0.143	0.041
L7	-7	-18.5	6.3	0.1	5	33700	5.41	0.0031	1.80	0.144	0.00011
L8	-5	-20.4	120	11	5	1540	3.00	0.019	2.55	0.074	0.0020
L9	-2	-17.5	1350	22	5	110	2.33	0.027	3.50	0.121	0.0011
L11	-2	-18.0	140	0.9	5	1990	3.82	0. 016	2.47	0.140	0.0037

Table D.2. Fitting results for the Ivanov model and the exponential model for sites with at least 5 measurements of the acrotelm transmissivity T_a on *Clara Bog West*. Measurements were done on different dates between 4th November 1992 and 23rd March 1993.

Site	Range of phreatic level *h* (cm above surface)		Range of measured T_a (m^2d^{-1})		*n*	Ivanov model $\log_{10}\frac{T_a}{m^2d^{-1}} = \log_{10}\frac{8.64a_I(1-\frac{h}{cm})^{1-m_I}}{m_I - 1}$			Exponential model $\log_{10}\frac{T_a}{m^2d^{-1}} = a_{exp} + b\frac{h}{cm}$		
	max.	min.	max.	min.		a_I	m_I	α_I	a_{exp}	b_{exp}	α_{exp}
A2	-1.6	-5.3	140	25	5	195	2.80	0.048	2.58	0.209	0.026
A3	-1.8	-11.6	190	26	7	87	2.29	0.0025	2.30	0.093	0.010
B1	-4.8	-8.9	880	60	5	1350000	5.50	0.017	4.28	0.273	0.0079
B2	-1.5	-9.3	1700	140	8	1100	2.58	0.00019	3.27	0.131	0.00051
B3	-1.5	-5.3	680	310	5	80	1.65	0.12	2.91	0.087	0.12
B4	0.0	-8.0	29	0.7	6	8	2.56	0.018	1.52	0.206	0.0035
C1	-7.7	-12.3	250	110	5	2490	2.77	0.16	3.22	0.098	0.15
C2	-1.0	-6.9	810	34	8	880	3.07	0.0013	3.10	0.231	0.00070
C3	-2.6	-10.3	2100	190	5	7110	2.99	0.0053	3.68	0.134	0.0014
C4	-1.0	-4.6	57	5.5	7	9	2.15	0.31	2.04	0.315	0.31
C5	-0.8	-4.4	320	68	7	-2	0.88	0.81	2.70	0.179	0.95
C7	-4.3	-14.2	87	5.5	5	2050	3.46	0.037	2.61	0.127	0.011
C9	-4.5	-11.7	600	50	5	1940	3.79	0.0052	3.31	0.144	0.012
D1	-5.4	-8.5	320	69	5	1290	2.88	0.39	3.45	0.205	0.42
D2	-4.3	-11.1	4000	38	5	55	2.47	0.13	5.24	0305	0.025
D3	-0.5	-8.0	140	33	6	15	1.62	0.066	2.25	0.082	0.018
E1	-4.1	-9.8	210	6.8	5	64400	4.66	0.13	3.88	0.275	0.085
F1	-2.0	-7.4	190	63	5	63	1.92	0.080	2.52	0.091	0.046
F3	-4.5	-11.9	230	21	5	6930	3.60	0.013	3.03	0.138	0.0025
F4	-1.3	-17.7	730	1.6	6	7730	3.53	0.099	3.65	0.184	0.011
F5	-6.5	-14.3	130	41	5	678	2.71	0.022	2.51	0.073	0.048
G1	-3.0	-12.7	1200	150	6	2010	2.53	0.0035	3.37	0.090	0.0013
G3	-3.0	-11.3	530	7.8	5	28400	4.19	0.062	3.67	0.222	0.026
G4	0.0	-11.4	280	10	6	41	2.06	0.030	2.51	0.122	0.0035
H3	-3.0	-14.7	940	3.0	6	510	2.03	0.091	4.38	0.237	0.025
H5	-2.0	-8.9	55	5.5	5	65	2.54	0.089	2.14	0.141	0.044
H9	-4.5	-14.5	450	41	6	3850	2.90	0.033	3.20	0.102	0.015
J1	-5.2	-15.5	530	74	5	7430	3.10	0.035	3.30	0.094	0.039

SYMBOLS AND ABBREVIATIONS

Symbol	Interpretation	Dimension
α	Level of significance	[1]
γ	Semivariance	square of quantity involved
γ	Psychrometric constant	$[ML^{-1}T^{-2}\theta^{-1}]$
δ_o	Decayed mass fraction of organic matter in a year	[1]
Δ	Slope $\frac{de_s}{dT_{air}}$ of the function of saturated water vapour pressure e_s versus air temperature T_{air}	$[ML^{-1}T^{-2}\theta^{-1}]$
ζ_a	Apparent relative subsidence or shrinkage	[1]
ζ_o	Fraction of volume of organic matter in peat lost by compaction over a year	[1]
η	Dynamic viscosity	$[ML^{-1}T^{-1}]$
λ	latent heat of vaporisation	$[L^2T^{-2}]$
μ	Storage coefficient	[1]
ρ	Mass density	$[ML^{-3}]$
ρ_o	Mass density of organic matter in peat	$[ML^{-3}]$
ρ_w	Mass density of water $[ML^{-3}]$	$[ML^{-3}]$
ς_a	Apparent subsidence	[1]
ϕ_o	Volume fraction of organic matter in peat	[1]
A	Area	$[L^2]$
A_c	Catchment area	$[L^2]$
A_p	Shape factor in the piezometer test to measure saturated hydraulic conductivity k	[L]
A_L	Area of a lysimeter	$[L^2]$
a_I	Parameter of Ivanov's empirical equation for the hydraulic conductivity of the acrotelm	depends on value of m in the same equation
a	Intercept in regression equations	
b	Regression coefficient	
b_{yx}	Regression coefficient of y on x	
b_{xy}	Regression coefficient of x on y	
B_{90}	90% bandwidth	depends on quantity
C	Vertical resistance	[T]
C_c	Vertical resistance of the catotelm	[T]
c	Parameter in non-linear regression	
D	Layer thickness	[L]

Symbol	Interpretation	Dimension
D_a	Acrotelm depth	[L]
D_c	Catotelm depth	[L]
D_o	Average partial thickness of solid matter in a peat layer	[L]
D_{op}	Average partial thickness of solid matter in a peat profile	[L]
D_P	Peat depth	[L]
d	Depth below a surface (land or water)	[L]
d_{imp}	Depth of an impervious layer below the cavity in the piezometer test	[L]
E_o	Open water evaporation rate (Penman)	$[ML^{-2}T^{-1}]$ (mass) $[LT^{-1}]$ (volume)
E_a	Isothermal evaporation rate	$[ML^{-2}T^{-1}]$ (mass) $[LT^{-1}]$ (volume)
ET	Evapotranspiration rate	$[ML^{-2}T^{-1}]$ (mass) $[LT^{-1}]$ (volume)
ET_{bog}	Evapotranspiration rate of a bog	$[ML^{-2}T^{-1}]$ (mass) $[LT^{-1}]$ (volume)
e_2	Water vapour pressure at 2 m above the surface	$[ML^{-1}T^{-2}]$
e_s	Saturated water vapour pressure	$[ML^{-1}T^{-2}]$
f	Indicator of parallel (f=1) or radial divergent flow (f=2) in flow equations of the (modified) Ground Water Mound Theory	[1]
f_b	Evapotranspiration ratio $\frac{ET_{bog}}{E_o}$	[1]
f_g	Crop factor to estimate the potential evapotranspiration rate of a grass covered surface from E_o	[1]
G	Heat flux density into the soil or a water body	$[MT^{-3}]$
H	Degree of humification according to Von Post	rank, scale 1-10
h	Hydraulic head, phreatic level	[L]
h^*	Depth of the phreatic level	[L]
$\bar{h}$	Mean depth of the phreatic level	[L]
h_{fb}	Height of a face bank	[L]
h_m	Phreatic level in the centre of a (theoretical) bog	[L]
I	Surface slope	[1]
K	Integration constant	depends on equation
k	Saturated hydraulic conductivity	$[LT^{-1}]$
k_a	Saturated hydraulic conductivity of the acrotelm	$[LT^{-1}]$

Symbol	Interpretation	Dimension
k_e	Saturated hydraulic conductivity estimated from volume fraction of organic matter ϕ_o	$[LT^{-1}]$
k_h	Effective horizontal saturated hydraulic conductivity	$[LT^{-1}]$
k_m	Measured saturated hydraulic conductivity	$[LT^{-1}]$
k_{hc}	Effective horizontal saturated hydraulic conductivity of the catotelm	$[LT^{-1}]$
k_v	Effective vertical saturated hydraulic conductivity	$[LT^{-1}]$
k_{vc}	Effective vertical saturated hydraulic conductivity of the catotelm	$[LT^{-1}]$
L	Length	[L]
L_F	Length of a flow path	[L]
L_c	Length of the cavity in a piezometer test	[L]
L_w	Length of the piezometer between phreatic level and cavity in a piezometer test	[L]
M	Production of dry mass per area	$[ML^{-2}]$
m_I	Parameter in Ivanov's empirical equation for the hydraulic conductivity of the acrotelm	[-]
m	Mass	[M]
m_d	Dry mass	[M]
m_L	Mass of a lysimeter	[M]
m_w	Wet mass	[M]
n	Number of data	[-]
n_w	Ratio of the well radius r_w and the distance over which the pumping effect is supposed to have extended in the semi-steady state acrotelm transmissivity test and the modified pit-bailing method	[1]
P	Precipitation rate	$[ML^{-2}T^{-1}]$ (mass) $[LT^{-1}]$ (volume)
P_e	Excess precipitation rate	$[ML^{-2}T^{-1}]$ (mass) $[LT^{-1}]$ (volume)
P_{ew}	Excess precipitation rate in the winter	$[ML^{-2}T^{-1}]$ (mass) $[LT^{-1}]$ (volume)
P^*	Precipitation sum	$[ML^{-2}]$ (mass) [L] (volume)
q	Flux per length, perpendicular to the flow direction	$[L^2T^{-1}]$
Q	Discharge	$[L^3T^{-1}]$
Q_a	Discharge *via* the acrotelm	$[L^3T^{-1}]$
Q_E	Evapotranspiration flux	$[L^3T^{-1}]$
Q_e	Discharge by exfiltration	$[L^3T^{-1}]$

Symbol	Interpretation	Dimension
Q_{hc}	Lateral discharge from the catotelm	$[L^3T^{-1}]$
Q_P	Precipitation flux	$[L^3T^{-1}]$
R	Radius, radiation flux density	[L], $[MT^{-3}]$
R_n	Net radiation flux density	$[MT^{-3}]$
r	Correlation coefficient	[1]
r	Distance to the middle of a circle	[L]
r_r	Relative distance to the centre of a circular or elliptic area	[1]
r_w	Well radius	[L]
S	Storage (volume of water in a volume of soil)	$[L^3]$
S_w	Specific storage (volume of water stored per area above a reference level)	[L]
S_{wL}	Specific storage of a lysimeter	[L]
s	Distance	[L]
$s_{..}$	Standard deviation (symbol of variable it refers to in subscript)	dimension of variable in subscript
t	Time	[T]
T	Transmissivity, temperature	$[L^2T^{-1}]$, $[\theta]$
T_2	Air temperature 2 m above the surface	$[\theta]$
T_a	Transmissivity of the acrotelm	$[L^2T^{-1}]$
T_c	Transmissivity of the catotelm	$[L^2T^{-1}]$
T_{air}	Air temperature	$[\theta]$
U_a	Acrotelm flow rate	$[LT^{-1}]$
U_c	Infiltration rate from the acrotelm into the catotelm	$[LT^{-1}]$
U_e	Exfiltration rate from the catotelm into the underlying mineral stratum	$[LT^{-1}]$
U_{hc}	Horizontal flow rate in the catotelm	$[LT^{-1}]$
U_{vc}	Vertical flow rate in the catotelm	$[LT^{-1}]$
u_2	Wind speed at 2 m above the surface	$[MT^{-1}]$
V	Volume	$[L^3]$
V_o	Volume of organic matter	$[L^3]$
V_s	Sample volume	$[L^3]$
V_w	Volume of water	$[L^3]$
v	Specific discharge	$[LT^{-1}]$
v_a	Specific discharge *via* the acrotelm	$[LT^{-1}]$
v_e	Specific discharge of exfiltration	$[LT^{-1}]$
v_{hc}	Specific horizontal (lateral) discharge *via* the catotelm	$[LT^{-1}]$
w	Width	[L]
w_o	Mass fraction of organic matter	[1]

Symbol	Interpretation	Dimension
X	Streamline length	[L]
x	Independent variable in regression	
x	Horizontal distance; perpendicular to the y-direction if in an (x,y) plane	[L]
y	Dependent variable in regression	
y	Drawdown or horizontal distance perpendicular to the direction of x in an (x,y) plane	[L]
y_w	Drawdown in a pumped well	[L]
z	Vertical position	[L]
z_a	Surface level of the acrotelm	[L]
z_{ac}	Level of transition from acrotelm to catotelm	[L]
z_b	Bottom level of the catotelm	[L]
z_s	Surface level	[L]

Abbreviation	Meaning
FP	Fen Peat
FSP	Fresh *Sphagnum* Peat
GMT	Ingram's Groundwater Mound Theory
GSI	Geological Survey of Ireland
HSP	Highly Humified *Sphagnum* Peat
OD	Ordnance datum (approximately equal to sea level)
OPW	Office of Public Works
RMA	Reduced Major Axis (a regression method)

ABOUT THE AUTHOR

The author was born in Haarlem on 6^{th} June 1941. He finished his secondary school at the Municipal Gymnasium of Leeuwarden in 1960.

In the same year, he began his study at Wageningen Agricultural University and graduated in 1968 with a major subject in soil science and minors in soil chemistry, geology and plant taxonomy and –geography.

From 1968 until 1989 he was employed by the Department of Land and Water Use of Wageningen University. Between 1968 and 1978 he worked on the design and development of electronic analogue computer systems for the calculation of groundwater flow. When these systems became obsolete as a result of the development of digital computing techniques, he became involved in the development of a computerised system for physical planning during 1978-1980. From 1980 to 1990 he worked on various hydrological projects, ranging from water management in nature reserves to drainage of built-up areas.

In 1989 he joined the newly formed Department of Hydrology, Soil Physics and Hydraulics, later Water Resources and became involved in the Irish-Dutch Raised Bog project in 1990. The fieldwork lasted until mid 1993. The writing of this thesis began in 1994. Because several reorganisations in the University took their toll, this work lasted considerably longer than originally envisaged. It was finished in the early spring of 1999.