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HYDROLOGY OF CLARA AND RAHEENMORE BOGS

**catchment definition; acrotelm survey;
determination of surface subsidence;
quality check of ground water data.**

H.A. Lensen

1991

Sketch of Clara Bog by Catherine O' Brien, Clara, County Offaly.

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Wageningen, July 1991

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PREFACE

This report has been based on a thesis concerning the agrohydrology of two Irish raised bogs. The work for this thesis was performed during five month in the graduate stage of my study at the Department of Hydrology, Soil physics and Hydraulics of the Agricultural University Wageningen.

The work would have been impossible without the help of many individuals. However, I am particularly grateful for the support of Sake van der Schaaf, Roel Dijksma and Kees De Vries for discussing the different subjects concerning this thesis; Lara Kelly, Mary Smith, Richard Henderson, Desiree Huisman, Kenneth Rijsdijk and Hans ten Kate for their hospitality and friendship, and; last but not least Mr. and Mrs. Dolan, Tom, Mary, Bill and Eileen for the teaching me how to enjoy Ireland.

Wageningen, July 1991
Henk Lensen

SUMMARY

For the development of programs concerning the conservation and management of two Irish raised bogs, being Clara and Raheenmore bogs (Fig.1), specific hydrologic knowledge is required which was assumed insufficient.

Therefore four hydrologic aspects were dealt with in the study for this thesis, being:

1) Catchment definition based on contour maps

Two techniques, being Kriging interpolation and Delaunay triangulation, were used for the computation of surface contour maps. The acquired contour maps could be used for the assessment of the catchment boundaries of both Clara (west) and Raheenmore bogs, assuming that the catchment boundaries for the ground water are the same as for the surface water, and the water flow is on average perpendicular to the surface contours. Consequently the sizes of the catchment areas of Clara (west) and Raheenmore bogs could be estimated; 100 ha and 33 ha, respectively. However no verification was realised which is certainly necessary.

2) Acrotelm survey

The earthning wire method which was based on the presence of sulphide showed less applicability in the mapping of the acrotelm of Raheenmore bog in winter. However using the conventional foot/spade method the area with no acrotelm could be assessed to the first 100-200 m of the periphery. This area equals 50 % of Raheenmore bog.

4) Determination of the surface subsidence

In order to determine the influence of (former) peat extraction and marginal drainage on the surface elevation of Raheenmore bog, elevation data of three years were compared:
1) The impact of the former peat extraction and drainage at the margins showed a general subsidence of Raheenmore bog over last 36-42 years varying between 0-1 cm/year. This was below average as mentioned by Ivanov (1981). The southern part of Raheenmore bog the rate of subsidence was higher than at the northern part.
2) The improvement of the marginal drainage system showed an increasing rate of peripheral subsidence during the last 6 years. The rate of subsidence was at the periphery (first 100-200 m from the marginal drain) 5 cm/year. No significant changes in subsidence rate of the rest of the bog could be noted.

4) Quality check of ground water data

Part of the hydrological field work consists of a two-weekly acquisition of ground water levels. These levels (phreatic and piezometric heads) are stored in a computer data base. Errors can occur during the acquisition and storage of these data.
A standard statistical method based on time series analysis was used to check the quality of the ground water data of Raheenmore bog (1990).
The detected errors present in the ground water data base could be divided into two types: 1) Acquisition errors (including decimeter, writing and shifting errors); 2) Storage errors (including typing errors)
Of all detected errors 30% was a result of a **typing error!**.

1 INTRODUCTION

In September 1989 an Irish-Dutch research project was initiated for an initial period of 3 years. One of the aims of this project is to develop appropriate programs concerning the conservation and management of two Irish raised bogs, being the bogs of Clara and Raheenmore (Fig.1).

Clara Bog with an area of 665 ha is one of the largest remaining midland raised bogs. It is the only relatively intact raised bog with a well-developed soak system. However, Raheenmore Bog with an area of 213 ha is one of the best examples of a raised bog in a basin situation. There are no pools, but as on Clara Bog, there are well-developed hummocks and hollows. The depth of the peat is estimated being over 15 m in places.

Figure 1 Location of Clara and Raheenmore bogs

For the development of programs concerning the conservation and management of raised bogs, specific knowledge is required. Especially knowledge of hydrology is indispensable, for a raised bog which mainly consists of water.
This hydrologic knowledge is assumed to be insufficient.

On the one hand to improve this knowledge a water balance study is being carried out. A model of this water balance can be used to simulate different options for the water conservation and management of (the two) raised bogs. In this way the sensitivity of the different options can be determined.
On the other hand mechanisms and parameters that control the hydrology of the two raised bogs are being examined.

The acquired knowledge can help in choosing the best option for the conservation and management of (the two) raised bogs. Moreover, this knowledge presumably can be implemented in the regeneration programs of the Dutch raised bogs.

Within this framework four (hydrologic) aspects were dealt with in the study for this thesis. The first two aspects discussed in this report were related to the water balance study; the third was related to the mechanisms and parameters that control the hydrology of the two bogs, and last but not least; the fourth aspect was of general importance for the total study.

Aspects related to the water balance study:

Generally, a prerequisite to a water balance study is the definition of the research area. In this thesis this area refers to the catchment area.

At first two interpolation techniques were compared for the computation of surface contour maps. The acquired contour maps were used for the definition of the catchment boundaries of both Clara bog (west) and Raheenmore bog. This is allowed when the catchment boundary for the ground water is the same as for the surface water, and the water flow is on average perpendicular to the surface contours.

Besides definition of the catchment boundary (2D), also definition of (at least) two boundaries in depth (3D) were assumed important for the water balance study.
The first boundary in depth was the boundary between acrotelm or layer of peat formation, and catotelm or layer of peat deposit. The second boundary was the boundary between catotelm and underlying assumed impermeable layer of lacustrine clay (Fig.2).

In this study only the first boundary was dealt with. A simple method was tested for the mapping of the acrotelm of Raheenmore bog.

An aspect related to the mechanisms and parameters that control the hydrology of the two raised bogs:

In order to determine the influence of (former) peat extraction and marginal drainage on the surface elevation of Raheenmore bog, elevation data of three years were compared. The used data were acquired in 1948 (Bord na Móna), 1984 and 1990 (Office of Public Works). These data restricted this study to only two transects.

Aspect of general importance for the total hydrologic study:

Part of the hydrological field work consists of a two-weekly acquisition of ground water levels. These levels (phreatic and piezometric heads) are stored in a computer data base. Errors can occur during the acquisition and storage of these data. It is apparent that before using a set of ground water data first these data should be checked for possible errors (quality check).

In this report a standard statistical method is described which was used to check the quality of the ground water data of Raheenmore bog (1990). This method was based on the time series analysis.

At first the water balance is briefly discussed in chapter 2, this before the catchment definition of both bogs is dealt with. Next, in chapter 3 the mapping method of the acrotelm is discussed. The influence of peat extraction and marginal drainage on the surface elevation of the bog is considered in chapter 4. Further, in chapter 5 the quality check of the ground water data is reviewed. Finally some conclusions are drawn in chapter 6.

2 WATER BALANCE AND CATCHMENT DEFINITION

2.1 Introduction

A water balance study can be useful when describing certain hydrological phenomena (soak at Clara bog), or when assessing the impact of different water conservation and management options. It is apparent that for the regeneration and conservation of raised bogs (which mainly consist of water) such studies are of great importance.

A water balance is always defined for a certain area (and time period). In this thesis this area refers to catchment area. Obviously the first step in a water balance study should be the definition of the catchment area. It is therefore that part of this (preliminary) research had been focused on the definition of the catchment areas of the two areas of interest, being Clara and Raheenmore bogs. In the following text "Clara bog" refers to only it's western part.

Before discussing these catchment definitions (§ 2.3) the hydrologic cycle and water balance of a raised bog are discussed briefly (§ 2.2).

2.2 The hydrologic cycle and water balance of a raised bog.

A raised bog can be seen as a hydrologic system consisting of two layers, being the acrotelm and the catotelm (Fig.2).
The acrotelm is the upper layer which is relatively thin with a relatively loose structure. It regulates and contains the ground water table. Moreover, in this layer the peat formation occurs. Altogether it is assumed to be the most important layer. The underlying and perennially water-logged catotelm is more compact than the acrotelm. Consequently the permeability of this layer is much lower (See Chapter 3 for more details).

2.2.1 The hydrologic cycle

The system of acrotelm and catotelm is bounded above by the bog surface, where exchange with the atmosphere takes place. At this level, on the one hand the direct precipitation comes into the system as (probably) the only input. On the other hand there is a continuous return of the water out of system into the atmosphere by means of evapotranspiration. In Clara and Raheenmore bogs the lower boundary is a layer of lacustrine clay which is assumed to be impermeable (no seepage), but at the moment this not certain. The drain is the last boundary, where the rain water also leaves the system (Fig.2).

Part of the precipitation is intercepted by the vegetation. It evaporates directly or it flows along the stem to the bog surface. Two things can happen with the rain water on the surface. Most likely the rain water infiltrates and recharges the soil water in the unsaturated zone (acrotelm). A part of this infiltrated water evaporates from the pores, while another part is taken up and transpirated by the vegetation. When the amount of water in the unsaturated zone exceeds the maximum amount of water which can be held in the "pores" against gravity (field capacity), it percolates down to the ground water table and replenishes the amount of ground water. Hence, the ground water table rises and the amount of ground water flow to the open drainage system (drain) increases. At locations where the acrotelm is missing (periphery) or at lower parts of the area, it is possible that ground water seeps out and runs off via the surface. In drier periods when the pressure head in the unsaturated zone is below equilibrium, water can rise from the ground water (capillary rise).

When, on the other hand, the rainfall intensity exceeds the infiltration capacity (e.g. at the periphery), the water surplus will first replenish the small terrain depressions (hollows etc.). Water in such depressions can infiltrate or evaporate after rainfall has stopped. After replenishment of the depressions rain water will flow over the surface to the open water system. Not all this water will be discharged in this way. A part will still infiltrate when locations are met with a higher infiltration capacity.

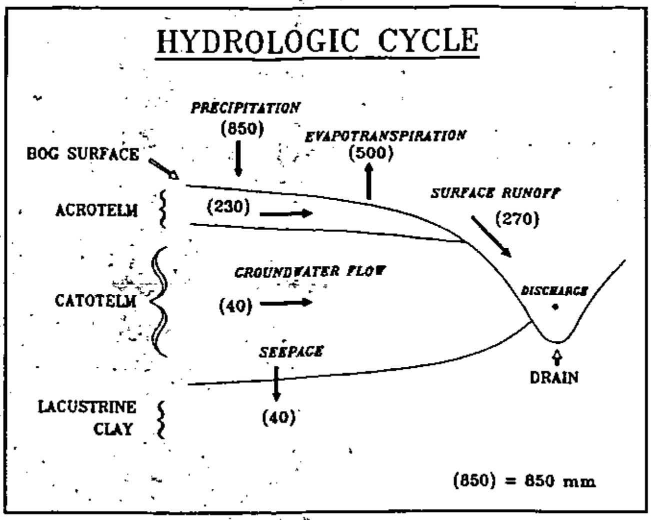

Figure 2 The hydrologic cycle of a raised bog

2.2.2 The water balance of a raised bog

The water balance of a hydrologic system as described above, is given by:

$$P - E - Q_s - Q_0 - S_w - U = \sigma \qquad \textbf{(1)}$$

with:

P	=	Precipitation	(mm)
U	=	Seepage	(mm)
E	=	Evapotranspiration	(mm)
Q_s	=	Surface runoff	(mm)
Q_0	=	Ground water flow (acrotelm + catotelm)	(mm)
S_W	=	Storage increase	(mm)
σ	=	A measure of the accuracy of the measurements	(mm)

(The change in storage over a long period is assumed to be zero. For this reason the storage (in acrotelm) is left out in Fig.2.)

As soon as one of the terms in the equation is unknown, σ is set zero. Then, the unknown term can be computed from the other measured terms, but no information is gained about the accuracy of the measurements.

At the moment the water balance study has been focused on Raheenmore bog. Knowledge gained at this site can be useful for a future water balance study of Clara bog (e.g. around the soak), which is assumed more complex.
In order to get sufficient insight in the different components of the water balance field measurements are being carried out at both bogs:

1) The precipitation is recorded continuously using a syphon (Raheenmore bog) and a tipping bucket rain gauge (Clara bog). Both are checked weekly using 125 cm² hand gauges;

2) The total discharge is also recorded continuously. At Raheenmore bog a Rossum weir is used to determine the discharge, and both a Rossum and a Thomson weir are used at Clara bog.

3) Evapotranspiration is measured using 16 lysimeters with four different (representative) vegetation units. Moreover, the change in storage can be monitored. The lysimeters are weighed every week (Raheenmore bog).

4) The hydraulic heads (phreatic and piezometric) are monitored every fortnight. Together with hydraulic conductivity measurements the ground water flow through the catotelm can be computed. (Raheenmore bog, Clara bog).

5) The ground water flow can be computed as soon as a relation is found between acrotelm transmissivity (T,kD), thickness and type, and the ground water level. Field measurements are carried out in order to find such a relation. A prerequisite to the computation of the acrotelm's ground water flow is the extrapolation of the field measurements over the total catchment area. This includes knowledge of the spatial distribution of acrotelm (thickness and type) and ground water levels.

6) At the periphery of the bog, where the acrotelm is absent (chapter 3) the main part of the ground water flow (acrotelmic) runs off via the surface. Therefore this surface runoff is basically determined from the total discharge.

7) As already mentioned, the seepage through the lacustrine clay layer is unknown. In order to get some estimate of this flow, it is suggested to measure temperature profiles from the lacustrine into the peat layer at different locations. Potential gradients in temperature could provide some estimates of the seepage.

A water balance is always defined for a certain area, in our case; catchment area. The definition of this catchment area includes both the determination of its size and shape. These are a prerequisite for finding appropriate locations for weirs and observation wells, and moreover, for the determination of the dimensions of the weirs.

In the next section a method is discussed which used surface contour maps for the definition of the catchment boundaries of both Clara and Raheenmore bogs.

2.3 Catchment definition using surface contour maps.

2.3.1 Introduction

A surface contour map can be used for the determination of the catchment boundaries, assuming that:
1) the catchment boundary for the ground water is the same as for the surface water;
2) the water flow is on average perpendicular to the surface contour lines.

For a raised bog with high water tables (0 - 30 cm below the surface) assumptions 1) and 2) seem quite reasonable (certainly in the winter and early spring, when water tables are at highest).

Different techniques are available for the computation of surface contour maps.
The Delaunay triangulation is a deterministic technique which uses the original elevation data **directly** for the positioning of the contours. Only the adjacent observations (elevation data) are used for the determination of the elevation of non-observed points. This technique therefore provides contour maps which resemble the manual mapping technique. The obtained maps using this technique were assumed to be sufficiently accurate for the definition of the catchment boundaries.

However, poor graphical possibilities of the available program forced us to search for another mapping program which produced more presentable maps. Within this other program (part of SURFER, 1990) a few interpolation techniques were available, among others the Kriging interpolation technique. This stochastic technique positions the contours using the original elevation data **indirectly**; all observation data are used for the determination of the elevation of non-observed points.

For the surface contour mapping of both Clara and Raheenmore bogs, a 100*100 m grid of elevation data was available. Locally data at a finer grid (30*30 m) were added. The levelling was carried out by levellers of the Irish Office of Public Works (OPW).

In this part of the research first the contour maps were compared produced by applying the Kriging interpolation and the Delaunay triangulation. Next the contour maps were used for the determination of the catchment areas of the two bogs. If the contour maps produced by using Kriging resembled the maps using Delaunay then presentable maps could be produced.

2.3.2 Delaunay triangulation and Kriging interpolation

When in a two-dimensional space different observation points are situated, values of other none-observation points are often needed. For example, when two neighbouring observation points (x_1,y_1) and (x_2,y_2) contain information about the respective surface elevations z_1 and z_2, and the surface elevation z_3 is wanted of a non-observed point (x_3,y_3) between those two points. This is usually the case when surface contour maps have to be computed from a set of observations, being elevation data.

For the computation of such contour maps different techniques are available. One technique is the Delaunay triangulation, which is a deterministic interpolation procedure. Neighbouring observations are connected by means of lines, yielding an interpolation surface composed of triangles. Every non-observed location is assigned the value defined by the triangle pertaining to that location (Stein, 1991).

Another technique of contour mapping uses the Kriging interpolation, which is a stochastic technique. This technique as applied in the program package SURFER (1990) is divided into two stages: 1) a primary interpolation from the (ir)regular original observations to a square or rectangular grid of interpolated values, and 2) a secondary linear interpolation from the interpolated grid of values to the positioning of the contour lines.

The primary interpolation according to Kriging, gives weights to the original observation points which depend on the distance to the predicting (non-observed) point. When the weights are multiplied with a factor to make the sum of the weights equal to one, the sum of the products between weights and according values gives an unbiased prediction. The Kriging method uses the covariance structure of the original observation points (x_i, y_i) for calculating the weights (Staritsky, 1989).

2.4 Results and discussion.

2.4.1 Results

Raheenmore bog with its convex shape was selected for the preliminary study on contour mapping.

The first method used was the Delaunay triangulation. This method used **directly** the original levelling data for the computation of the contours positions (Fig.3).
After using the Delaunay technique, Kriging (within SURFER) was used to produce another contour map. The settings within the program were constantly changed until a map was obtained which resembled the one produced using Delaunay. This included a transformation of the original input data into a regular 25 * 25 m grid. The finer grid automatically produced a map with the contour lines more smooth (Fig.4).

From Fig.3 and 4 it can be seen that there are only slight differences between the positions of the contour lines which are inherent to the used interpolation methods. At the periphery the differences are at largest.
Using Kriging and the same settings (Appendix 1) also the contour map of Clara bog could be produced, including a detailed map of the area around the soak. These three maps are shown in appendices 2, 3 and 4.

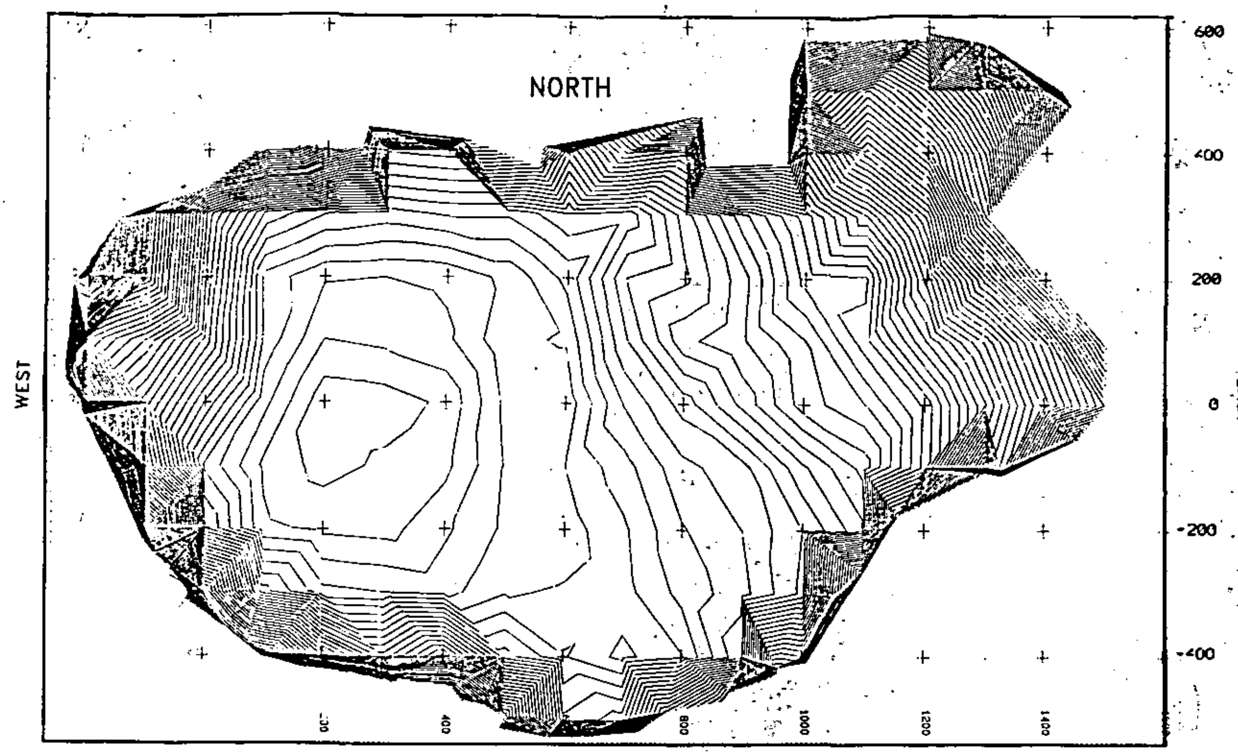

Figure 3 Surface contour map Raheenmore bog (1990) using Delaunay triangulation

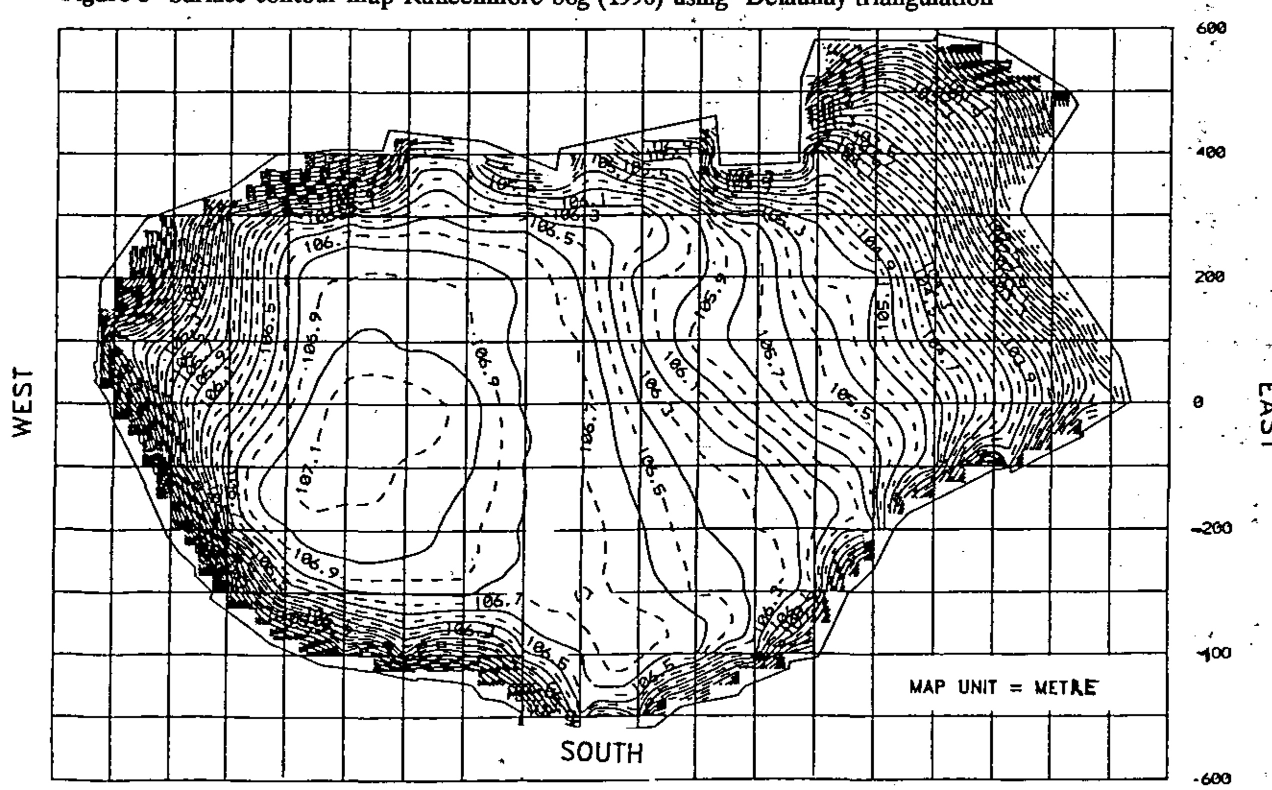

Figure 4 Surface contour map Raheenmore bog (1990) using Kriging interpolation

The catchment areas of Clara and Raheenmore bogs were determined using these surface contour maps. At Raheenmore bog the catchment boundary could be found by drawing a line from the outlet (= weir) to the ends of a collector drain in the north and in the south (Appendix 5, A-A'). From these ends two lines were drawn perpendicularly to the surface contour lines till they meet each other on top of the dome (Fig.5).

The same method was used for Clara bog (Fig.6). Moreover, a detailed contour map of the area around the soak and the two weirs could be used (Appendix 4). The triangular shape below on the map are the collector drains of Clara bog. The circular shape in the middle is the soak (pond).

The results of the contour mapping and determination of the catchment area are summarized in Table 1.

Table 1 Summary of the contour mapping and catchment determination of Clara (west) and Raheenmore bogs.

FEATURE	CLARA-WEST	RAHEENMORE
Total Surface area (ha)	251	137
Catchment area (ha)	100	33
Minimum Altitude (m O.D)	52.6	98.5
Maximum Altitude (m O.D)	62.2	107.2
Position (N.latitude)	53° 20'	53° 20'
Position (W.longitude)	7° 38'	7° 17'

From Table I it can be read that the sizes of Clara bog (west) and Raheenmore were respectively 251 ha and 137 ha. Both values refer to the bog areas excluding lagzones and cutaway bog. The sizes of the catchment areas were for Clara bog 100 ha (40 %), and for Raheenmore bog 33 ha (24 %).
Note the difference between the size of Raheenmore bog with and without lagzones and cutaway area, respectively 213 and 137 ha. The mentioned size of Clara bog only refers to the western part of the bog.

The differences between minimum and maximum altitude were for both bogs 9-10 m. Moreover, the difference in elevation between Clara and Raheenmore bog was approximately 45 m.

2.4.2 Discussion

The Kriging interpolation assumes no trend in the input elevation data. Nevertheless, there certainly were trends present in the elevation data of both bogs. These trends were at largest at the periphery. Consequently, the position of the contour lines at the periphery was presumably less accurate. However, for the determination of the catchment boundaries, which were located more to the centre of the bog these inaccuracies were assumed irrelevant.(Fig.5 and 6).(Unfortunately SURFER provides no measures of accuracy for the positioning of the contours.)

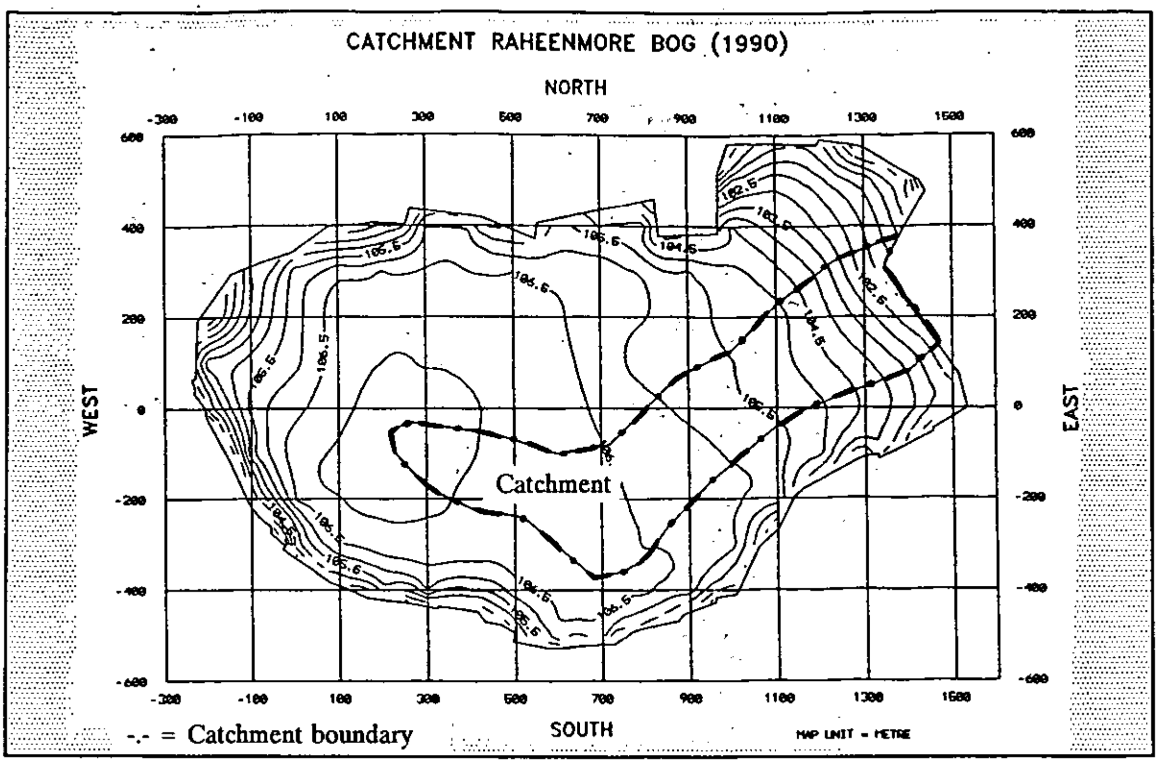

Figure 5 Catchment area Raheenmore bog (1990)

The contour interval for the maps was set to 10, 20 and 50 cm for respectively the maps of Fig. 3 and 4, Appendices 2, 3, 4, and Fig. 5 and 6. This as a result of the different purposes and clarity of the maps. A map with contours every 10 cm would imply that every detail on the area up to 5 cm (up or down) was known. For the two raised bogs with their hummocks and hollows this was certainly not true. An average height of the hummocks of say 25 cm would already imply a contour map with intervals at least every 50 cm.

However, for the catchment definition an interval of every 10 or 20 cm) was necessary. For this the surface trend was assumed to be more important than the surface details as hummocks and hollows.

At Raheenmore bog there was besides the mentioned collector drains also a network of old transversal drains (Appendix 5). Tough most of these drains had completely been overgrown and consequently lost their function, in some of them there was still some flow that bypassed the weir (at high discharges).
During the assessment of the catchment boundaries this leakage was impossible to accounted for. However, by measuring the hydraulic gradient in those drains the location can be determined where this gradient equals zero i.e. the catchment boundary.

The assessment of the catchment boundary is relatively subjective. The drawing of so many people resulted in so many catchment areas. Therefore care should be taken when using the mentioned values. Better is first to verify the size of the catchment areas with cumulative rainfall and discharge.
When comparing two equally wet periods then the cumulative rainfall (input) equals the cumulative evapotranspiration and discharge (taking an estimate for the seepage and the change in storage zero). With an estimate for the evapotranspiration the catchment areas can be verified. Also aerial photographs can possibly provide extra information (wet and dry areas etc.) which help with this verification.

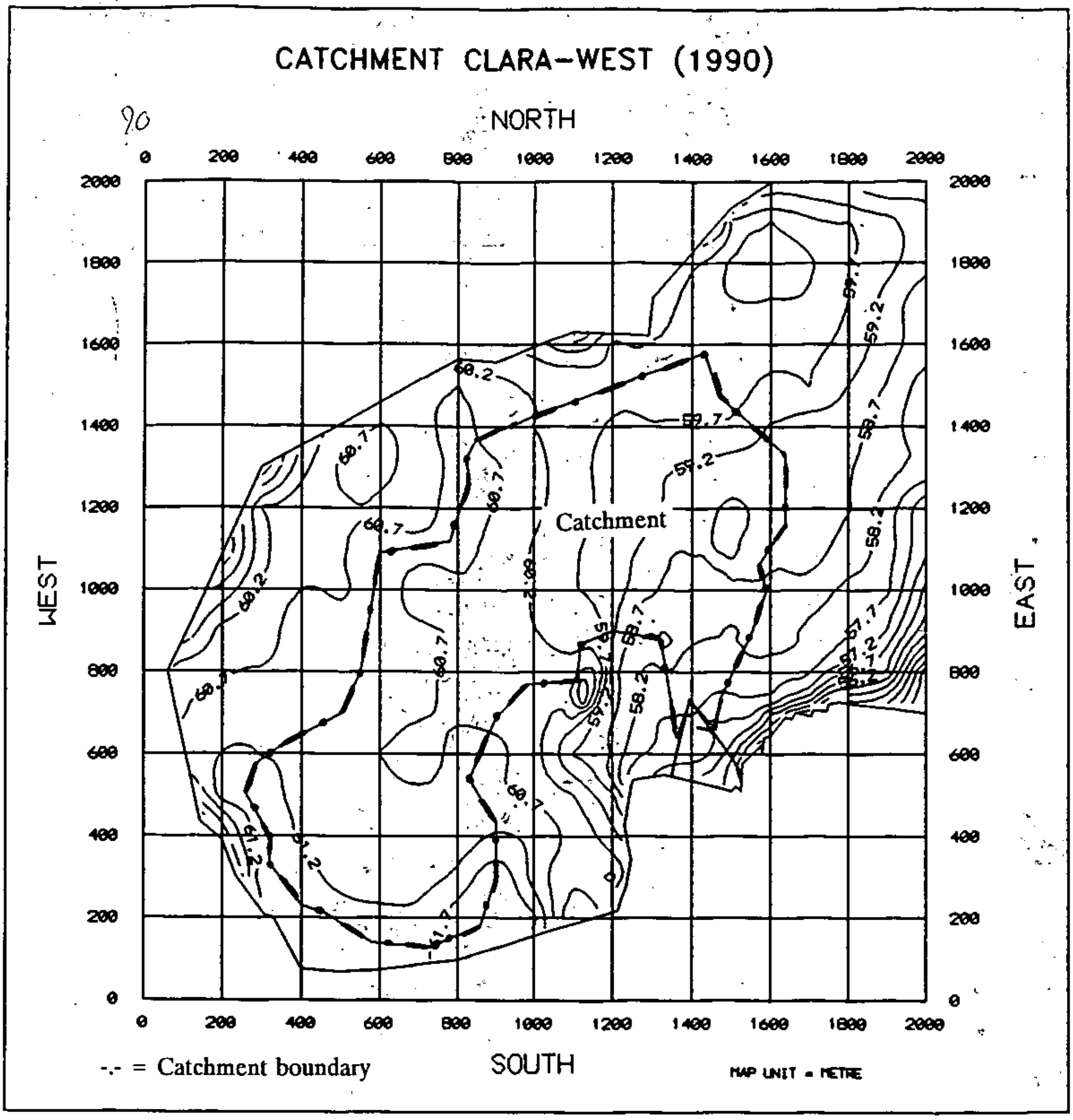

Figure 6 Catchment area Clara bog west (1990)

2.5 Conclusions

The Kriging interpolation method (within SURFER) produced surface contour maps of both bogs which looked like the ones produced by using the Delaunay triangulation. This was true for the central part of the bog, i.e. the weakly convex part. At the periphery (strongly convex) some differences in location of the contour lines could be noted. (Partly this was inherent to Kriging itself, which assumes no trend in the input data.)
However, these contour maps could be used for the assessment of the catchment boundaries. Consequently the sizes of the catchment areas of Clara (west) and Raheenmore bogs could be estimated; 100 ha and 33 ha, respectively. However no verification was realised which is certainly necessary. Especially for Raheenmore bog where a little shift of the catchment boundaries can result in significant changes of area, due to the "boot-shape" of this area.

3 THE DIPLOTELMIC BOG

3.1 Introduction

In a raised bog two layers can be distinguished (Fig 2):
1) the acrotelm, being the uppermost layer where peat is formed, and;
2) the catotelm where peat is deposited.

The hydrological characteristics of both layers differ in nature or extent. Obviously for a water balance study knowledge of nature and extent of these characteristics is indispensable.

The research of this thesis has been focused on one of these characteristics, being the thickness of the acrotelm. A simple method is discussed which could be used for the determination of the acrotelm's thickness. This method was based on the presence of sulphide.

Implementing this method at a 50 * 50 m grid at Raheenmore bog and using the Kriging interpolation technique, a map of the depth of the sulphide zone could be obtained. Under certain conditions a map of the sulphide zone equals the map of the acrotelm's thickness.

Such a map can help with the allocation of appropriate sites for the field measurements of the transmissivity of the acrotelm. Moreover, such a mapping is indispensable for the translation of the field measurements to model parameters.

At first the characteristics of both acrotelm and catotelm are reviewed. Using these characteristics the importance of the acrotelm could be examined (§ 3.2). After this examination the method for the determination of the acrotelm's thickness was dealt with (§ 3.3). Finally the results (§ 3.4) and conclusions (§ 3.5) were discussed.

3.2 The importance of the acrotelm

In a raised bog two layers can be distinguished (Ingram and Bragg, 1984):
1) the acrotelm, being the uppermost layer where peat is formed, and;
2) the catotelm where peat is deposited.

A bog with both acrotelm and catotelm is said to be diplotelmic (Fig 2).

Various processes differ in nature or extent between these two layers. Their characteristics are summarised by Ivanov (1981):

The acrotelm.

(1) An intensive exchange of moisture with the atmosphere and the surrounding area.
(2) Frequent fluctuations in the level of the water table and a changing content of moisture.
(3) High hydraulic conductivity and water yield and a rapid decline of these with depth.
(4) Periodic access of air to its pores.
(5) A large quantity of aerobic bacteria and micro-organisms facilitating the rapid decomposition and transformation into peat of each years dying vegetation.
(6) The presence of living plant cover, which constitutes the top layer of the acrotelm.

The catotelm.

(1) A constant or little changing water content.
(2) A very slow exchange of water with the subjacent mineral strata and the area surrounding it.
(3) Very low hydraulic conductivity in comparison with the acrotelm (a difference of 3-5 orders of magnitude).
(4) No access of atmospheric oxygen to the pores of the soil.
(5) No aerobic micro-organisms and a reduced quantity of other kinds in comparison with the acrotelm.

The most important physical characteristic of the acrotelm is the presence of the water table within it. Since the acrotelm is a thin layer, seldom more than a few tens of centimetres thick, this means that the water table is also perennially shallow. Soils of this kind are described as being waterlogged. Soil waterlogging causes anaerobic conditions to prevail in the catotelm and lower acrotelm. Under these conditions an inefficient decomposition takes place which allow a mixture of fibrous and colloidal organic matter to persist long past the time when all such material would have decayed in an aerobic medium (Ingram, 1987). It is apparent that the presence of the water table within the acrotelm is indispensable for the formation and persistence of peat deposits.

The acrotelm is therefore seen to possess the essential characteristics of a layer which retains the water table close to the surface, neither descending to the catotelm nor rising beyond the surface. For, a prolonged water table draw-down below the acrotelm would cause death of the *Sphagnum* carpet by desiccation and therefore cessation of peat-forming.

Moreover the catotelm could undergo irreversible de-watering. This would initiate a complex sequence of shrinkage and slumping, accompanied by catastrophic alteration of the acrotelm and hence basic ecological change in the system as a whole.

On the other hand, prolonged raising of the water table would lead to a prolonged reduction or cessation of aeration of the acrotelm. This would produce a decrease in the growth of plants and a decrease in the annual increment of the mass of vegetable matter, as a result of which the plant cover would begin to decay and peat accumulation would cease. Moreover, rising of the water table beyond the surface could cause sheet (surface) flow. The erosive force of this sheet flow could strip away the *Sphagnum* cover (Ivanov, 1981; Ingram and Bragg, 1984; Ingram, 1987).

A third aspect which can be mentioned with respect to the loss of acrotelm is the burning of parts of the bog for agricultural purposes. Probably a botanical study can give some insight in this aspect.

The presence of the water table in the acrotelm is caused by its composition, that is, the range of its hydraulic conductivities. The carpet of *Sphagnum* undergoes humification and compaction as it passes downwards through the acrotelm. Therefore, the conductivity of the acrotelm is much more high at the surface than below (Ingram, 1987).

Bragg (1982, in: Ingram and Bragg, 1984) computed the hydraulic conductivity of two parts of the acrotelm at different depth by varying the height of the water table (Fig. 7).
The upper curves (LIII) relate to a part of acrotelm dominated by *Sphagnum magellanicum*; the lower to a part dominated by *S. capillifolium*. It is apparent firstly that the coarser species is at least half an order of magnitude more conductive than the finer; secondly that the hydraulic conductivity of both species is greater by some three orders of magnitude towards the top of the acrotelm than near its base.

The above mentioned considerations serves to emphasise the importance of studying the hydraulics of the acrotelm by all possible means, including the lysimeter techniques. These will provide insight in among others changes in storage in relation to the fluctuating water table.

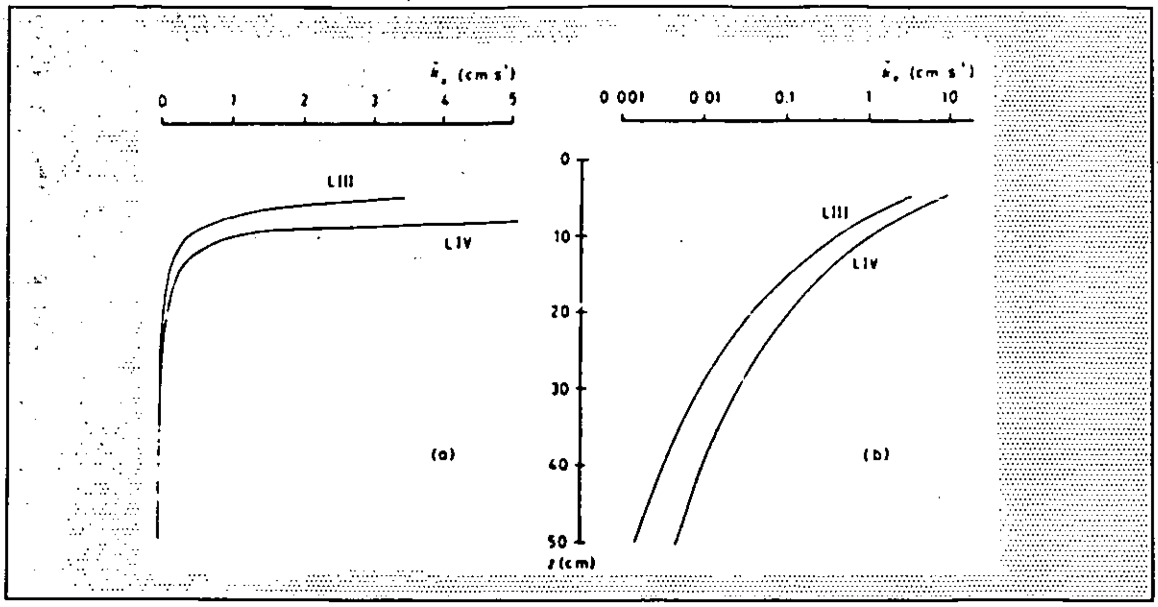

Figure 7 Variation with depth z of the mean estimate of hydraulic conductivity k_Z in the acrotelm of the mire expanse at Dun Moss (Scotland). Laboratory filtration flume tests on monoliths LIII (with a cover of *Sphagnum capillifolium*) and LIV (with a cover of *S. magellanicum*). (a) with linear scale and (b) with logarithmic scale of k_Z. From Bragg (1982, in: Ingram and Bragg, 1984).

Until the results of such work become available, it will be difficult to model the water balance and, therefore, to forecast the effects of different water management option upon bog systems.

The mapping of the acrotelm's thickness was the first step in the project research on acrotelm hydraulics. In the next section a method is discussed for the determination of the thickness of the acrotelm.

3.3 Testing a method for mapping the acrotelm

The method discussed in this section was based on a difference in characteristics between acrotelm and catotelm. Where as the acrotelm is characterised by the presence of a fluctuating water table, the catotelm is perennial water-logged. The periodic access of oxygen in the pores of the acrotelm cause periodic **aerobic** conditions. For, in the water-logged catotelm **anaerobic** conditions prevail.

A direct method for mapping the acrotelm would imply the monitoring of phreatic heads of total Raheenmore bog during summer as Ivanov (1981) suggest with his definition of acrotelm:
'The thickness of the acrotelm is equal to the distance from the surface of the mire to the average minimum level of the water table in the warm season.'

Though, this was not applicable. Therefore, another method was chosen. The method was less laborious and yet, seemed to provide useful data in a relative small amount of time (2 weeks).

The method was based on the presence of sulphide in the catotelm. In raised bogs sulphide are formed under anaerobic conditions. They are derived from the sulphate reduction by the bacteria *Desulvibrio desulfuricans* (van der Molen, 1986).

A characteristic of sulphide is that it blackens silver or copper. Instead of using (expensive) silver or copper, Wiegers (in: van der Molen, 1986) suggest the use of earthning wire with a yellow/green plastic mantle. The plastic mantle turns brown under the influence of (hydrogen) sulphide. The method has a number of advantages (after: van der Molen, 1986):

1) It is cheap and the material (wire) is nearly everywhere readily available.
2) It can provide accurate information in a relatively small amount of time.
3) The browning of the wire is (to a certain extent) probably related to the amount of sulphide present. A small amount of sulphide causes little browning, while the wire turns completely brown in the real anaerobic zone.
4) The browning of the wire is irreversible, which means that the observations can later be checked.
5) The destruction of the vegetation is minimal, especially if inserted with a bamboo stick.

In the experiment a yellow/green earthning wire ($\phi \approx 0.002$ m) was used. It was pushed down 0.5 m into the bog using a small bamboo stick leaving 0.1 m above the surface. Red insolation was used for the indication of the wires position.
The wires were inserted in a regular (50*50 m) grid at the end of January and left for one month. No wires were inserted where the acrotelm was absent (periphery of the bog).
After one month the wires were collected and the length to the real browned part measured. In this manner the depth of the sulphide zone was detected, which was an indication of anaerobic conditions. These anaerobic conditions were assumed to give some idea of the depth of the top of the catotelm and, therefore the thickness of the acrotelm.

3.4 Results and discussion

3.4.1 Results

The results of the sulphide zone mapping are presented in Fig. 8.

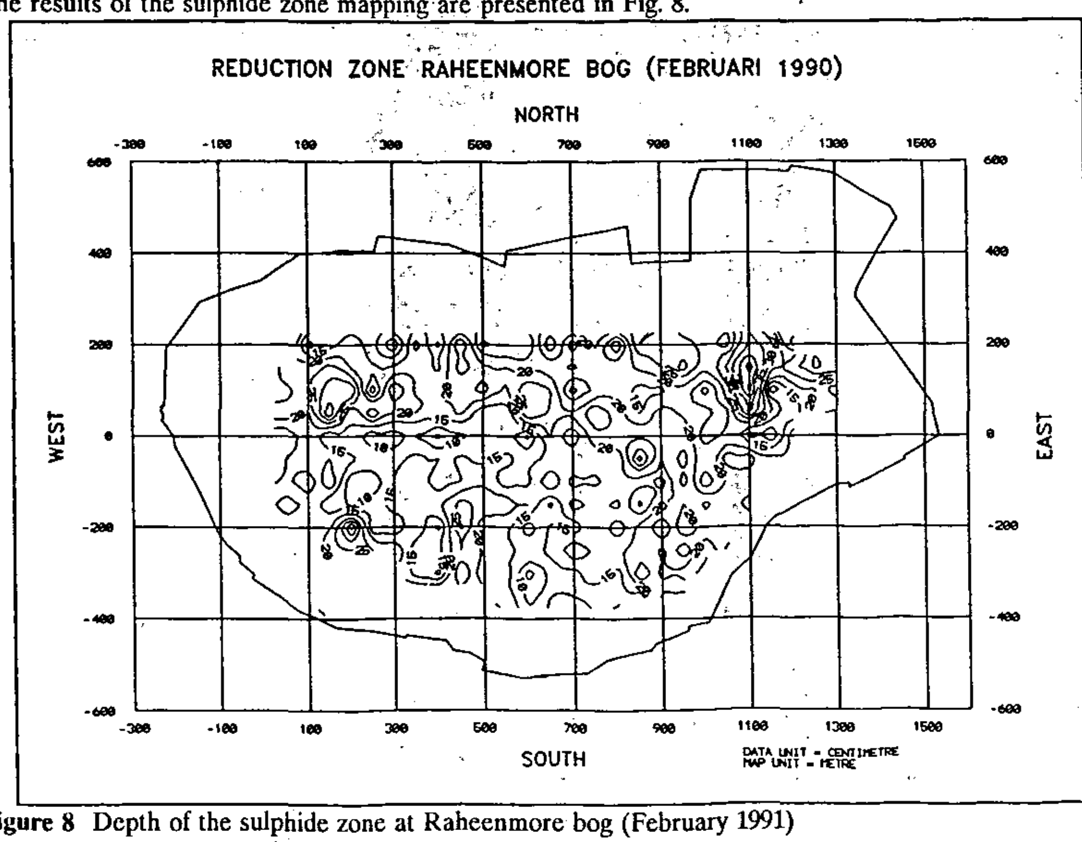

Figure 8 Depth of the sulphide zone at Raheenmore bog (February 1991)

This figure was acquired by using the Kriging interpolation technique. The underlying data are shown in Appendix 1a. (Both contour lines and field data are in centimetres beneath surface level).
The results of Fig. 8 are summarized in Table 2.

Table II Depth classes sulphide zone Raheenmore bog (February 1991)

Depth Class (cm)	Area (ha)	Percentage
0 - 10	68	0.50
10 - 20	41	0.30
20 - 30	25	0.18
30 - 40	3	0.02
40 - 50	0	0.00

From this table it can be seen that the acrotelm was absent at half of Raheenmore bog (sulphide zone class 0 - 10 cm). Note at this part of the bog (periphery) no wires were inserted. The absence of the acrotelm could be noted just by walking over the bog surface, now and then checking with a spade.

3.4.2 Discussion

In the experiment the earthning wires were left in the peat for one month. Due to the relatively cold period of the year (February) the browning of the wire took more time than the initially planned 1-2 weeks.

Rainfall during the experiment presumably caused fluctuations of the ground water table. A higher ground water table with its sulphide zone beneath it (in: van der Molen, 1986) might have caused (irreversible) browning of the wire, which remained in position when the water table drops.
Moreover, the ground water tables in February are presumably higher than in the driest period of the year (i.e. end of summer).
Both suggests that the used measuring method can yield different results for the same location, due to differences in water table depth. Therefore, the depth of the sulphide zone (Fig.8) represented the **minimum thickness** of the acrotelm rather than **the** thickness.
Presumably the used method is only applicable in the summer. Besides the slower chemical processes which colour the wire, also the biological activity of the bacteria *Desulvibrio desulfuricans* will presumably slow down by lower temperatures

3.5 Conclusions and recommendations

At 50 % of Raheenmore bog no acrotelm was present. This was equal to approximately the first 100-200 m of the periphery.(This value was obtained by using the conventional foot/spade method.)
The non-destructive wire method provided information on the depth of the sulphide zone in February. These depths probably were an underestimation of the acrotelm's thickness, and therefore could be seen as minimum depths. Probably also the spatial variability of the acrotelm was somewhat exaggerated.

The wire method should be repeated at the end of the summer (September) when the ground water table is at its lowest and the temperatures higher. Another method is suggested which uses an auger. This method can be applied at any time of the year. However, it is a destructive method.

Besides the determination of the thickness of the acrotelm and the measurement of it's transmissivity also it's composition, i.e. type of *Sphagnum*, should be mapped. Probably aerial photographs can be used for this purpose.

4 IMPACT OF INTENSIVE DRAINAGE ON THE SURFACE ELEVATION OF RAHEENMORE BOG

4.1 Introduction

In 1987 the Irish Wildlife service bought Raheenmore bog as a nature reserve. Until then, turf had been extracted at the periphery. Further, a peripheral drainage system had been taken care of the discharge of the water surplus from the (cut-away) bog and the surrounding farmlands.

In 1984 this peripheral drainage system was changed in order to improve the surrounding farmlands. This included (Wildlife Service, Mullingar):

1) the connection of the peripheral drains resulting in one surrounding drain, further referred to as the marginal drain;
2) the deepening of (parts of) this marginal drain.

Currently this drain is approximately 1-1.5 m wide, and 2-4 m deep. These dimensions were assumed to be similar to the ones of 1984, after the "amelioration" works.

At the beginning of the project no information was available about the impact of the former marginal peat extraction and drainage on Raheenmore bog. Moreover the effect of the amelioration works on the bog was unknown. Therefore, the study of this section had been focused on this item.

Generally drainage of peatlands causes subsidence of the surface and underlying layers. This subsidence is partly caused by compaction and partly by loss of organic matter (Schothorst, 1979).

In order to investigate the effect of the former peat extraction and drainage on the surface elevation of Raheenmore, elevation data of three years (1948, 1984, 1990) were compared. Moreover, in this way the effect of the amelioration works could be evaluated.

The elevation data used for this study were acquired by Bord na Móna (1948), and the Irish Office of Public Works (1984 and 1990). Due to the limited overlap of the elevation data the study was restricted to two transects: the one heading south-north; the other west-east (respectively, S-N and W-E, see Appendix 5).

The results of this study could provide insight in the former and current subsidence rate of the surface of Raheenmore bog due to marginal drainage and peat extraction.

The acquired knowledge could help balancing the different options for the conservation and management of the (two) Irish raised bogs. On the one hand these options would be provided by the model of the water balance. However, on the other hand options could be formulated using the newly gained insight in the (other) mechanisms and parameters which also influence the hydrology of the bogs.
In this prospect the inquiry into the impact of the marginal drainage on the bog's elevation must be seen.

At first the theory of intensive drainage on peatlands is discussed (§ 4.2). Next the method of using the different elevation plots is dealt with in § 4.3. Before drawing some conclusions in (§ 4.5) the results are presented in § 4.4.

4.2 Theory

Intensive (deep) drainage of peatlands generally causes subsidence of the surface and underlying peat layers. This subsidence is a result of different (paedogenetic) processes which gradually change the peat into a peat soil.

These processes include subsidence due to (Schothorst, 1979):
1) lowering of the piezometric head;
2) shrinkage;
3) oxidation, and;
4) humification.

Ad 1) Subsidence due to lowering of the piezometric head.

This is a soil mechanical process of compaction of the peat body. The pressure of the peat's own weight (which, after the lowering of the water table, is no longer suspended in water) and capillary tension, also resulting from the lowering of the water table, leads to shrinkage of the whole peat deposit. A characteristic of this process is that because of the irreversible loss of water the volume change is permanent (Ivanov, 1981).

Ad 2) Subsidence due to shrinkage.

This is a physical process of compaction as a result of water loss by the vegetation (transpiration). The roots of the vegetation absorb moisture from the soil equal to wilting point (pF = 4.2) or even higher, while from deep drainage the
water pressure drops down to field capacity, i.e. pF 2.0 - 2.2 (Schothorst, 1979).

Ad 3) Subsidence due to oxidation.

This is a bio-chemical process. Deep drainage increases aeration and temperature of the peat and consequently the bio-chemical processes which lead to the oxidation of organic material are activated. The original red/brownish colours disappear and the peat turns black. Usually in this stage of the decomposition only organisms as fungi and bacteria are capable of decomposing the peat substance. Organic matter disappears and consequently the surface drops (van Heuveln, 1976).

Ad 4) Subsidence due to humification.

While the organic structure stays visible during the oxidation, during the humification these structures are decomposed by macro organisms. Centipedes and earthworms, for example, use the peat as food and change it into excrements. This process can be repeated, while in the excrements bacteria and fungi the organic matter further disintegrate. Gradually the organic structure disappears and becomes a kind of humus depending on the environment. In very dry conditions peat becomes turf (Jongmans et al., 1983). During this humification organic matter disappears and hence the surface falls.

It is apparent that due to the intensive drainage the *Sphagnum* carpet is the first layer that will disappear, and consequently peat formation will stop. Moreover, before the acrotelm disappears totally, its hydraulic features will change as a result of compaction and (accelerated) humification. Hence the acrotelm will lose its regulating function, so that during wet periods overland flow is stimulated, while during drier periods the desiccated peat is subjected to wind erosion. Both also accelerate the destruction and disappearance of the bog.

According to the observations in different countries and climates, the average rate of collapse of a peat deposit after drying over a period of 40-50 years varies widely from 1-2 to 8 cm/year. In some cases, rates of 20-40 cm/year have been recorded in the first years after draining, when the water table was not lowered significantly (by not more than 80 cm).
Research shows that if the average water table in a peat is stabilized at some new depth after draining, then the speed of subsidence, which is at its greatest in the first years after lowering, gradually slows down, and the thickness of the peat deposit tends towards some new limit (Ivanov, 1981).

4.3 Methods and materials

Surface elevations of Raheenmore bog were compared in order to investigate the impact of former turf extraction and drainage. Moreover, the effect of the amelioration works, carried out in 1984, could be estimated.

The surface elevation data used for this study were acquired by Bord na Móna (1948), and the Irish Office of Public Works (1984 and 1990). Due to the limited overlap of these data the study was restricted to two transects: the one heading south-north; the other west-east (respectively, S-N and W-E, see Appendix 5)

When comparing the surface elevations of the different years, the surface trends should be compared rather than the individual elevation data. There are a few aspects which support this statement:

1) The used surface elevations were determined at a priori chosen locations. For 1948 and 1984 these locations were the same. However, for 1990 different locations were chosen. The elevation data of each location represent the local elevation rather than their respective area averages. Moreover, the surface elevation can vary by 25 cm within a horizontal distance of a few metres due to the roughness of the surface (hummock and hollow complexes).

2) No information on the moisture condition (water storage) of the three years was available. Differences in moisture conditions can cause swell and shrinkage of the bog (acrotelm). As a result different surface elevations can be measured within a year. The amplitude of these surface oscillation can vary up to 0.10 - 0.15 m (Ivanov, 1981).
When comparing surface elevations of different years, differences in moisture condition can be expected which exaggerate or understate the differences in the respective surface elevations.

For the South-north transect, the changes in surface elevation could be estimated according the mentioned method (i.e. estimating the changes in surface elevation by comparing the trends in the elevation data).

However, for the West-east transect a slightly different approach was used, which appeared more applicable.
For this approach the elevation data of the different years were delineated in a single plot. The changes in elevation between the years were measured from this plot, and used in another plot which then showed the temporal changes in elevation (subsidence). By dividing these temporal changes by their respective time period, the plot of the subsidence rates was obtained. This was done for the different time periods.

The results of this exercise were acquired by taking average values from the respective plots. These are discussed in the next section.

4.4 Results and discussion

In Fig.9 the surface elevations are depicted along the South-north transect. For this transect only the elevation data of 1948 and 1990 were available.
In these 42 years the surface has subsided 20-30 cm in the south (0.5-0.7 cm/year). This value gradually declined to 0 cm when heading north.

The surface elevations along the West-east transect are depicted in Appendix 6. Besides elevation data of 1948 and 1990, also data of 1984 were available.
A plot was produced showing the changes in surface elevation, in order to make the changes (as shown in Appendix 6) more apparent (Appendix 7). A plot of the relative changes could be derived from the former by dividing its values by the respective time periods (Fig.10).

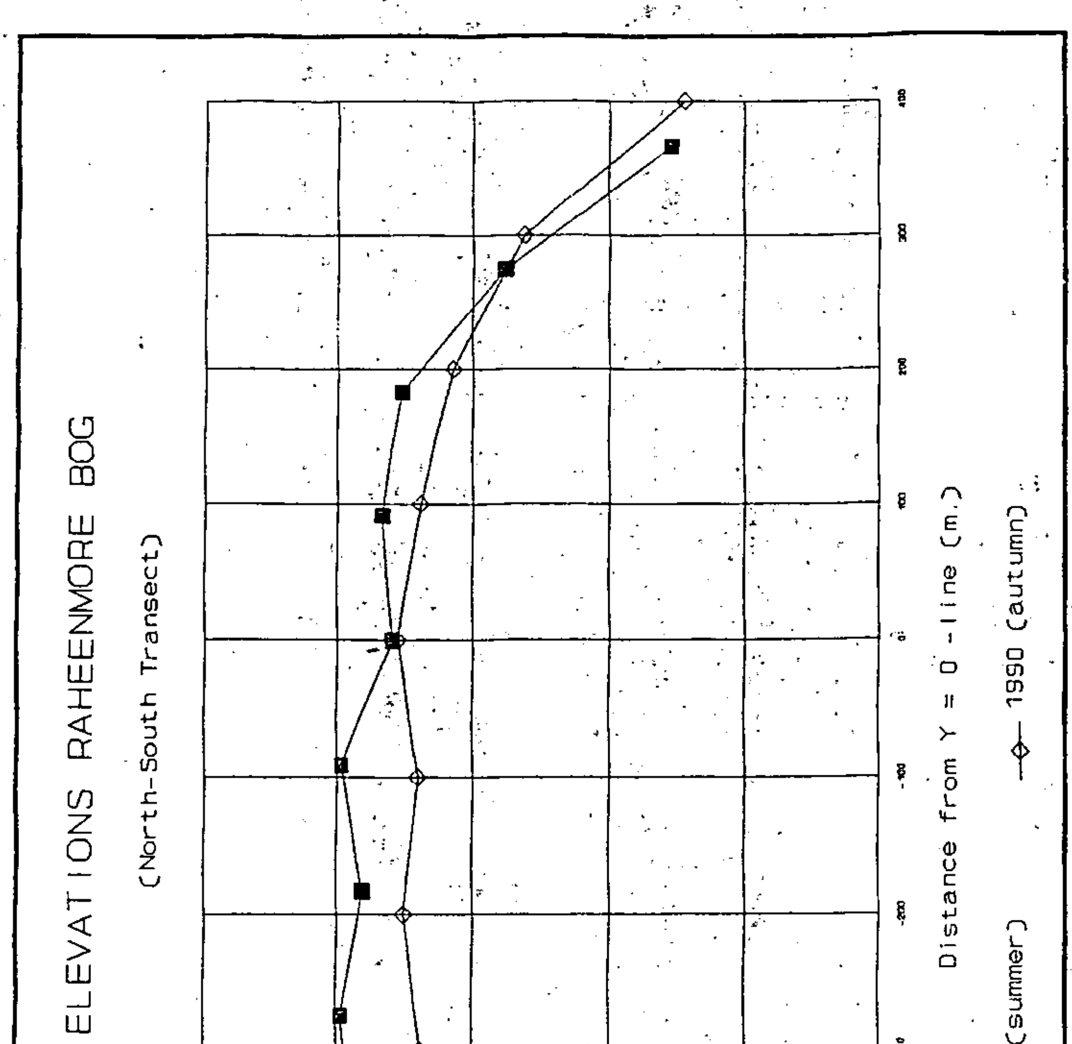

Figure 9 Surface elevations Raheenmore bog South-north transect (1948 and 1990)

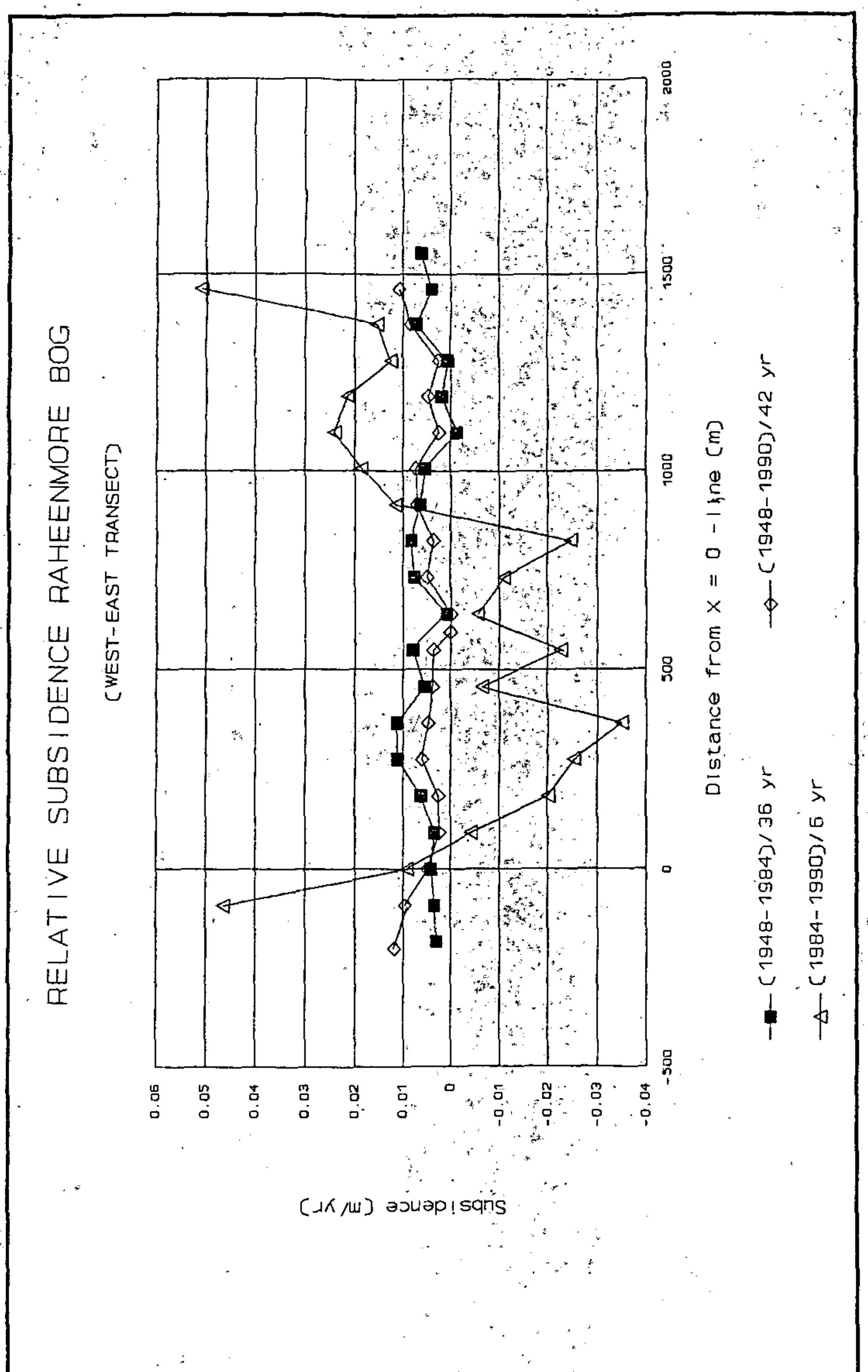

Figure 10 Relative subsidence Raheenmore bog West-east transect

Figure 10 shows on average a surface subsidence of 10-30 cm over the last 42 years (0.2-0.7 cm/year). During the last 6 years the central part of the bog has risen on average 10 cm, but at the periphery it has fallen 10-30 cm (1.7-5.0 cm/year).

Note:
The rise of the bog surface has occurred at that part of the bog where the acrotelm was present, i.e. the part where "Mooratmung" or bog surface oscillation took place (Bader et al., 1964). The subsidence has happened at the bogs periphery (approximately the first 200 m from the marginal drain). At this area the acrotelm was absent.

The plot of the elevations along the South-north transect, suggests a rise of 10-15 cm in 42 years. However, when drawing a smooth line through the elevation data of the two years, no rise can be seen. Also a surface rise would be strange at an area where the acrotelm is absent, for it is the acrotelm where both the peat production and surface oscillation take place. Probably the suggested rise was caused by local variability of the surface elevation (consideration 1, § 4.3).

On the other hand presence of acrotelm can cause temporary rise of the surface. Due to these surface oscillations the elevation in the summer is probably somewhat lower than in autumn (wetter) of the same year. A difference of say 10 cm, would let the difference in elevation between 1984 and 1990 disappear. Moreover, then the long-term subsidence (1948-1990) would also be 10 cm higher (30-40 cm). However, the subsidence rate would still be small; below 1 cm/year. At the periphery where the acrotelm was absent, this effect could be neglected, so that these values were rather representative for the subsidence.

Assuming that the elevation data were acquired by means of appropriate levelling (which can cause problems at the part of the bog with a well developed acrotelm) the following general conclusions might be drawn (§ 4.5).

4.5 Conclusions and recommendations

4.5.1 Conclusions

1) The impact of the former peat extraction and drainage at the margins showed a general subsidence of Raheenmore bog over last 36-42 years varying between 0-1 cm/year. This was below average as mentioned by Ivanov (1981). The southern part of Raheenmore bog the rate of subsidence was higher than at the northern part.

2) The improvement of the marginal drainage system showed an increasing rate of peripheral subsidence during the last 6 years. The rate of subsidence was at the periphery (first 100-200 m from the marginal drain) 5 cm/years. No significant changes in subsidence rate of the rest of the bog could be noted. According the theory the rate at the periphery will gradually slow down (when the same water level is maintained in the marginal drain).

4.5.2 Recommendations

1) In order to monitor potential changes in subsidence rates the surface levelling should be repeated, say over a period of 5 years. Then also the values of rates at the periphery due to the amelioration works can be verified. By leaving the current pegs in position the exact locations for the levelling can be taken.

2) Installation of fixed equipment where the subsidence of the surface can be monitored accurately.

3) Repetition of the acrotelm mapping in order to monitor the changes along the periphery (including monitoring of potential changes in vegetation). Again current and future aerial photographs are needed with this kind of work.

5 QUALITY CHECK OF GROUND WATER DATA

5.1 Introduction

Part of the hydrological field work consists of a two-weekly acquisition of ground water levels. These levels (phreatic and piezometric heads) are stored in a computer data base. In this way the field data can easily be accessed e.g. by a computer model of the water balance.
During the acquisition and storage of the ground water data errors can occur. Obviously before using the ground water data in a model of the water balance these data should be checked for possible errors (= quality check).

In this part of the thesis the quality check of the ground water data of Raheenmore bog (1990) is discussed.
These data were acquired from two transects of observation wells by various people. Together these transects contain slightly more than the 148 observation wells used for this research. Most of the observation wells have a diameter of 0.025 m, the remaining part 0.05 m. All are made of p.v.c., except the wooden sticks in the drains. The measurements were done by means of an acoustic dipper.

A set of ground water data can be seen as a hydrologic time series which consists of deterministic and stochastic components. The mentioned quality check implied the removal of the deterministic components and application of standard statistical techniques on the remaining stochastic components. Using these techniques (auto- and cross correlation) estimates could be made of the original ground water data. The differences between the newly acquired estimates and the original data were a measure for the quality of the set.

The quality check applied in this inquiry was developed and discussed by van der Schaaf (1986). Consequently part of the theory was adopted from this report. This quality check was based on the standard statistical theory on time series. A part of this theory was adopted from Yevjevich (1972).

At first in § 5.2 the statistical background of (hydrologic) time series is reviewed. In § 5.3 the auto- and cross correlation are described. Further in § 5.4 is dealt with the procedure of the used quality check. Next the results of this quality check are discussed. Because nothing special can be seen from a reliable data set, these results are more focused on the kind of occurring errors in the original data set (§ 5.4). Finally conclusions are drawn in § 5.5

5.2 Hydrologic Time Series

A time series is a sequence of a variable which is observed or recorded in time, such as the ground water levels at Raheenmore bog. It will generally consist of stochastic components superimposed on deterministic components (Haan, 1982). Figure 11 shows the simplified time series as assumed by van der Schaaf (1986) for the "Gelderse Vallei" and applied in this research.

5.2.1 Deterministic components

Transient series:

These types of series are only casual components of hydrologic series, superposed on other components - usually on periodic and stochastic components. These transient components are best described by a deterministic time-varying function and can be of any shape. However, two simple types of transient components are , most commonly detected in hydrology - linear, or nonlinear trends of power functions type, and jump (Yevjevich, 1972)

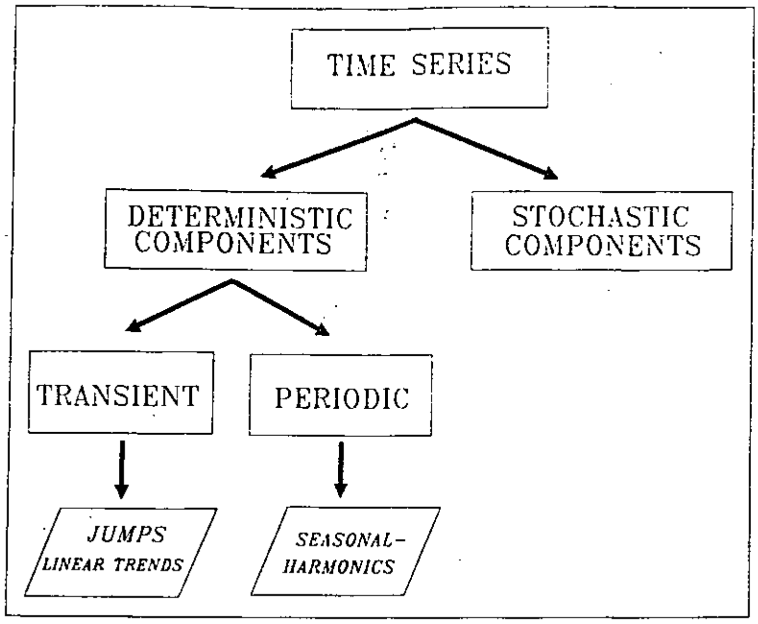

Figure 11 Simplified composition of a hydrologic time series

Trends in a hydrologic time series can result from gradual natural or man-induced changes in the hydrologic environment producing the time series. For example, a gradual change in the watershed characteristics of the time series with the time. For a relatively short series (few years), an apparent trend can also be caused by for example a sequence of wet or dry years (van der Schaaf, 1986).

Another transient component is the jump. It occurs in the mean of a stochastic time series, though, it may be present in any other parameter of a hydrologic time series. Jumps are created by sudden changes that are either man-made or they occur by various kinds of changes in nature (Yevjevich, 1972).

In § 5.3 the double-mass technique is discussed which sometimes is applied in the hydrology to check the data set's consistency, e.g. for possible jumps.

Periodic series:

Astronomic cycles are generally responsible for periodicities in natural hydrologic time series. Normally the most important is the seasonal component, i.e. a period of one year. This is the only period considered in the data set.

5.2.2 Stochastic components

Generally a time series consists of stochastic and deterministic components. After identification of these deterministic components, estimation of their parameters, and removal of these components from the series, the stochastic components will remain. Most of these components may be considered approximately stationary once the known deterministic components have been removed.
The considered time series are referred to as stationary time series, and are important in hydrology mainly for the reason that the mathematical techniques for the analysis of this series are well developed (Yevjevich, 1972).

Two of these techniques for the analysis of the remaining stochastic components of the series are the auto- and cross-correlation. Both techniques can be used to estimate values respectively within and between time series. These are discussed in the next section.

5.3 Auto-correlation and Cross-correlation

5.3.1 Estimation using data from the same time series

The investigation of the sequential properties of a series by autocorrelation analysis is already a classical statistical technique. It is used to determine the linear dependence among the successive values of a series that are a given lag apart.

In the case of two series, the lag cross correlation, with the positive or negative lag, gives the linear dependence of the successive values of the two series that are a given lag apart. According to Yevjevich (1972) there is sufficient support for the use in hydrology of linear autocorrelation and linear lag cross correlation.

For discrete time series used in this study, the population autocorrelation coefficient ρ_k, for lag k is defined by:

$$\rho_k = \frac{cov(x_t, x_{t+k})}{\sqrt{var(x_t)\ var(x_{t+k})}} \tag{2}$$

in which x_t and x_{t+k} are observations at time t and t+k, respectively, cov (x_t, x_{t+k}) is the autocovariance function, and var (x_t) and var (x_{t+k}) are variances at lag 0 and lag k, respectively.

For the open time series, ρ_k, is estimated by the sample correlation coefficients r_k, as follows (Bullard et al., 1976):

$$r_k = \frac{\frac{1}{n-k}\sum_{t=1}^{n-k} x_t x_{t+k} - \frac{1}{(n-k)^2}\sum_{t=1}^{n-k} x_t \sum_{t=1}^{n-k} x_{t+k}}{\sqrt{\frac{1}{n-k}\sum_{t=1}^{n-k} x_t^2 - \frac{1}{(n-k)^2}\left(\sum_{t=1}^{n-k} x_t\right)^2}\sqrt{\frac{1}{n-k}\sum_{t=1}^{n-k} (x_{t+k})^2 - \frac{1}{(n-k)^2}\left(\sum_{t=1}^{n-k} x_{t+k}\right)^2}} \tag{3}$$

with n = the total number of sample observations and {n-k} = the number of pairs (x_t, x_{t+k}).

The values of ρ_0 and r_0 are 1, because these are related to two identical series. The ρ_k of the two-weekly ground water observations at the Irish raised bogs, shall quickly approach 0 when k increases. This because of the quickly reacting ground water levels. The previous levels (k=-1) contain relatively less information on the considered levels, i.e. relatively low correlated. This indicates that for the ground water levels of such time series almost always states:

$$r_1 > r_k, \qquad k > 1 \tag{4}$$

Hence, for a value of x_t in the series can be expected that it resembles the most the directly preceding x_{t-1} (or the next value x_{t+1}).

For the considered observation network it is assumed that for series ρ_2 is much smaller than ρ_1. In such a situation it is of less value to use values in the estimations else then the directly preceding, respectively, next value.

This results in the use of a simple estimation model:

$$\hat{x}_t = x_{t-1} \tag{5}$$

and

$$\hat{x}_t = x_{t+1} \tag{6}$$

A combination of (5) and (6) yields:

$$\hat{x}_t = \frac{x_{t-1} + x_{t+1}}{2} \tag{7}$$

This is a linear interpolation between the two neighbour values of x_t.

Estimation methods (5) and (6) are only as good as (7), when for all x_t the information in x_{t-1} the same is as in x_{t+1}, vice verse; with the assumption of stationarity in the expectation E(x), and $\rho_2 < 1$ (van der Schaaf, 1986).

Using (7) requires a value directly preceding and a value directly following the value to be estimated. Application of (5) or (6) require only the directly preceding, respectively, next value. More than two missing observation in sequence can not be estimated with models (5), (6) or (7). Then another technique must be used as discussed next.

5.3.2 Estimation with help of the best resembling series

The technique used is linear regression. For estimation of value x_t in a series i on observation time t, we must have access to another synchronic series j, in which on time t an observation is available. The two series i and j need to be correlated as good as possible. This in order to get an estimation as good as possible. The best with i correlated series j can be found by means of a correlation structure of m-series $x_{i,t}$. This can be visualized by an assembly of correlation matrices (Salas et al., 1980 § 2.5; in: van der Schaaf, 1986):

$$\hat{M}_k = \begin{pmatrix} r_{11,k} & r_{12,k} & \cdot & \cdot & r_{1m,k} \\ r_{21,k} & r_{22,k} & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ r_{m1,k} & \cdot & \cdot & \cdot & r_{mm,k} \end{pmatrix} \tag{8}$$

where

$r_{ij,k}$ is the estimated correlation coefficient of the series which consists of respectively the first n-k values from series i and the last n-k value from series j.

$\hat{M}_k$ is diagonally symmetric: $r_{ij,k} = r_{ji,k}$. $\hat{M}_0$ contains the estimated correlation coefficients of all pairs from series which compared to each other are not shifted in time. The diagonal $r_{ii,k}$ shows the estimated autocorrelation coefficients r_k of the series $x_{i,t}$.

The element from the assembly

$$r_{ij,k} \in \hat{M}_k \wedge i \neq j \wedge 0 < i \leq m \wedge 0 < j \leq m \qquad \textbf{(9)}$$

with the highest absolute value, provides the most suitable series j for estimating the value on the t-th position in series i, when the series j contains an observation on position t+k. When this is not the case, then the second largest value $|r_{ij,k}|$ is chosen, etc. In practice most of the time it is enough to find the highest $r_{ij,k}$, because high negative correlations between ground water series very seldom occur (van der Schaaf, 1986).

Presumable the $|r_{ij,0}|$ have a higher value than the corresponding $|r_{ij,k}|$, k>0. The in-time-shifted ground water series look less similar than the not-in-time-shifted series (k=0), certainly in the Irish raised bogs where the ground water table oscillates rapidly.

That is why it is reasonable to use only $\hat{M}_0$ to evade loads of computation with low efficiency. Therefore, in the ensuing text ground water series are used without considering a time lag.

The estimation method used is the least squares method which estimates parameters a and b of the model:

$$x_{i,t} = a + b\, x_{j,t} \qquad \textbf{(10)}$$

and next the estimated model was used to estimate the value $x_{i,t}$.

5.4 Quality check

5.4.1 Introduction

Ground water levels at Raheenmore bog are recorded every two weeks. These levels (phreatic and piezometric heads) are stored in a computer data base. In this way the field data can easily be accessed by e.g. a computer model of the water balance.
During the acquisition and storage of the ground water data errors can occur. Obviously before using the ground water data in a model of the water balance these data should be checked for possible errors. This is further referred to as quality check.

This quality check can be divided into:

1) identification of the deterministic components, estimation of their parameters, and removal of these components from the series;
2) after removal of the deterministic components, identification of the remaining stochastic components.

Auto- and cross correlation are standard statistical techniques which can be used for the examination of the remaining stochastic components. Using these techniques estimates can be made of the original ground water data. Differences between these original data and the acquired estimates are a measure for the quality of the original data set.

In the next sub-section the in this inquiry used quality check is discussed step by step.

5.4.2 Procedure

One of the aims of this part of the inquiry was to obtain a reliable ground water data set for Raheenmore bog. Such a set is indispensable for proper research on the hydrology c.q. water balance.

A reliable data set could be obtained by implementation of a quality check on the original ground water data. The flow chart of the used procedure is depicted in Fig.12. In the ensuing text the separate elements of this chart are discussed (The underlying time series theory was dealt with in the previous section).

Identification and removal of jumps

Double-mass curves:

The observation wells on Raheenmore were levelled a few times in the last years (North-south (Wildlife) transect: 1987, 1990 and 1991; East-west (Dutch) transect: 1989, 1990 and 1991). Differences in the acquired elevations suggested inconsistency of the wells, and therefore also of the ground water data. In order to get some insight in this assumed inconsistency the double-mass curves technique was applied upon the ground water data.

The double-mass curve is a simple method to check the consistency of many kinds of hydrologic data by comparing these data for a single station with that of a pattern composed of data from several other stations in the area. Amongst others, it can be used to adjust inconsistent precipitation data.
The graph of the cumulative data of one variable versus the cumulative data of a related variable is a straight line so long as the relation between the variables is a fixed ratio. Changes in this ratio causes breaks in the double-mass curve. These changes may be due to changes in method of data collection or to physical changes that affect the relation (Searcy et al., 1963).
The observation wells within the East-west transect were selected for the consistency check. Water depth of three deep piezometers (206D,210D and 212D, all ≈ 5m deep) were taken as pattern. The average value of this pattern (which was assumed consistent in time) per time-step (observation date) was accumulated and compared with the cumulative values of other observation wells. Appendix 8 shows an example of the double-mass curve of the accumulated waterdepth of observation well 204D (≈ 4.5m deep) and the pattern.

Consistency would imply one straight line so long as the relation between the variables is a fixed ratio. Hence, deviations from one straight line (e.g. a bench or curve) would indicate inconsistency.

In order to magnify the deviations of the double-mass curve in Appendix 8, residual values were computed.
A straight line was fitted through the double-mass curve using linear regression. The residual values were obtained by subtracting the regression line from the double-mass curve. The residuals together with their accumulated values were plotted against time. These accumulated residuals are an amplification of the residuals (See Appendix 9).

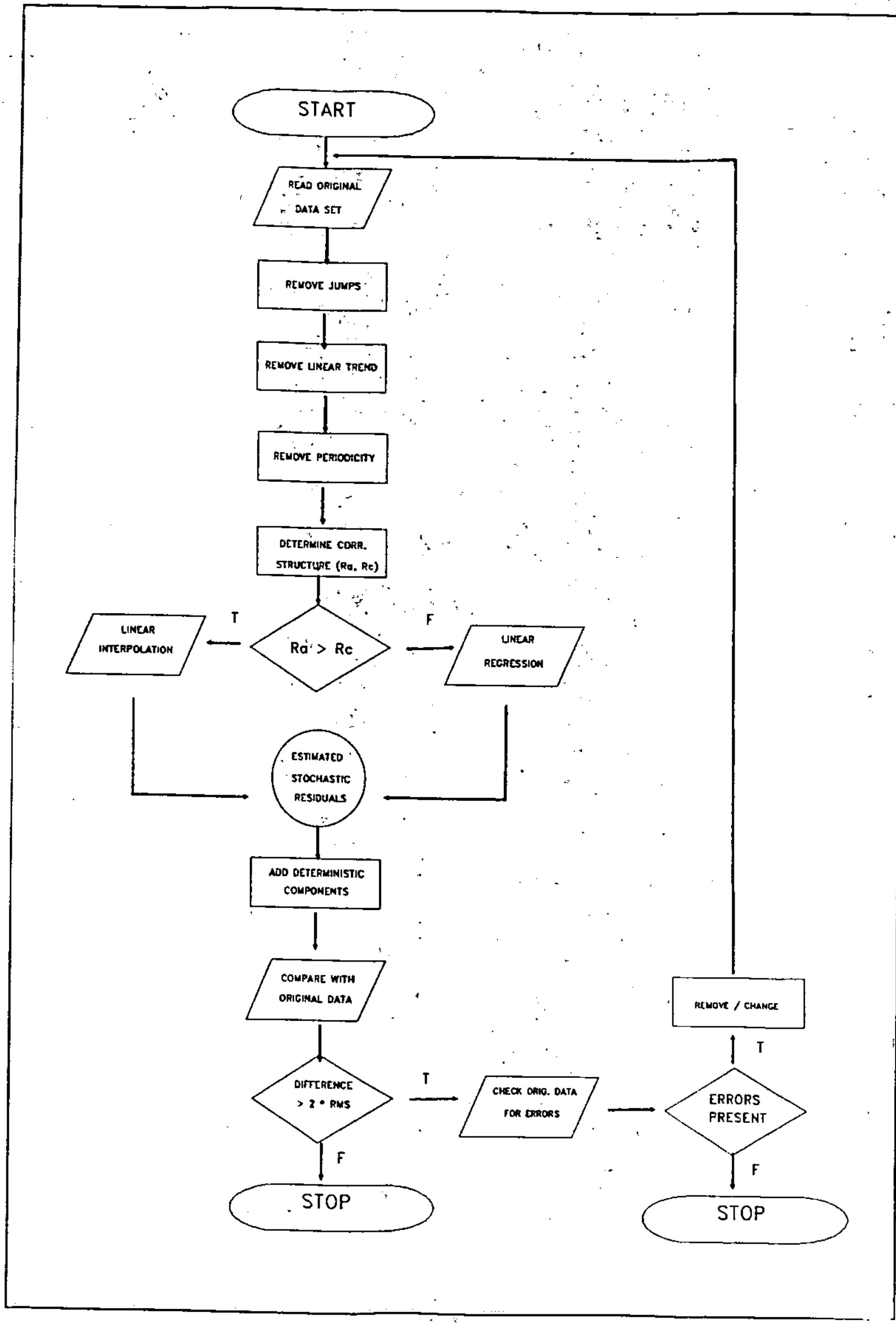

Figure 12 Quality check ground water level data

(The residual curve is a sine with period one year and a few superimposed harmonics. When integrating this sine (= accumulated residuals curve) the harmonics will attenuate: Integral { sin(x) + sin (2x) } = cos (x) + 0.5 sin (2x) + c. This is why the curve of the accumulated residuals is a "nicer" sine.)

Appendix 9 shows a certain seasonal effect in the ground water data of well 204D compared with the average data of the pattern. Other tested observation wells showed a same kind of effect.
There were a few possible explanations for this effect:

a) the ratio between the accumulated water depth of the observed well and pattern was not fixed, but periodical;
b) the observed well fluctuated (between 0-15 cm which could be caused by "surface oscillation") and therefore not consistent, including it's ground water data;
c) a) and b).

Hence, the double-mass technique appeared not to be a proper tool for the consistency check of the observation well data. Consequently, with regard to these curves, no further conclusions were drawn i.e. modifications of the original data set.

Correction of data using historical information:

The observation wells most of the time are clustered in a set of 4 to 6 (phreatic and piezometer) wells. Although installed at the same elevation, the wells had moved relative to each other in time. This movement was assumed to be stopped by connecting the wells with timber. After this the wells were "topped", i.e. cut at the same level. This was done at the end of 1990.

Consequently: 1) the levelling of such a set could be done by only one reading; 2) the observations of a such a set could already be compared in the field, and therefore reduces the change on "misreading"; 3) the deep piezometers which were assumed to be consistent could hold the shallower ones at the same level.
However, the topping of observation wells caused jumps in the ground water data set. In order to compare ground water data before and after the topping, they should be corrected for present jumps. Then besides comparison of ground water data within a series (autocorrelation) they also can be compared with another series (cross correlation). Hence, for further analysis of the ground water data first the jumps had to be identified and removed.

Identification and removal of linear trend

Trends in the ground water data can result from gradual natural or man-induced changes in the hydrologic environment. Although many types of trends are possible in this inquiry only a possible linear trend was assumed. This trend could be estimated according:

$$x_t = a + b_t \qquad (11)$$

with a the shift and b the coefficient of the trend. The constants a and b could be estimated using linear regression (van der Schaaf, 1986).

Identification and removal of periodicities

Astronomic cycles are generally responsible for periodicities in natural hydrologic time series. Such periodicities can be estimated by a Fourier series, which is represented by a fundamental period ω and some or all of its subharmonics.

Each periodic hydrologic parameter is modeled as a sum of several independent sine and cosine functions.

Thus, if υ_t is the value of any periodic parameter (such as the mean ground water level) at time t within a fundamental period ω of a given hydrologic series, then (Bullard et al., 1976):

$$\nu_t = \overline{\nu} + \sum_{j=1}^{l} \left[A_j COS\left(\frac{2\pi jt}{\omega}\right) + B_j SIN\left(\frac{2\pi jt}{\omega}\right) \right] \qquad (12)$$

where

$$\overline{\nu} = \frac{1}{\omega}\sum_{t=1}^{\omega} \nu_t \qquad (13)$$

the mean of the υ_t series, with υ_t the parameter values along the period ω, and l = number of significant harmonics.

The Fourier coefficients A_j and B_j of significant harmonics, are obtained from estimates V_t of υ_t by using the least squares estimation method (Bullard et al., 1976):

$$\hat{A}_j = \frac{2}{\omega} \sum_{t=1}^{\omega} V_t \cos\left(\frac{2\pi jt}{\omega}\right) \qquad (14)$$

and

$$\hat{B}_j = \frac{2}{\omega} \sum_{t=1}^{\omega} V_t \sin\left(\frac{2\pi jt}{\omega}\right) \qquad (15)$$

Normally the most important is the seasonal component, i.e. a period of one year. Accordingly, this period was the only period considered in the ground water data set.

Applying (12) can be disputable in certain circumstances, depending on the relation of standard deviation and expectation of x(t). (Yevjevich, 1972; Bullard et al., 1976). In the ensuing research (12) was used without applying these considerations.

Computation autocorrelation and cross correlation

After identification and removal of the deterministic components only the stochastic components of the time series were assumed to remain.

Using these (stationary) stochastic components first the auto- and cross correlation were estimated. Next the estimated autocorrelation (r_a, lag 1) was compared with the estimated cross correlations (r_c, lag 0) of the well of interest.

On the one hand when the autocorrelation coefficient was larger than the cross correlation, a simple linear interpolation was used to estimate the residual of the well of interest. This was done using adjacent observations. Though on the other hand when the cross correlation coefficient was equal or larger than the autocorrelation coefficient, the desired residual was estimated using linear regression (Fig.12).

Further, the to the newly acquired stochastic set of residuals, the earlier removed deterministic components were added again. In this way a set of estimated ground water levels was obtained for (possibly) each observation well and date.

Comparison observed and estimated ground water levels

The obtained set of estimated ground water data was compared with the original set of field data. When the difference between the original and estimated data was more than twice the value of the standard deviation of the original series, output was produced. In this way doubtful data could be examined more carefully. Data were changed, or removed from the original set, only when sufficient reason was available. In other cases no action was undertaken.

A reliable ground water data set was assumed to be acquired after repetition (3 times) of the above mentioned procedure.

Nota bene,
the major part of the procedure was automated except for: a) the identification and removal of possible jumps in the original ground water data set; b) the check for possible errors in the set after the comparison with the estimated data set, and; c) the possible changes and/or removals of original ground water data.

5.4.3 Influence of missing data

The parameters of the two estimation models had to be determined with a series including missing ground water data. During the estimation using the data of another series (regression), no special difficulties are countered, as long as a reasonable amount of data is available. This is also the case when trend and annual cycle are to be determined.

In the described research a two weekly measured observation set from January 1990 until January 1991 was used. Only an estimation was made with 50% or more data available. Otherwise no estimation was done.

The limitation during the estimation of data using data of the same series (linear interpolation) are already mentioned in § 5.3.1. During estimation using linear regression the availability of data for the considered date in other series than the considered are necessary. When in the data base all the data from one observation day were missing, again no estimation was performed.

5.5 Results, conclusions and recommendations

For 1990 a reliable ground water data set of Raheenmore bog was acquired after execution of the quality check. Besides a reliable data set, also the detected errors in the original set are important for further research.
Analyzing these data errors can reduce them during further acquisition and storage. Therefore the errors detected during this quality check are listed next:

Acquisition errors

1) decimeter error, i.e. reading the centimetres at the ruler (dipper) and adding wrong decimeters (36 <---> 26);
2) writing error, i.e. writing the reading wrongly (64 <---> 46);
3) shifting error, i.e. shifting the readings within an observation nest (in sequence: A, E, C, D with readings of respectively A,C,D,E);

Storage errors

1) typing error, i.e. typing another data than shown on the field register.

Of all detected errors 30% was a result of a **typing error!** Therefore, another storage method is suggested which implies double input of field data into the computer data base. At the end of the first session, the total input procedure must be repeated. Consequently, the second data input can be compared automatically (computer program!) with the first one, and in this way reduces significantly the errors category.

Also another storage method is suggested for the fixed observation well data such as among others position and altitude of the well. The new method should allow a computer program direct access to the fixed data in order to combine them with the ground water field data. In this way this field data (with reference level top observation well) can automatically be transformed to ground water levels (with reference level e.g. Ordnance Datum).

6 CONCLUSIONS AND RECOMMENDATIONS

For the development of programs concerning conservation and management of two Irish raised bogs (Clara and Raheenmore bogs), specific knowledge is required, among others hydrologic knowledge. This hydrologic knowledge was assumed insufficient. Therefore, in the study of this thesis four aspects were examined which were assumed to improve this hydrologic knowledge:

1) The determination of the catchments of both Clara and Raheenmore bogs using surface contour maps.
2) The application of a method for the acrotelm mapping of Raheenmore bog.
3) The determination of the impact of former peat extraction and marginal drainage on the surface elevation of Raheenmore bog.
4) The quality check of the ground water data of Raheenmore bog.

Ad 1) Catchment determination

Conclusions

The contour maps computed according the Kriging interpolation (within SURFER) could be used for the assessment of the catchment boundaries. Consequently the sizes of the catchment areas of Clara (west) and Raheenmore bogs could be estimated; 100 ha and 33 ha, respectively. However no verification was realised which is certainly necessary. Especially for Raheenmore bog where a little shift of the catchment boundaries can result in significant changes of area, due to the "boot-shape" of this area.

Recommendations

The dimensions of the catchment areas should be verified using cumulative values of rainfall, discharge and estimated evapotranspiration for a period between to equally wet field conditions. Moreover, presumably aerial photographs can provide extra information about the catchments' dimensions.

Ad 2) Acrotelm mapping

Conclusions

At 50 % of Raheenmore bog no acrotelm was present. This was equal to approximately the first 100-200 m of the periphery.
(This value was obtained by using the conventional foot/spade method.)

The non-destructive wire method provided information on the depth of the sulphide zone in February. These depths probably were an underestimation of the acrotelm's thickness, and therefore could be seen as minimum depths. Probably also the spatial variability of the acrotelm is somewhat exaggerated.

Recommendations

The wire method should be repeated at the end of the summer (September) when the ground water table is at its lowest and the temperatures higher.
Another method is suggested which uses an auger. This method can be applied at any time of the year. However, it is a destructive method.
Besides the determination of the thickness of the acrotelm and the measurement of it's transmissivity also it's composition, i.e. type of *Sphagnum*, should be mapped. Probably aerial photographs can be used for this purpose.

Ad 3) Surface subsidence

Conclusions

1) The impact of the former peat extraction and drainage at the margins showed a general subsidence of Raheenmore bog over last 36-42 years varying between 0-1 cm/year. This was below average as mentioned by Ivanov (1981). The southern part of Raheenmore bog the rate of subsidence was higher than at the northern part.

2) The improvement of the marginal drainage system showed an increasing rate of peripheral subsidence during the last 6 years. The rate of subsidence was at the periphery (first 100-200 m from the marginal drain) 5 cm/year. No significant changes in subsidence rate of the rest of the bog could be noted.

Recommendations

1) In order to monitor potential changes in subsidence rates the surface levelling should be repeated, say over a period of 5 years. Then also the values of rates at the periphery due to the amelioration works can be verified. By leaving the current pegs in position the exact locations for the levelling can be taken.

2) Installation of fixed equipment where the subsidence of the surface can be monitored accurately.

3) Repetition of the acrotelm mapping in order to monitor the changes along the periphery (including monitoring of potential changes in vegetation). Again current and future aerial photographs are needed with this kind of work.

Ad 4) Quality check

Conclusions

The errors present in the ground water data base used for the quality check could be divided into two types:

Acquisition errors

1) decimeter error, i.e. reading the centimetres at the ruler (dipper) and adding wrong decimeters (36 <---> 26);
2) writing error, i.e. writing the reading wrongly (64 <---> 46);
3) shifting error, i.e. shifting the readings within an observation nest (in sequence: A, E, C, D with readings of respectively A,C,D,E);

Storage errors

1) typing error, i.e. typing another data than shown on the field register (Of all detected errors 30% was a result of a typing error!).

Recommendations

Therefore, another storage method is suggested which implies double input of field data into the computer data base. At the end of the first session, the total input procedure must be repeated. Consequently, the second data input can be compared automatically (computer program!) with the first one, and in this way reduces significantly the errors category.
Also another storage method is suggested for the fixed observation well data such as among others position and altitude of the well. The new method should allow a computer program direct access to the fixed data in order to combine them with the ground water field data. In this way this field data (with reference level top observation well) can automatically be transformed to ground water levels (with reference level e.g. Ordnance Datum).

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Y      3           -527            591           -600            600
Z      4           98.5         107.17

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     Discard data: Yes                      Nearest Points: 8
Duplicate points: Delete                       X Grid Size: 77 (25)
      Grid Method: Kriging                     Y Grid Size: 49 (25)

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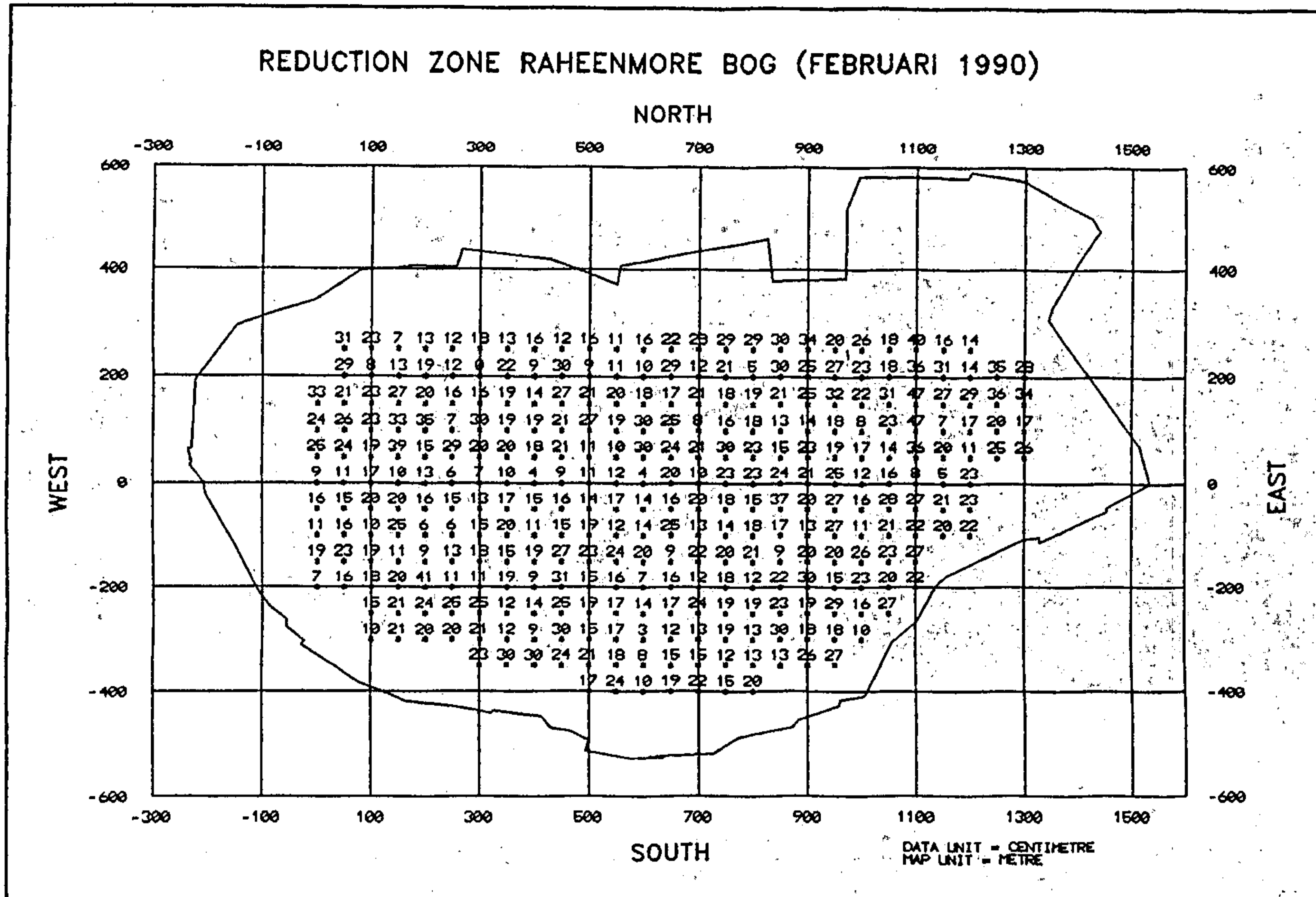
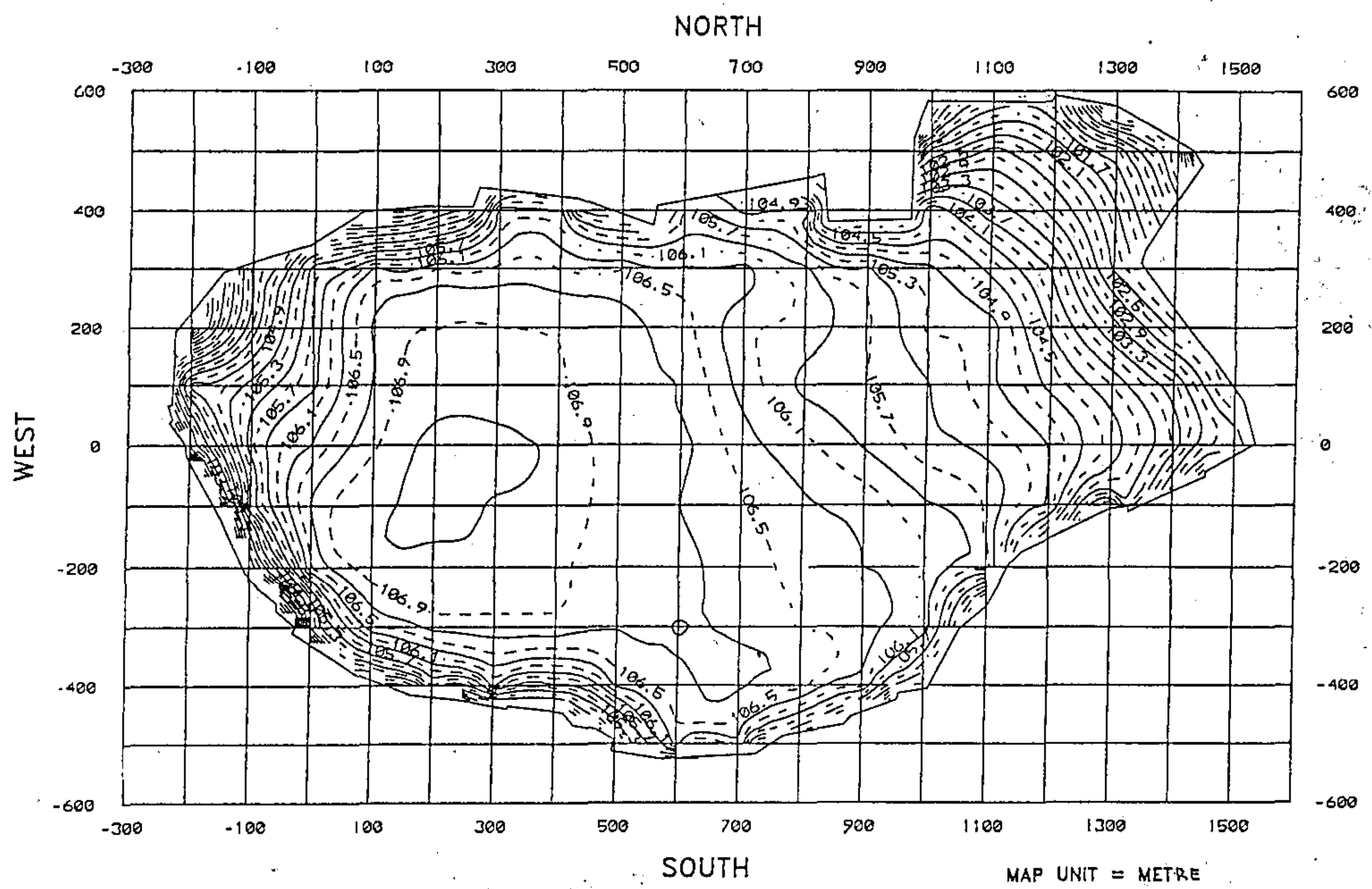
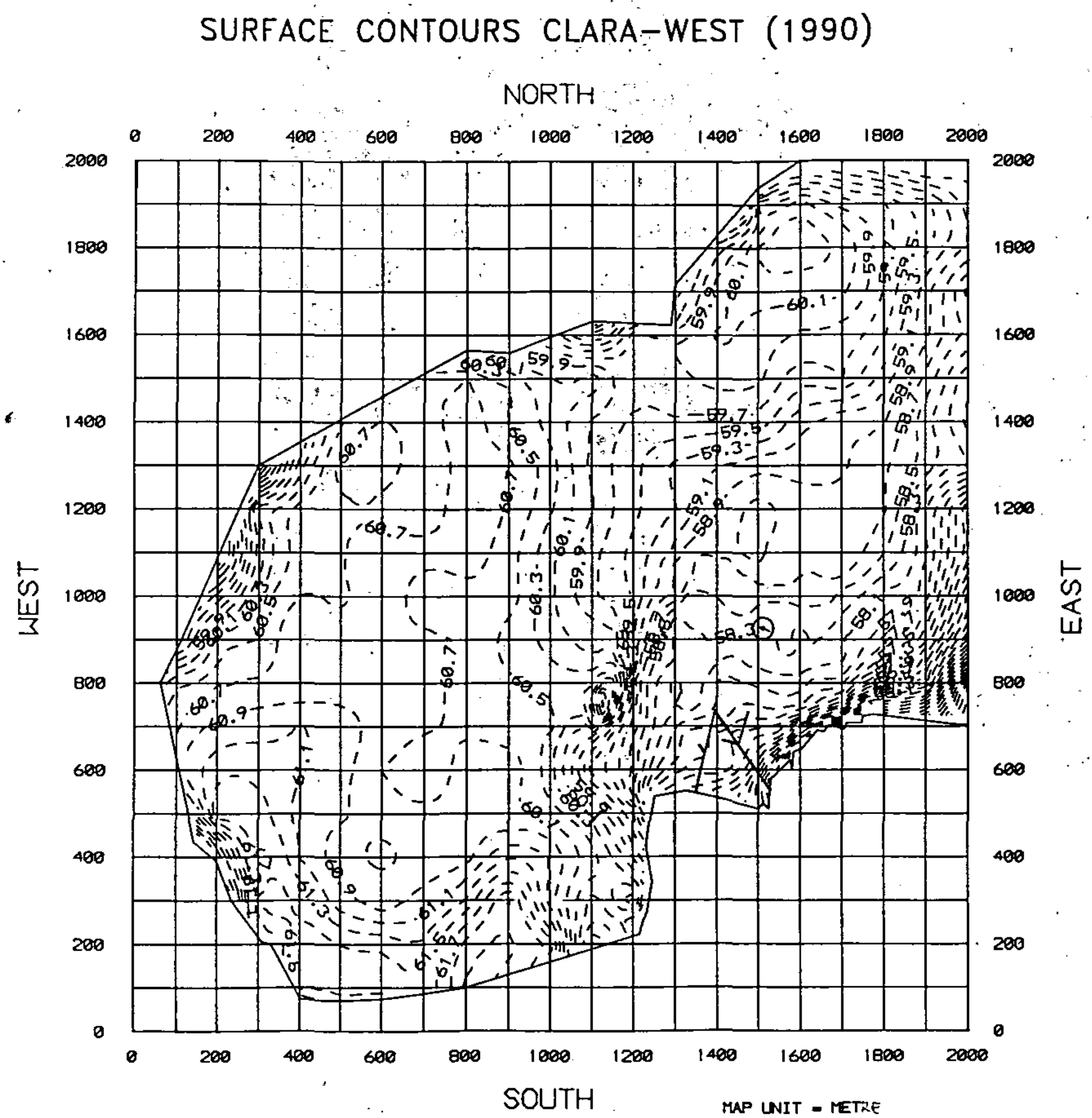


APPENDIX 1A DATA POINTS SULPHIDE (REDUCTION) ZONE

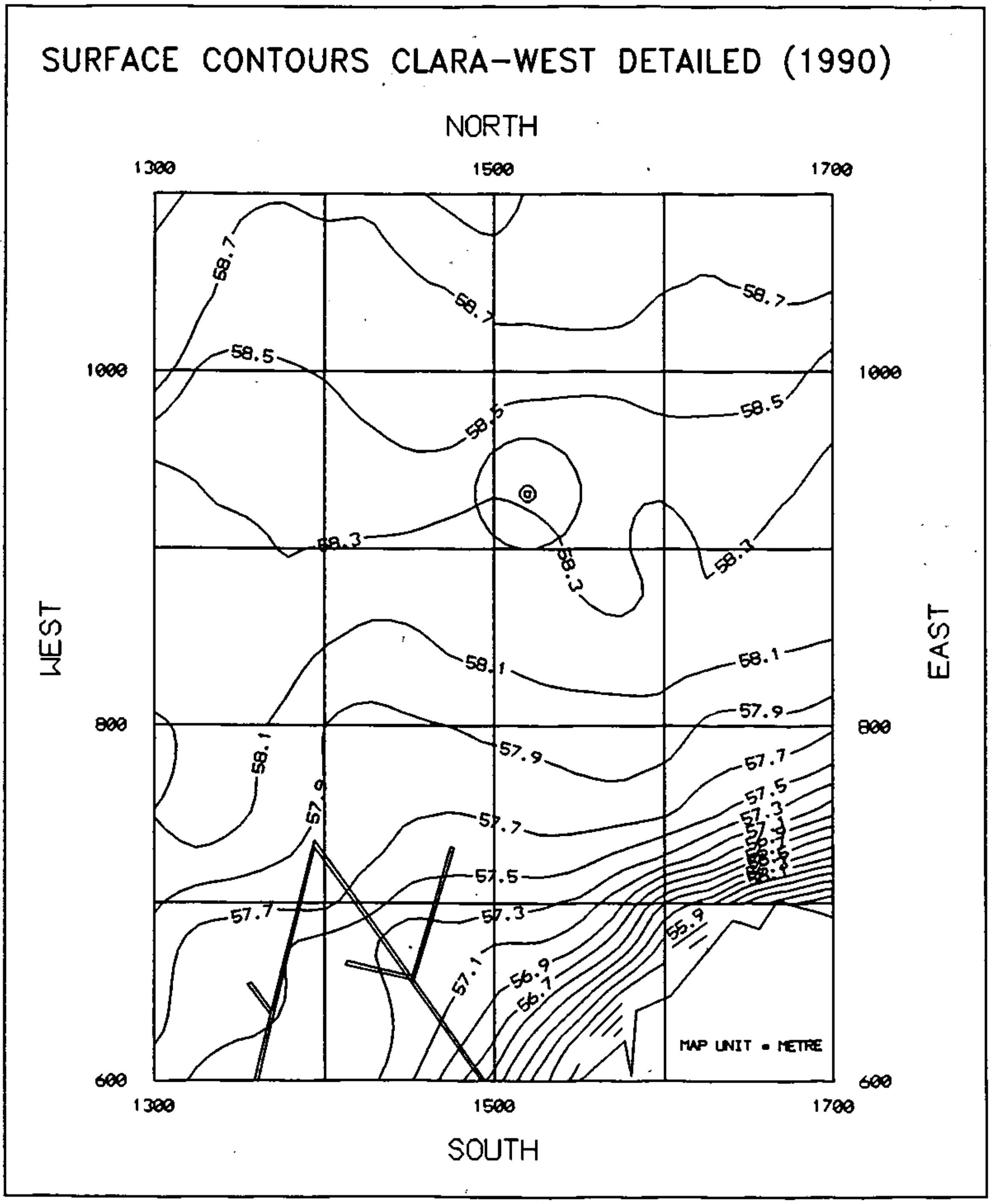
SURFACE CONTOURS RAHEENMORE BOG (1990)



APPENDIX 3 SURFACE CONTOUR MAP CLARA BOG (WEST)

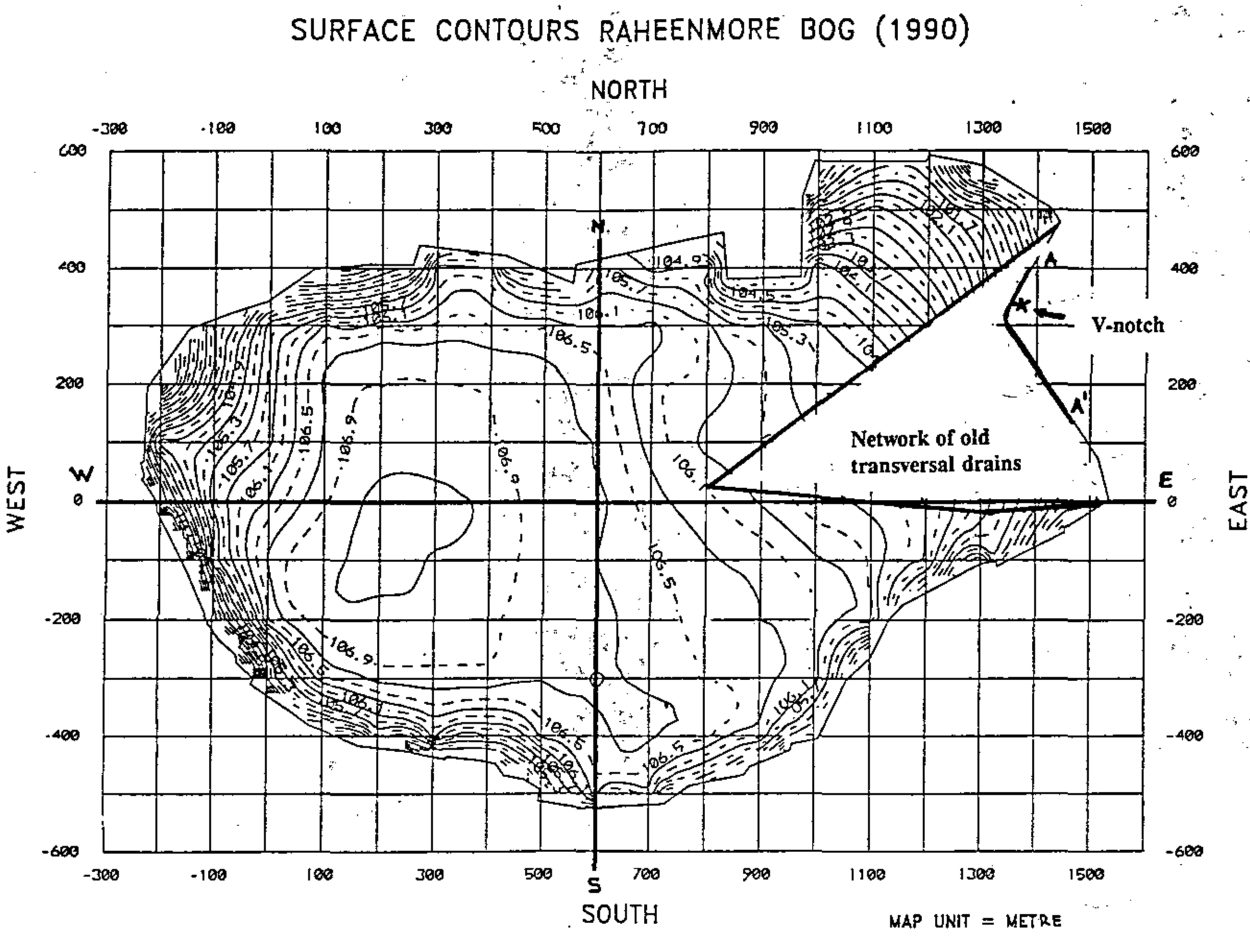


APPENDIX 4 SURFACE CONTOUR MAP SOAK CLARA BOG

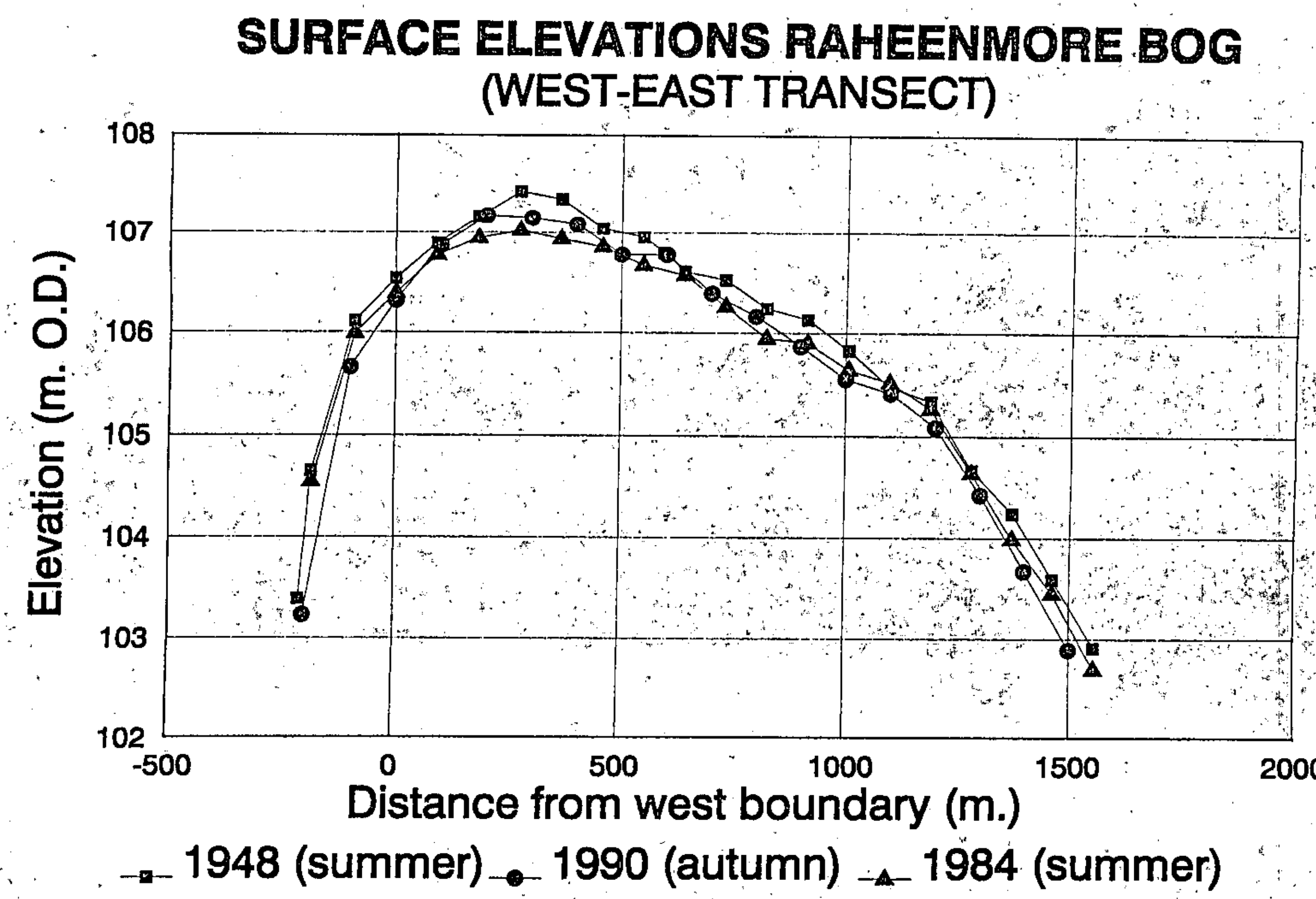


APPENDIX 5 RAHEENMORE BOG; WEIR, COLLECTOR DRAINS, LEVELLING TRANSECTS

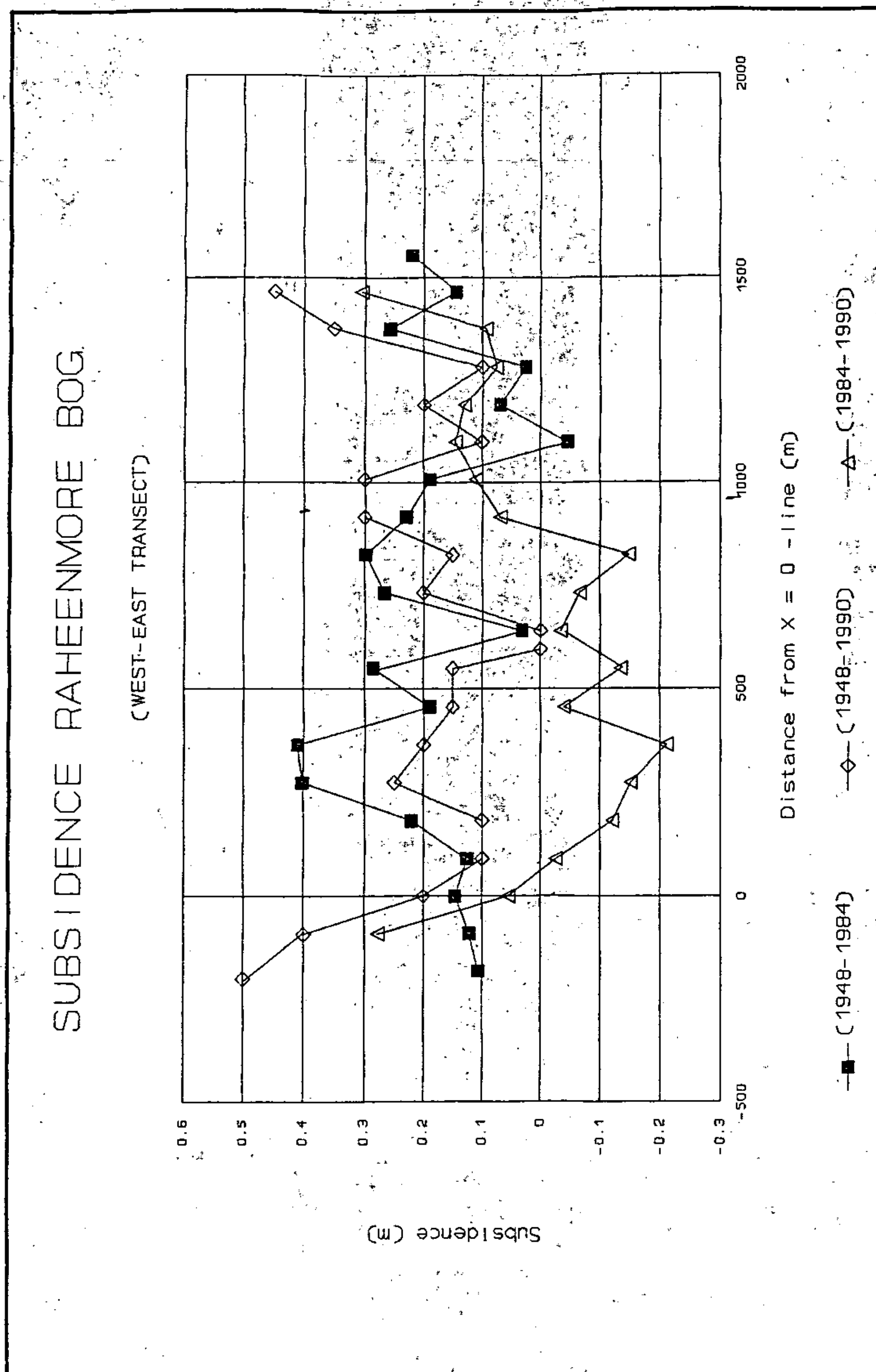
A-A' : Collector drains
S-N : South-north levelling transect
W-E : West-east levelling transect



APPENDIX 6 SURFACE ELEVATIONS ALONG WEST-EAST TRANSECT (RAHEENMORE BOG)

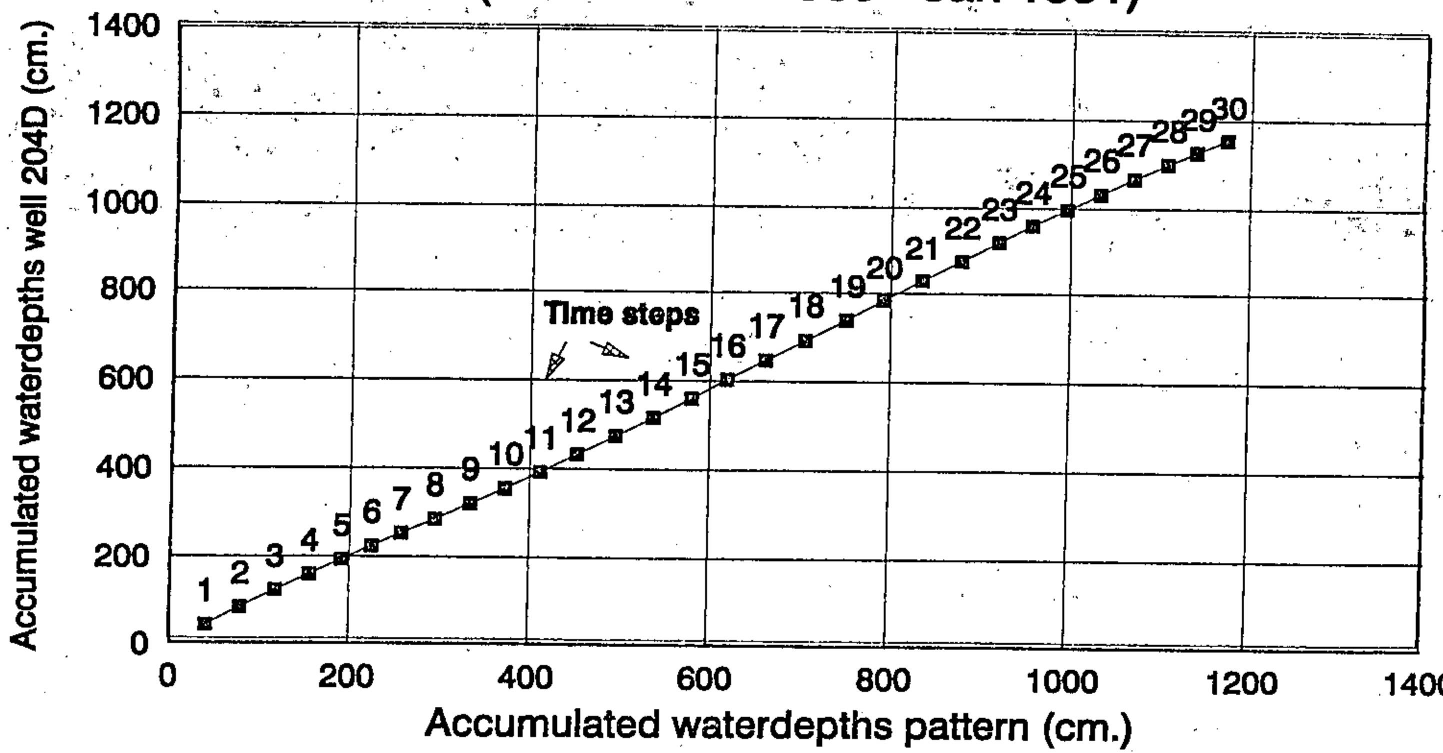


APPENDIX 7 RELATIVE DIFFERENCES SURFACE ELEVATION ALONG WEST-EAST TRANSECT (RAHEENMORE BOG)



DOUBLE-MASS CURVE RAHEENMORE

(Period: Dec 1989 - Jan 1991)



Pattern = average of wells (206D, 210d and 212D)