IRISH - DUTCH RAISED BOG STUDY
GEOHYDROLOGY AND ECOLOGY

- National Parks and Wildlife Service of the Office of Public Works, Dublin
- Geological Survey of Ireland, Dublin
- Department of Nature Conservation, Environmental Protection and Wildlife Management, The Hague
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Hydrological effects of various methods to conserve Clara Bog

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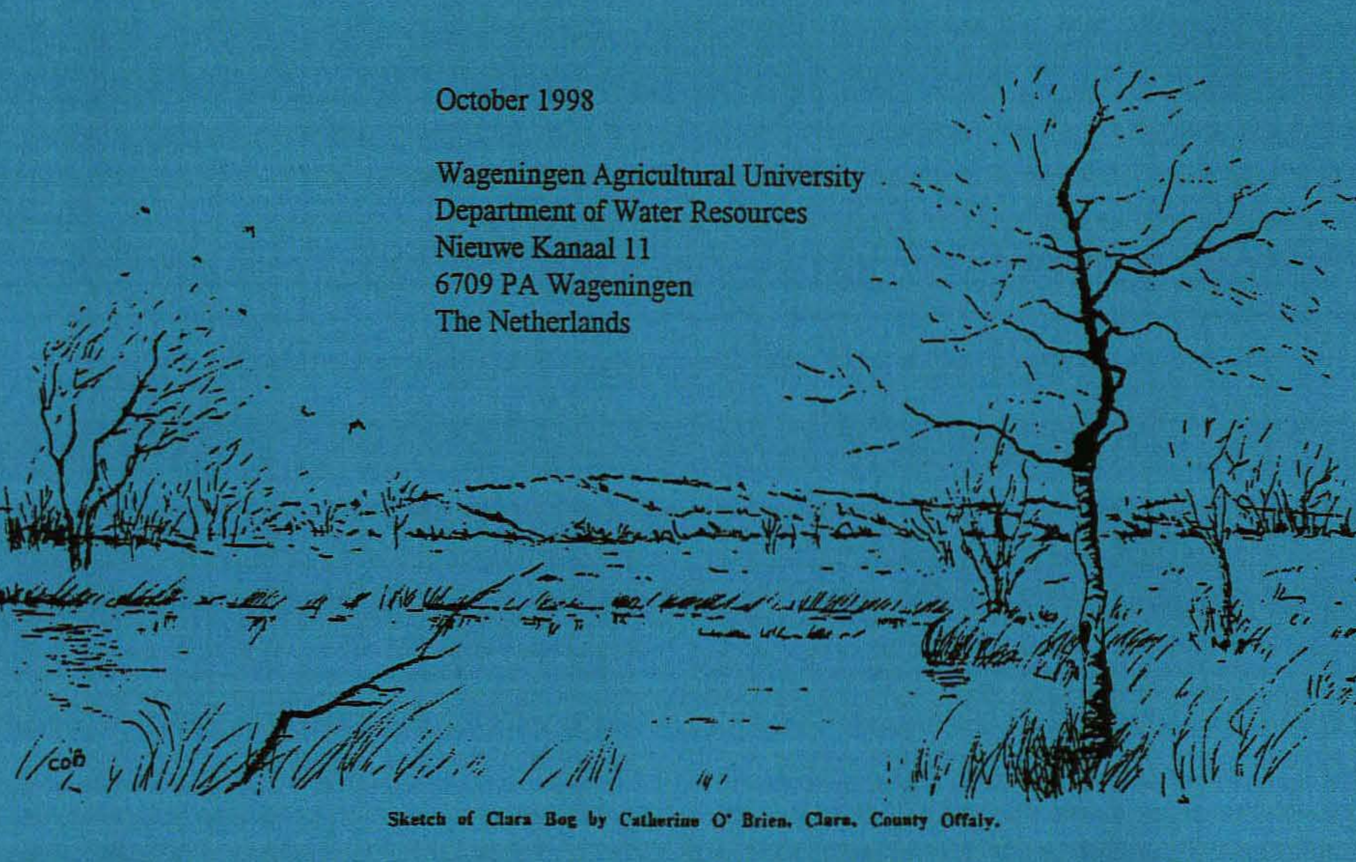

Sketch of Clara Bog by Catherine O' Brien, Clara, County Offaly.

HYDROLOGICAL EFFECTS OF VARIOUS METHODS TO CONSERVE CLARA BOG

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PREFACE

This report is the result of a six-month project and is written within the framework of the "Irish-Dutch Raised Bog Project". We would like to thank Sake van der Schaaf and George Bier for their supervision and help during this period. During our stay in Ireland Michael Gill and John Bennett showed us round, for which we are grateful. For their help in gathering the necessary data, we would also like to thank Jan Streefkerk and Michael Gill. For relaxing coffee-breaks and lunches we could always count on our fellow students.

Wageningen, October 1998,

Francine Engelsman
Ate Oosterhof

SUMMARY

This report was written within the framework of the 'Irish-Dutch Raised Bog Project'. The report deals with two objectives. The first objective is the improvement of the existing hydrological model of Clara Bog. The second objective is to calculate effects of different scenarios on phreatic and piezometric levels to show which of a set of proposed measures will probably be the most effective to stop the drying out of the Bog.

1) The hydrological model

In order to improve the hydrological model made in 1996, fieldwork was done to solve some remaining questions. The fieldwork consisted of pumping tests to obtain additional values of aquifer transmissivities and to locate the different till outcrops. These new data were used to improve the existing model.
Changes made in the model were:
- The former boundaries affected the area of interest and are located further away from the area in the new model.
-In the enlarged model, additional drains and data had to be entered.
- The precipitation surplus used in the old model had been derived from a relatively wet year and was changed for a average annual precipitation surplus in the new model.
- The till outcrops were modelled separately in the new model.
- Clay resistances based on the fieldwork done by Lenting (1993) were entered in the area south of the bog, as well as the results of the fieldwork done by the authors.

After having made the first improvements a sensitivity analysis was done. The main goal of the sensitivity analysis was to find which parameters were the most sensitive and which measures would probably give the best results in improving the model. The most sensitive parameters were the drainage resistances and the transmissivities.
With these results, the model was calibrated. For the calibration the hydraulic heads of wells, boreholes and piezometers in and around Clara Bog were used. These heads were measured from October 1991 until October 1992. The calibration led to the following conclusions:
- some wells were not levelled right; large errors were found between the individual levelling of the wells and the digital levelchart which was used. The wells which showed large errors were 05, 08, 09 and 16. Also cobradrilling 4 showed a difference of more than a metre. Because of these errors these points were left out of the further calculations.
- The average difference at the remaining 29 observation points after calibration is 0.13 metre.

2) the scenarios

In the model four scenarios were entered and calculated. All the scenarios had the objective of stopping any further drying out of the southern bog area or even to reverse this process. These four scenarios were:
1) Blocking the drains along the road
2) Raising the waterlevel in the drains along the road to the height of the road
3) Building a dam across the road in the area of the forest

4) Blocking the drains south of proposed dam alignment.

Scenario 1 and 2 showed only small difference in hydraulic heads and the area affected was very small. Scenario 3 caused large increases in hydraulic head in front of and behind the dam. The effective area included almost three-quarters of the high bog. Just behind the dam the downward seepage changed into an upward seepage of 1.14 mm/d. Scenario 4 did show some additional difference in hydraulic head but the area which was affected was almost completely outside the bog area.

The most important conclusions and recommendations were:
-Wells 5, 8, 9 and 16 are levelled wrong so they could not be used for further calibration.
-Scenario 3, building the dam across the road is the most effective one.
- This model represents a large area in and around clara bog; to simulate local effects near planned dams a more detailed model should preferably be used. This model should refer to the regional model.
- The swelling of the catotelm has not been modelled yet. It would be advisable to do more study about this and to model effects according to the relationship of hydraulic conductivity and volume fraction of solid matter found by Moll & Peters (1996a).

CONTENTS

1. INTRODUCTION

1.1 Description of site

Clara Bog is recognised as an important nature reserve as it is one of the largest, nearly intact raised bogs in Western Europe. It is situated two kilometres south of Clara, in County Offaly, in the Irish Midlands. The bog is famous for its soaks and hummock-hollow systems. About two third of the bog is owned by the Irish National Parks and Wildlife Service.
Clara Bog is bisected by a road which leads from Clara to Rahan, in the south. On either side of the road there is a drain. Figure 1.1 shows the location of the bog in Ireland, figure 1.2 shows the bog and its surroundings.

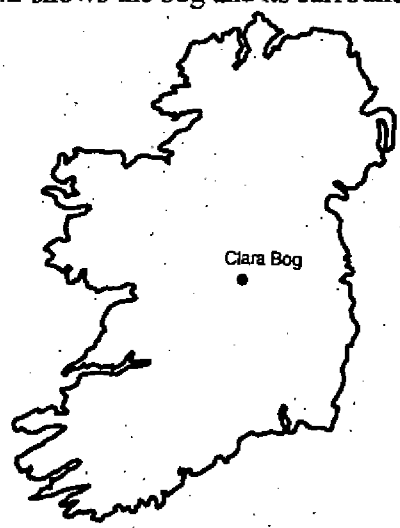

figure 1.1 Position of Clara Bog.

1.2 Purpose of the study

Due to the Bog Road the bog already subsided more than 5 metres in 160 years and this process will go on unless dams are built to stop the drainage. The dams will result in a rise of the groundwaterlevel. The subsidence of the bog will stop and due to the dams Clara East and Clara West will eventually be connected again.
Because the site of the dams is very important (a wrong placement of the dams may cause instability) a hydrological model is needed to predict the effects of the dams. The groundwatermodel MicroFem is used in this project.

1.3 Objectives

There are two objectives concerning this study. The first is to improve the existing model, which calculated hydraulic heads that were too high and the second is to simulate the hydrological effects of the dams, which was not done yet. The model will be adjusted and scenarios with different positions and heights of the dams will be simulated in the model to predict the effect on the geohydrological situation.

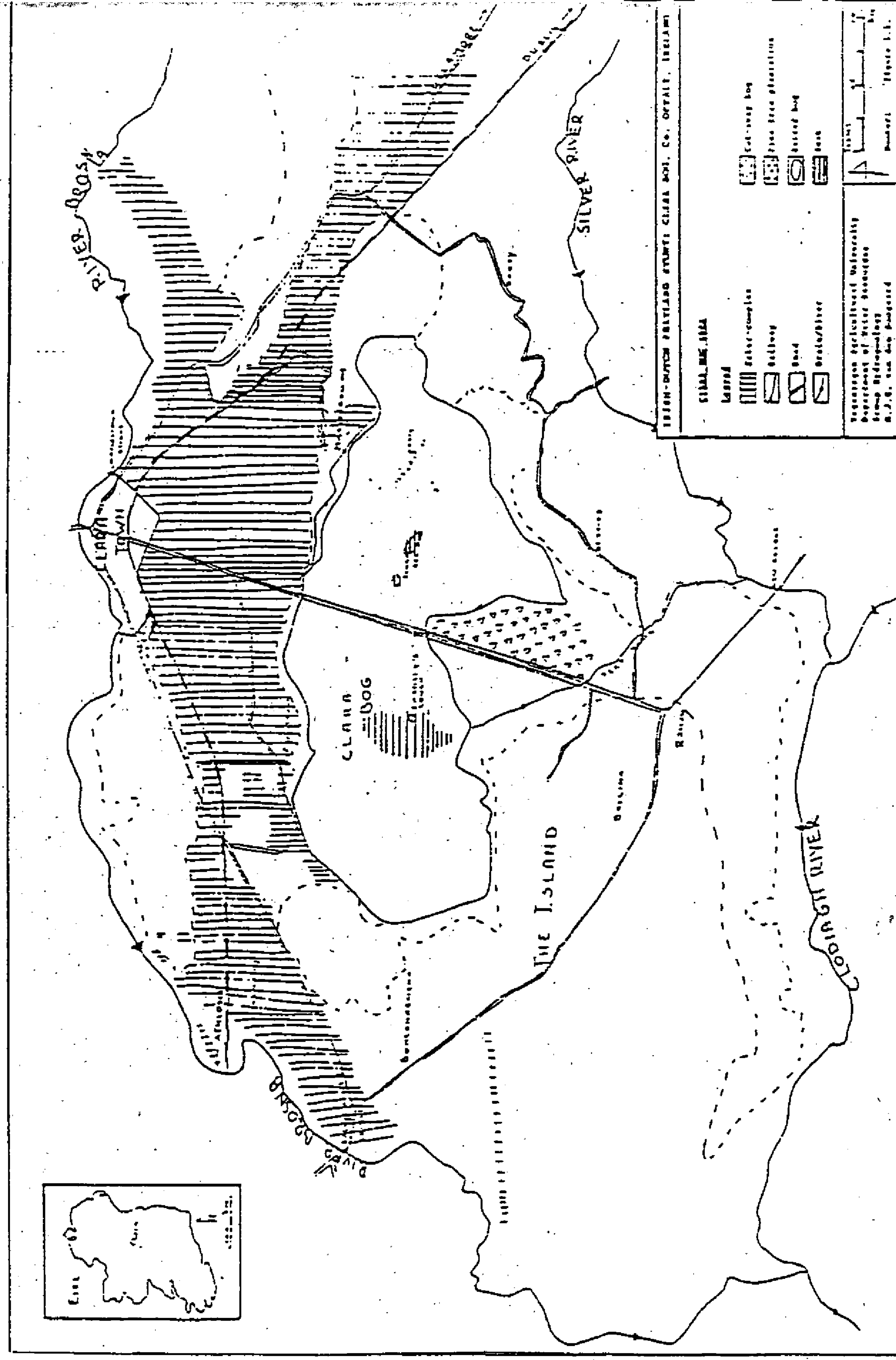

figure 1.2 Clara Bog and its surroundings

1.4 Strategy and structure of the report

In order to make this report readable a scheme figure 1.3 is made to clarify the strategy followed in the study.

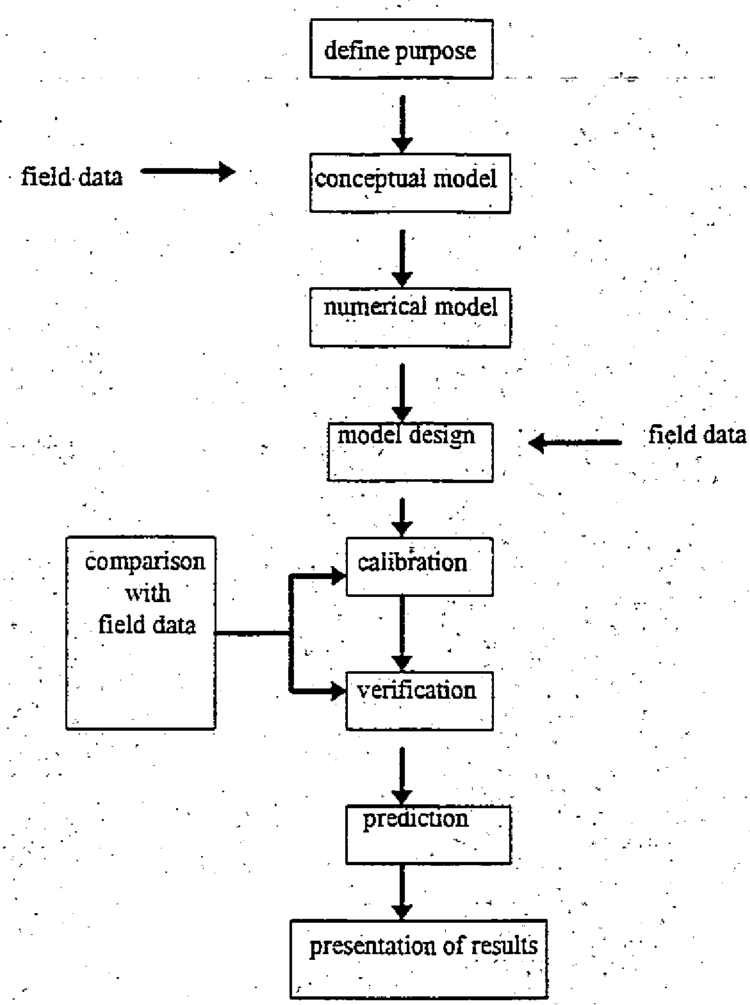

figure 1.3 strategy

This introduction has given the purpose of the study. The conceptual model will be dealt with in Chapter 2 where first a description of the geology and hydrogeology is given. In Chapter 3 the numerical model is explained and the parameter values and boundaries in the model will be discussed. Next the sensitivity analysis (Chapter 4) and the calibration (Chapter 5) will be described. All these chapters meet the first objective of the study, the improvement of the existing model. The second objective, the dam prediction is dealt with in Chapter 6 where the scenarios are entered in the model and discussed. A feed-back on the model (limitations, reliability, uncertainty) is given in Chapter 7. The report will end with the conclusions and recommendations found during the study (Chapter 8).

2. HYDROGEOLOGY

2.1 Geomorphology

The present landscape of the Irish Midlands, part of the Central limestone plain (Van Den Boogaard, 1993), is largely a feature of the Quaternary period. The Clara Bog region is dominated by glacial deposits and bog development. The region is characterised by a hilly topography of eskers in the north-north east. The Clara esker (esker Riada) is a broad ridge with multiple crests, the height is 10-25 m above the surface of Clara Bog. At the southern part of Clara Bog the most pronounced topographical feature is Ballina Hill (20 m above the surface of Clara Bog). Ballina Hill is the eastern part of an elevated area, called 'The Island'. (Van Tatenhove, 1990). The Island is an area of undulating to hilly topography. Figure 2.1 shows the topographical map, according to levellings done by OPW.

2.2 Geologic setting

2.2.1 Geology

The Clara Bog region is underlain by Carboniferous limestone. During the maximum extent of the landice cover the area was covered by an icesheet. Underneath the actively moving ice a basal till sheet accumulated (overconsolidated and a high clay-content). The eskers, narrow ridges of coarse gravel and boulders deposited in tunnels in the ice sheet are formed in the same period. In the late stages of glaciation ablation tills were deposited by the meltwater of the icebody (variable in grainsize and composition) Tills in the area mainly consist of coarse materials and are poorly sorted (boulders).

The ablation till formed an irregular knobbly and hilly terrain with interconnected and isolated lakes and pools. After deglaciation the eskers formed the only continuous higher grounds. Streams or rivers had not formed yet. Meltwater stagnated in the natural depressions, behind the positive landforms and against the icebody, resulting in a landscape dominated by lakes and puddles. The meltwater of the ice sheet brought with it substantial quantities of finely sorted material (silts and clay) that were the product of weathering and especially of erosion of higher grounds. These fine materials accumulated in the ponds and lakes as lacustrine sediments. The remaining course lag deposits on slopes is indicated as wash-out deposit. The fine deposits in the basins sometimes contain coarse material like stones, the latter may have been brought in by floating ice.

A drainage system or stream network slowly developed. These streams drained some of the lakes, eroded the subsoil in the connecting channels, deposited fluvial sediments and redeposited some of the finer material. As the climate slowly improved during the Holocene, vegetation returned and after some time peat started to develop in the wettest areas.

2.2.2 Aerial distribution of geological units

In the whole region Quaternary deposits are present at the surface (Van Tatenhove, 1990). The (fluvio-)glacial deposits (esker, till) are the oldest. There are several kinds of till (varying from clayey to gravely till) found in the region. Most typical for the Clara bog region is the till that has a sandy-loamy and stony texture, with a high content of big boulders.

Gravely till is sometimes clearly related to the geomorphology. Ballina Hill consists of limestone. The esker deposits are found in the area north of the bog.

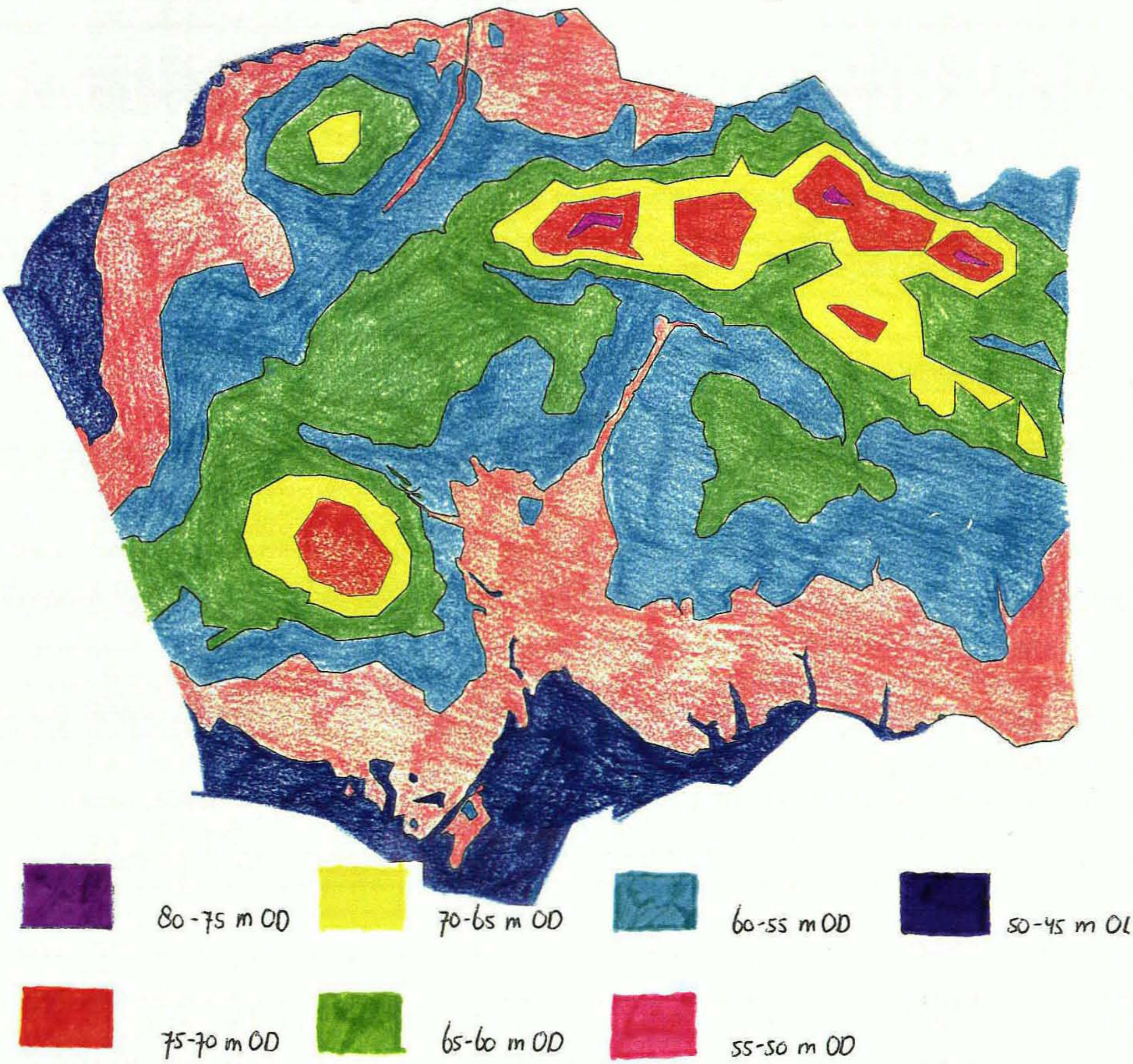

figure 2.1 topographical map

Clara Bog was formed in a depression where the glacial deposits at first had been covered by a blanket of lacustrine deposits which seals the peat from the bedrock. The thickness of the clay varies from 0.1 to 5.5 m (Bloetjes, 1992). Bloetjes (1992) also found marl on top of the clay in the area near the Bog Road. Another deposit that can be distinguished is the Holocene river-deposit, near the River Brosna and the Silver river. Fen peat and Spaghnum peat are found on the bog. Figure 2.2 shows the aereal distribution of the geological units described above.

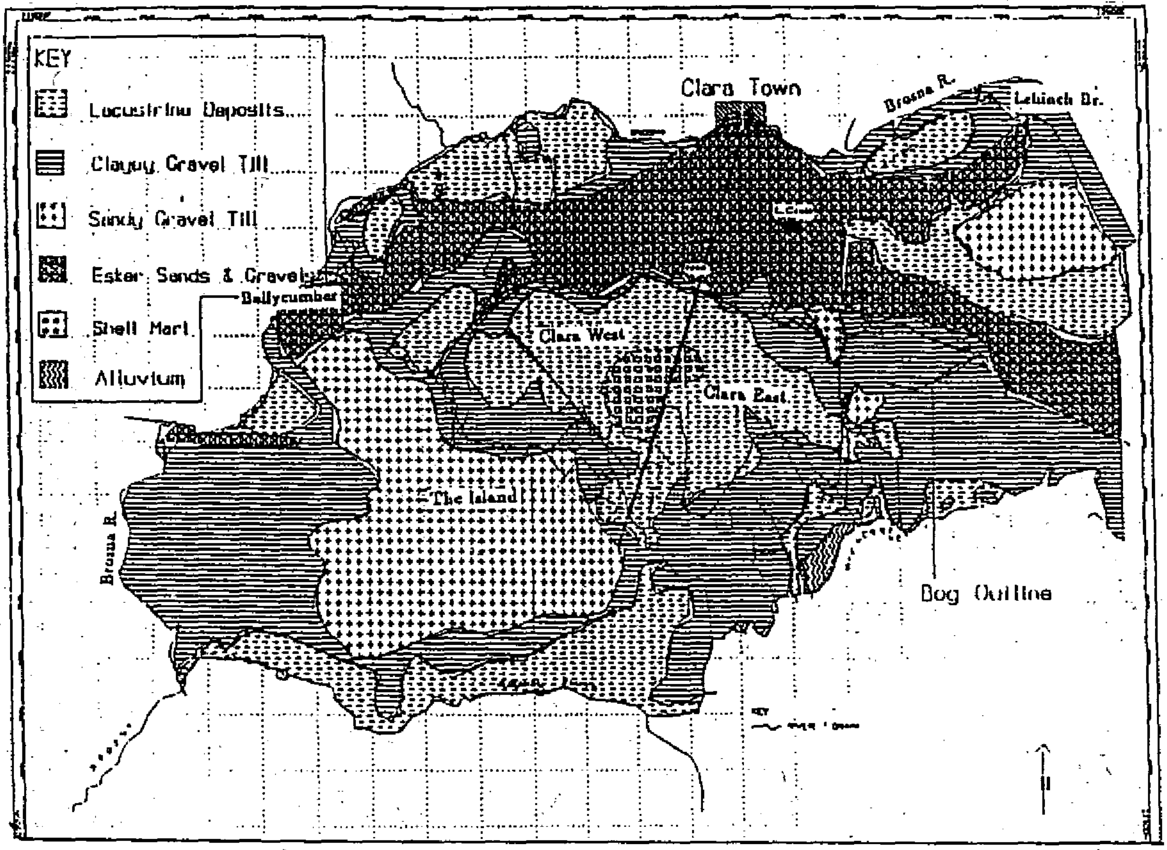

figure 2.2 aereal distribution of geological units (S. van der Schaaf, in prep.)

2.2.3 Composition of the geological units

Carboniferous limestone
The limestone, further referred to as bedrock, can be found in the whole area. The rock outcrops at the northern boundary of the area, in the river Brosna. Two lithologies are found in the region: a muddy limestone in the north and a more clayey unit in the south of the area.

Glacial tills
The tills that are found in the area are mostly poorly sorted. Large boulders are common. The lithology varies from gravelly to sandy. The clayey till can be found underneath the bog, whereas the gravelly till can be found everywhere.

Esker deposits
Esker deposits mainly consist of sands and gravels. Silt and clay layers are common but are only a few centimetres thick. Esker deposits are only found in the northern part of the area.

Lacustrine deposits
The lacustrine clay underlies the bog and the cutover areas. The texture of the deposit varies from sandy clayey loam to silty loam. In the central part of the bog Bloetjes (1992) found shell marl, an indication of water over saturated with calcium carbonate in the past.

Fen peat
The fen peat is the lower peatlayer and is usually overlain by Sphagnum peat (bog peat). Fen peat contains reed, sedges and wood, which accumulated under mesotrophic to eutrophic conditions. In the fenpeat of Clara Bog wood becomes more abundant near the bog margins. In the cutover area south of the bog fenpeat still occurs.

Sphagnum peat
Sphagnum peat is a younger form, which covers the fen peat. It mainly consists of Spagnum mosses, which depend on an ombrotrophic situation.
This deposit can only be found on the bog.

2.3 Hydrogeological parameters

2.3.1 Raised bog properties

A raised bog consists of two layers: the acrotelm and the catotelm. The acrotelm layer lies above the catotelm layer and is 5-40 cm thick (figure 2.3). It contains the fluctuating phreatic level. The hydraulic conductivity is high near the surface and declines rapidly with depth. The transmissivity varies over the whole bog, due to hummocks and hollows and with the phreatic level. The catotelm has a constant or little changing water content. In comparison to the acrotelm, the transmissivity is very low. The acrotelm protects the catotelm from drying and oxidation (Lensen, 1991).

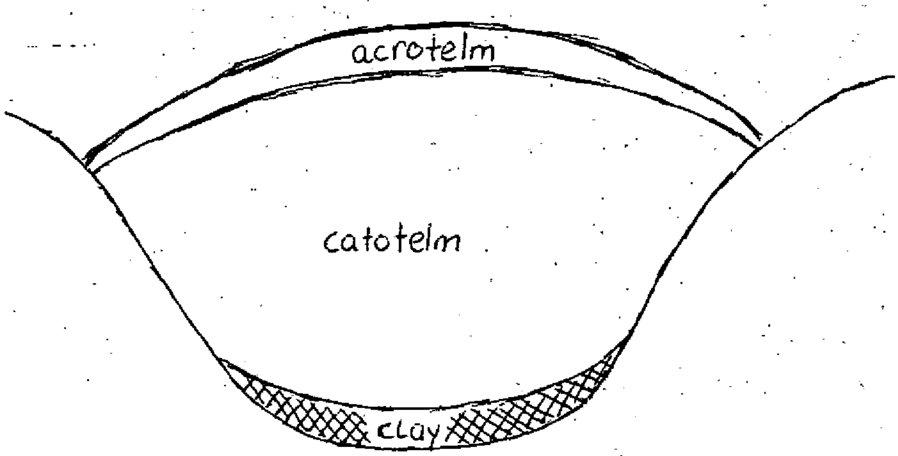

figure 2.3 raised bog

2.3.2 Permeability

In this chapter the permeabilities of the different deposits are listed. The permeability of the peat depends on the botanical composition, the degree of humification (humification degree of 2-4 gives a high permeability), bulk densitiy, fibre content, porosity and surface loading (Van Den Boogaard, 1993). The permeability of the acrotelm is high, the transmissivity varies from 1 m^2/d (at the margins) to more than 1000 m^2/d (in the centre of the bog). The permeability of the catotelm is very low, compared to the acrotelm (1-10^{-5} m/d). The fenpeat also has low permeabilities.
The limestone bedrock has a low permeability due to the lack of fissures. The glacial tills can be divided into sandy, loamy and clayey till, with a permeability of 10^{-1}-10^{-7} m/d, and gravelly till, with a higher permeability (10 m/d).
The esker deposits have a high permeability, in the range of 10-100 m/d. The lacustrine clay found in the area is the confining layer on top of the till layer, with permeabilities of 10^{-4} m/d or less.
In order to get the transmissivities of the deposits the permeabilities must be multiplied by the thickness of the layer, according to the following equation:

$$T = \int_{z_1}^{z_2} k(z)dz \qquad (2.1)$$

Where T = transmissivity [m^2/d]
k = permeability [m/d]
z = depth [m]

2.3.3 Pumping tests

During the fieldwork pumping tests were done on boreholes. With the use of a little pump, which had only a capacity of about six litres a minute, a cone of depression was made on which the drawdown was measured against the time. This was done until a steady state was reached. The results (measurements and graphs) can be found in Appendix A. For the calculation of the transmissivity the Jacob's straight-line method has been used (Kruseman & De Ridder, 1983), which can be used for single-well constant discharge tests. The Jacob method uses the following equation:

$$T = \frac{2{,}30 * Q}{4 * \pi * \Delta s} \qquad (2.2)$$

Where T = transmissivity [m^2/d]
Q = pump discharge [m^3/d]
Δs = drawdown (per log cycle of time) [m]

The tests have been done on clbh4, clbh5, clbh9, BH14 and BH16. On clbh4 the Jacob method could not be used because the aquifer was not confined. In this case the Thiem method has been used which uses the next equation:

$$T = \frac{2{,}30 * Q * \log\left(\frac{r_1}{r_w}\right)}{2 * \pi * \Delta s} \qquad (2.3)$$

Where: r_1 = distance from the well [m]
r_w = radius of the well [m]
Δs = drawdown [m]

Because there wasn't a piezometer at some distance in which the drawdown could be measured also, the assumption was made that at a distance of $1000 * r_w$ the well didn't influence the waterlevel. The transmissivities found are listed in table 2.1.

table 2.1 transmissivities

Borehole	clbh4	clbh5	clbh9	BH14	BH16
filter in	esker deposits	silty clay	silty/fine gravel	silty, stony clay	glacial tills
T [m^2/d]	82.5	24	69	0.65	11.5

2.4 Groundwater flow

Figure 2.4 shows the flow direction of the groundwater in the first and the second aquifer (Moll & Peters, 1996b). The direction of the flow is as expected. The first aquifer is only valid on the bog (the acrotelm). The water flows to the drains and the rivers. Near the Bog Road upward seepage occurs.

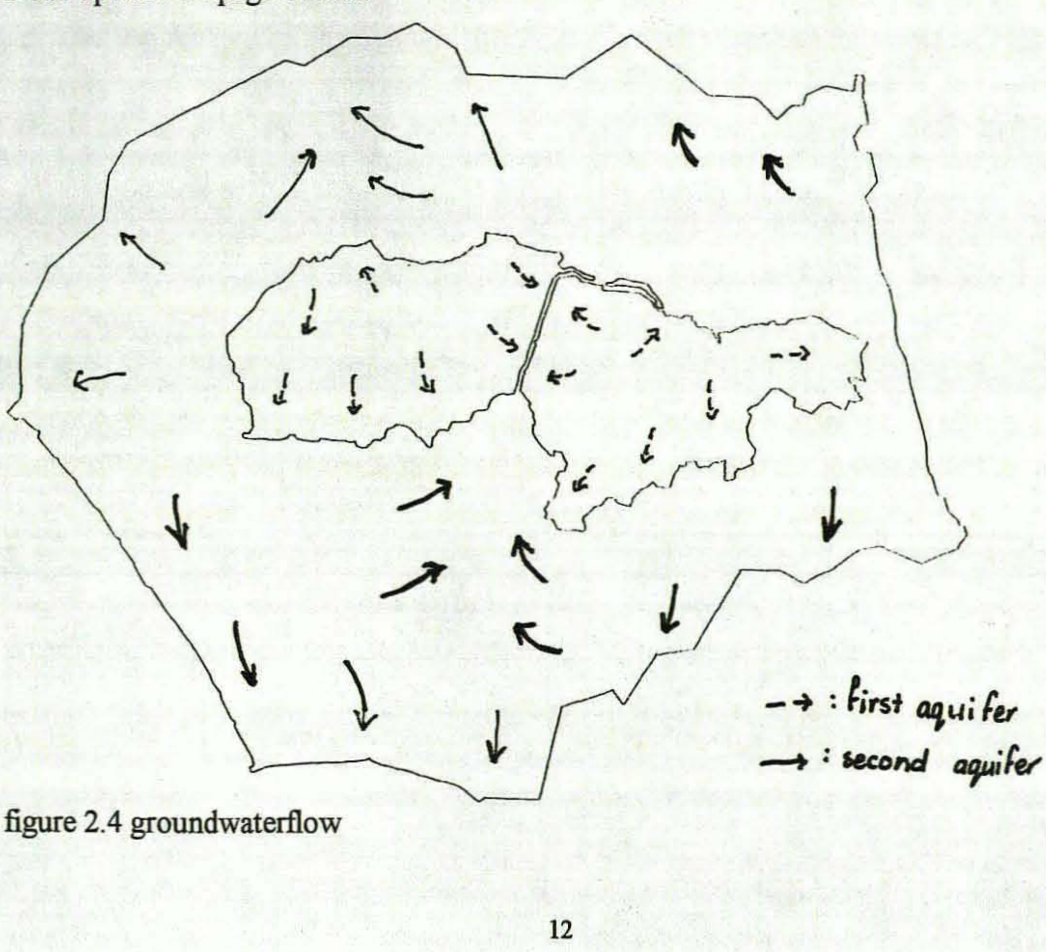

figure 2.4 groundwaterflow

3 THE HYDROLOGICAL MODEL

3.1 Groundwaterflow modelling

3.1.1 Groundwaterflow equations

In order to solve groundwaterflow problems one can simplify the flow pattern. This can be done by using the Dupuit-Forchheimer assumption: in the aquifers there is only a horizontal flow and in aquitards water only flows vertically. This reduces a 3-D groundwater flow problem to 2 dimensions. The following equation can now be used:

$$\frac{\partial}{\partial x}\left(T\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial H}{\partial y}\right)+q=S\frac{\partial H}{\partial t} \qquad (3.1)$$

Where H = hydraulic head [m]
T = transmissivity [m^2/d]
q = sink term [m/d]
S = storage coefficient (-)
t = time [d]

This equation is the result of the combination of Darcy's law and the mass balance (also called the continuity equation). Darcy's law in formula:

$$v_x=-k\frac{\partial H}{\partial x} \qquad (3.2)$$

and

$$v_y=-k\frac{\partial H}{\partial y} \qquad (3.3)$$

Where v = flux density [m/d]
k = permeability [m/d]
$\frac{\partial H}{\partial x}$ = direction derivation of H [-]

Mass balance in equation:

$$Q_i-Q_0=\Delta S \qquad (3.4)$$

Where Q_i = total inflow $[\frac{m^3}{d}]$

Q_o = total outflow $[\frac{m^3}{d}]$

ΔS = Change in storage [-]

By using a sequence of aquifers and aquitards with horizontal flow in the aquifers and vertical flow in the aquitards a quasi third dimension is added.

3.1.2 Finite element method

In order to calculate the waterflow in hydrologic systems, numerical solution techniques are used most often. In this study the groundwatermodelling package MicroFem is used, which is based on the finite elements method. A short description of this method follows hereafter.
The finite element method divides the model area into a finite number of triangular elements. The hydraulic heads are calculated with a linear function over the nodes. Finally the mass of each element is relocated over the three nodes of the triangle. When the model has done this for all the elements, it solves the new mass balances for the nodes.

3.1.3 MicroFem

MicroFem generates a network of triangular elements, which allows great flexibility in entering details in the model. In MicroFem a dense network can be made in the interest area and a less dense one at the boundaries of the model. MicroFem works with aquifers and aquitards of confining layers which have a transmissivity (T) and a resistance (c). In the aquifers a discharge or recharge can be entered. The first layer is described as toplayer: in this layer drains, rivers, lakes and surface run-off (diffuse drainage) are entered in terms of a drainage resistance and a drainage level. The values for transmissivity and resistance can be entered for known points, MicroFem can interpolate between points.
Important programs in MicroFem are:
- FemGrid: generates a mesh based on a subdivision of the area into irregular polygons with uniform internal noding spacing
- FemMesh: same as FemGrid, but is useful for models with high contrasts in nodal spacing.
- FeModel: the pre- and postprocessor in MicroFem
- FemPlot: makes graphs and drawings of the model
- FemBaln: makes a detailed waterbalance for the model
- FemCat: deals with transient calculations and specific drainage conditions
- FemCurv: shows time-head graphs of files written by FemCat

3.2 Conceptual model

A conceptual model was made to describe the groundwaterflow. In order to define the different layers (aquifers and aquitards) MicroFem requires, a general idea of the hydrostratigraphic units is needed. These units can be found on geological maps (Van Tatenhove, 1991), topographical maps (figure 2.1) and thickness contour maps (Dik & Verstraelen, 1995). The conceptual model should comprise geological units of similar hydrogeological properties. In figure 3.1 the different deposits found in the region are shown in transects from north to south and west to east.

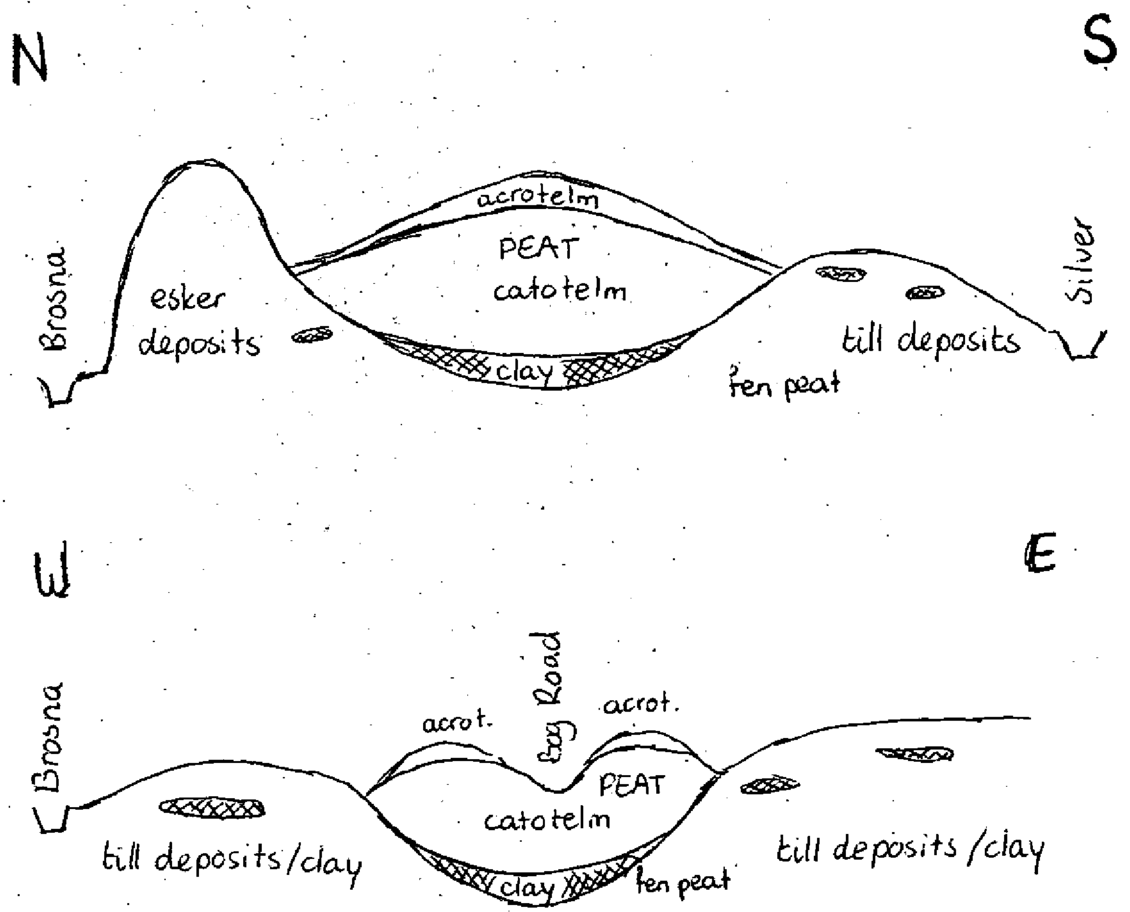

figure 3.1 schematic transects N-S and W-E

Hydrological boundaries are the River Brosna in the north and the Silver river in the south. The boundaries in the west and in the east should be situated so far from the area of interest that they do not influence that area. These boundaries should also be hydrologically justified, e.g. no-flow boundaries. In order to build a reliable model, field data are needed of the whole area. There is a considerable amount of information concerning the bog and the area south of it, but less data are available of the regions to the west and north-east. This lack of information will have to be taken into account when building the modelnetwork.

3.3 Translation conceptual model to MicroFem

To build the conceptual model in MicroFem, described in chapter 3.1, the boundaries must be constructed and they have to meet a boundary condition. There are three types of boundary conditions:
-Dirichlet condition (specified head boundaries)
-Neumann condition (flux across the boundary is given)
-Cauchy condition (head-dependent flow boundaries)
The model will only calculate steady-state conditions, so no initial conditions have to be defined. Chapter 3.3.1 will describe the schematisation of the field, whereas in chapter 3.3.2 the designed grid is explained. In chapter 3.3.3.1 and 3.3.3.2 the hydrological parameters (transmissivity, resistance, recharge) will be dealt with.

3.3.1 Schematisation

MicroFem requires defined aquifers and aquitards, so these will have to be determined. The Clara Bog region is underlain by limestone which will be the hydrological base for the model. In the Northern part of the area esker deposits are found. The area south of the bog consists of till deposits (clayey to gravely). These two deposits are put together to form the aquifer right above the hydrological base (referred to as aquifer 3).
The bog and cutover areas are underlain by lacustrine clay. Together with the catotelm, only found on the bog, this forms the aquitard above the till aquifer (referred to as aquitard 2).
The first aquifer and aquitard (figure 3.2) only occur on the bog. The acrotelm has a high transmissivity and is therefor entered as an aquifer (aquifer 1). Although the catotelm has a low permeability and thus a low transmissivity this layer is also entered as an aquifer, with low transmissivities (aquifer 2), this was done to make it possible to model changes in the transmissivities of the catotelm aquifer, which may occure when building a dam. Aquitard 1 is the resistance layer between the acrotelm and the catotelm.

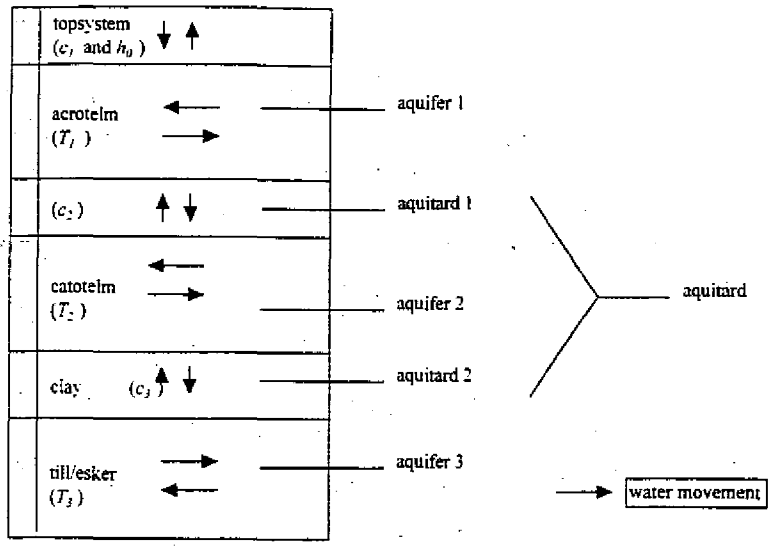

figure 3.2 schematisation of the layers

table 3.1 explanation of parameters

h_0	drainage level in or on top of the toplayer. This parameter is only used when dealing with a drainage resistance
c_1	drainage resistance entered for rivers, large drains and surface run-off
c_2-c_3	hydraulic resistances of the aquitards
T_1-T_3	transmissivities of the aquifers
h_1-h_3	hydraulic heads in the aquifer, calculated
q_1	precipitation surplus
q_2-q_3	discharge, in case of a well

3.3.2 Grid design and model boundaries

The model was based on the existing model of Moll & Peters (1996b). It had to comprise the whole bog, the area of interest. The eastern boundary drawn in earlier models was situated in Clara-East, inside the bog. A new boundary was put more to the East, perpendicular to the two rivers (Brosna and Silver) that form the Northern and Southern boundary (Neumann condition). The rivers Brosna and Silver are defined as boundaries with a Dirichlet condition. The bedrock is near the bed level of the rivers so there is no aquifer beneath them. The boundary in the West was also located further away from the bog. This was done because the former boundary was put on the Island and thus didn't meet any boundary condition. The new boundary is situated to the west of the Island and is perpendicular to the rivers (flowlines). Figure 3.3 shows the new and the old boundaries.

The grid of the model was adjusted to these new boundaries. Some new drains are entered, due to the enlarging of the model. The new model has 7349 nodes. The network is shown in figure 3.4

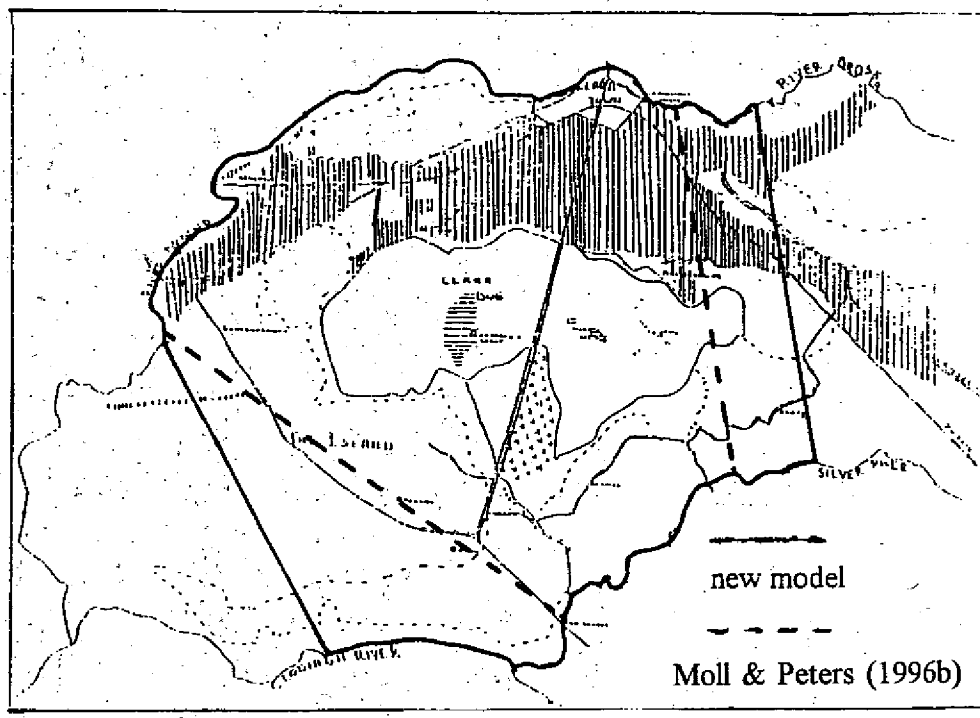

figure 3.3 model boundaries

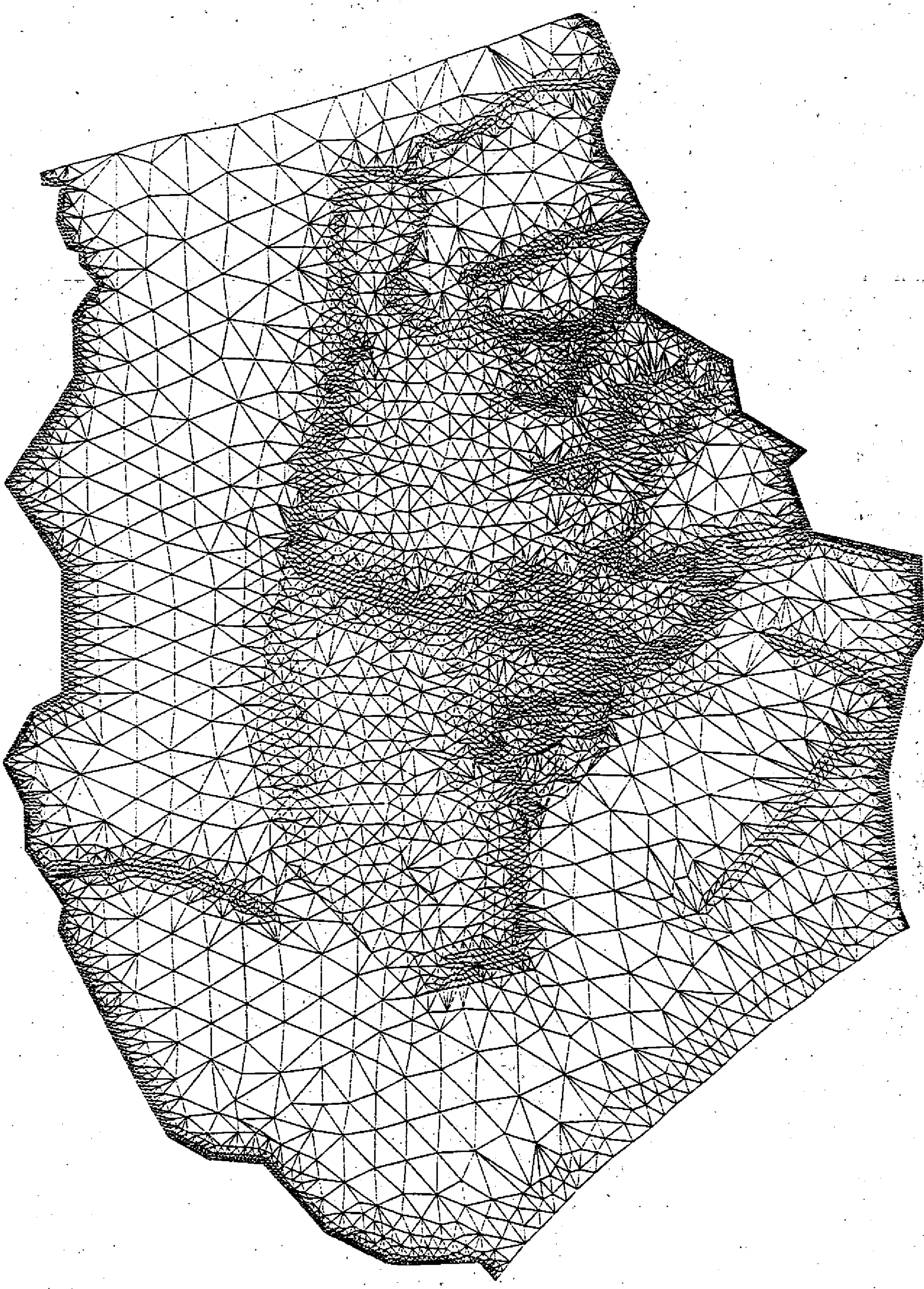

figure 3.4 model network

3.3.3 Parameters

The parameters required by MicroFem are the discharges in the aquifers, the transmissivities of the aquifers, the resistances of the aquitards, the drainage resistance in the topsystem and the drainage levels. The values Moll & Peters (1996b) used were examined and corrected when necessary. The changes have been split up into the transmissivities and resistances in section 3.3.3.1 and in the recharge in section 3.3.3.2

3.3.3.1 Hydrogeological parameters

The bog
The bog was kept unchanged. Only the part of the bog that is entered in the model due to the enlarging of the model was added. This part of the bog has been given the same values of transmissivity and resistance as the rest of the bog.

The forest
The forest that is situated at the south east of the bog was given an estimated drainage resistance of 50 days. For the forest also vertical resistances (c_3) for the clay were entered, according to the results found by Lenting & Van Der Meer (1993). The thickness' of the layers are translated to resistances using table 3.2 (Moll & Peters, 1996b).

table 3.2 resistances

layer	resistance
clay	10,000 d/m
clayey till	1,000 d/m
sandy till	100 d/m
fenpeat	1,000 d/m

In figure 3.5 and figure 3.6 a contour map of the resistance layer (aquitard 2) for this area can be found.

The fenpeat
A diffuse drainage system is entered for the fenpeat, to simulate the surface run-off. This drainage resistance is given an estimated value of 50 days. The other parameters are kept the same.

The Mound
With the help of aerial photographs and field observations the Island was entered in the model. Lenting & Van Der Meer (1993) also measured clay thickness' at the area southern of Clara West so an estimation could be given of the resistance of the mound there (figure 3.5). Further to the west less data were available, so an average resistance and an average transmissivity was entered for the second aquitard and the third aquifer.

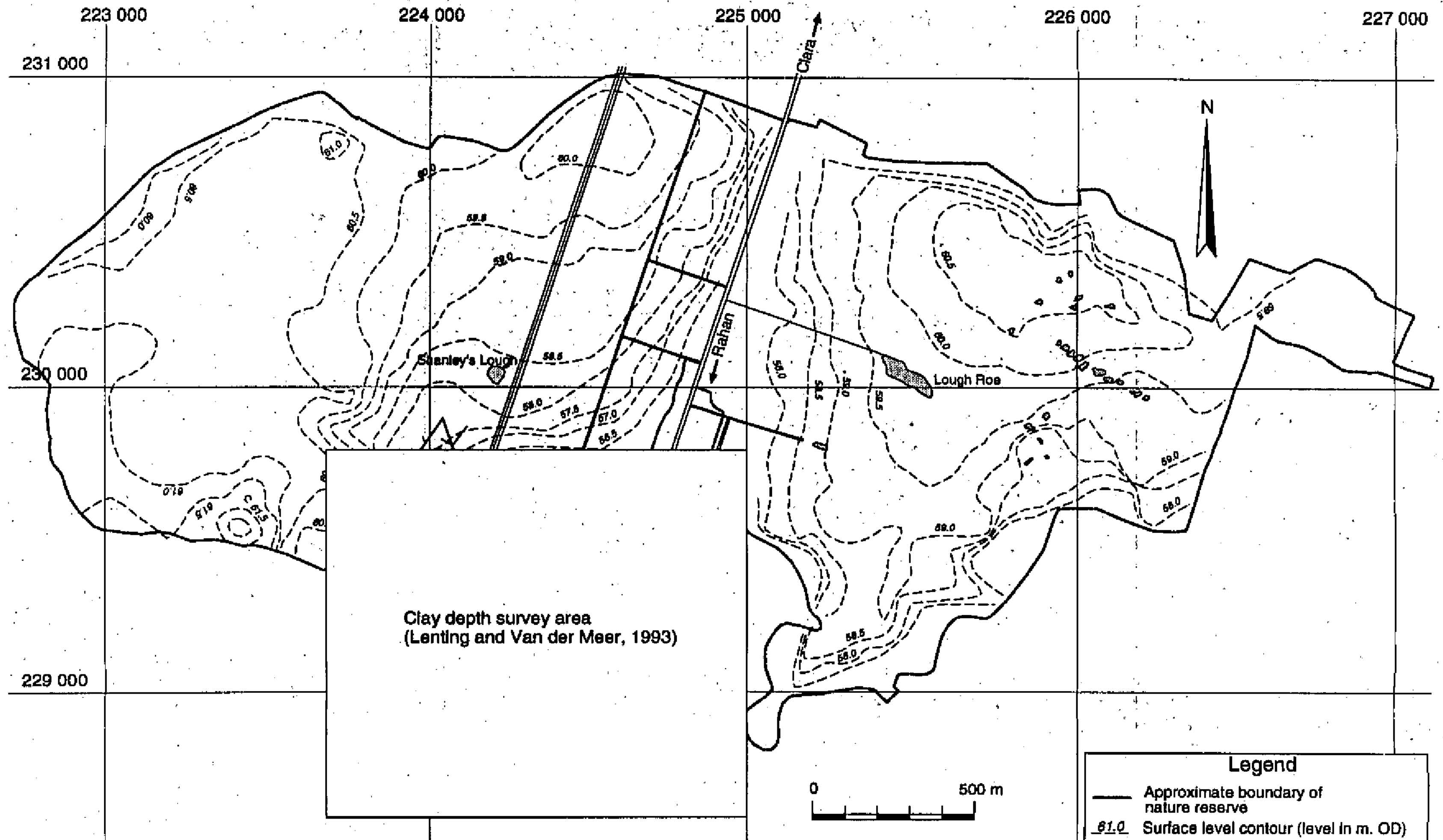

figure 3.5 resistance contourmap in relation to Clara Bog

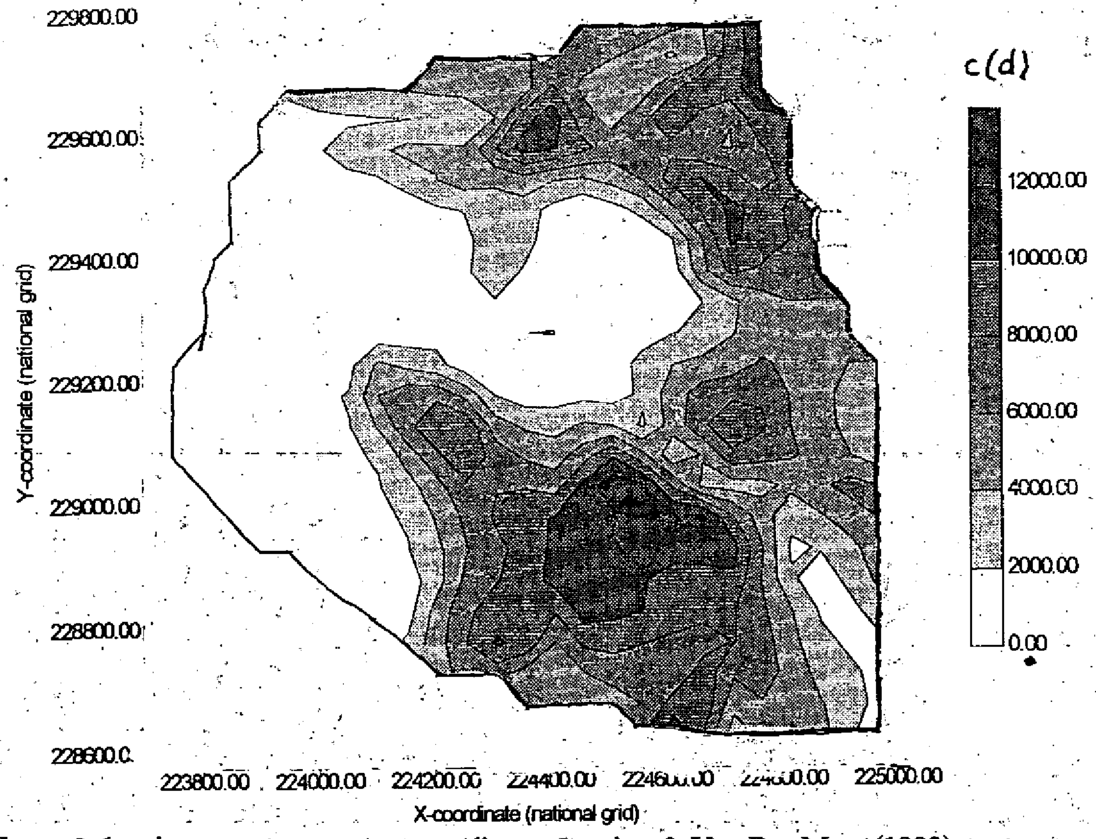

figure 3.6 resistance contourmap according to Lenting & Van Der Meer (1993)

The till areas
During the fieldtrip exact locations of till areas were identified (Appendix B). As accurately as possible they were entered in the model. From the aerial photographs a till area in the south eastern part of the model was located. Measurements of Lenting & Van Der Meer (1993) were entered and the areas without known values were given an average value for the whole area.

The esker
The esker, which is situated between the town of Clara and Clara Bog, was given more attention. Moll & Peters (1996b) already concluded that the calculated heads in the esker were too high, probably due to the fact that the assumed transmissivities were too low. Due to the lack of data on the esker, the transmissivities were adjusted until the model result was reasonable.

The alluvial deposits
In the area between the river Brosna and the esker alluvial deposits occur. This area was given different values for both transmissivity and resistance due to the fact that here alluvial deposits are found. The resistance was given an estimated value of 2000 days. The transmissivity is lower than the transmissivity of the esker. The same strategy is followed for the area near the Silver river. The transmissivity there is lower than near the river Brosna (Van Tatenhove & Van Der Meer, 1993).

The drains
Besides the drains entered by Moll & Peters (1996b) new drains were inserted, due to the enlarging of the model. These drains are located in the south-western part and in the

south-eastern part of the model. Also some diffuse drainage systems were put in the model, near the south-western boundary (runoff from the Mound) and northern of Clara East, where forestry is located.

The rivers
Due to the enlarging of the model, the rivers were extended. The river levels were based on the same gradient data Moll & Peters (1996b) used. The drainage resistance is estimated on 20 days.

In Appendix C the entered parametervalues are summarised.

3.3.3.2 Recharge

The period between October 1991 and October 1992 was chosen as a reference year because this was an average period in regard to recharge, which is necessary for a steady state model. Also a lot of data was collected in that time. The value for the precipitation of this period was used. The measuring with the two handgauges on the bog gave a value of 877,0 mm. For the evapotranspiration the following values were taken, according to Leene & Tiebosch (1993):

Evapotranspiration grass : 473 mm/year
peat : 587 mm/year
forestry : 534 mm/year

The precipitation surplus, and thus groundwater recharge for the area now becomes ((precipitation - evapotranspiration) / 365)
grass : 1,10 mm/day
forestry : 1,00 mm/day
peat : 0,79 mm/day

3.3.4 Waterbalance

A waterbalance of Clara Bog West based on field observations was made by Leene and Tiebosch (1993). They used the period between the 1st of August 1992 and the 28th of July 1993. In this period the precipitation was above average. Their waterbalance for the bog is given in table 3.3.

table 3.3 waterbalance of Clara Bog West

description	sum (mm/y)
precipitation	922
evapotranspiration	587
vertical seepage	14
discharge	300
change in storage	20
total	0

3.4 Discussion on uncertainties in the model

During the modeling several assumptions were made. Because of the lack of geological data in the surrounding of the bog and because very few augerings were done there, many uncertainties existed about the transmissivities of the different layers. Another difficulty was the large spatial variability of the layers, e.g. the till outcrops at the south-east of the bog area. The thickness and the spreading of the clay layer is not well known. In the north-east of the bog near the forest marl was found (pers.obs.), which was not mentioned in the literature before.

The comparison of the results of pumping tests, done by different people with different methods also shows large differences up to factor two to three for some tests.

4. SENSITIVITY ANALYSIS

4.1 Introduction

The purpose of the sensitivity analysis is to find which parameters are the most sensitive to changes. These parameters are e.g. the resistance of the clay, the transmissivity of the acrotelm and the precipitation surplus. With the sensitivity analysis one can calibrate and adjust the model where necessary. For reason of clarity, the model was given a zonation into several areas so an insight could be obtained in local effects. In Appendix D the different zones of the model, in which the parameters have been changed separately, can be found. These are:
-the bog itself (zone HIGH BOG)
-the bog margin (zone BOG MARGIN)
-the forest south of Clara Bog (zone FOREST)
-the fenpeat (zone FENPEAT)
-the Island (zone MOUND)
-the surroundings of which includes till (zone TILL)
-the esker north of Clara Bog (zone ESKER).

4.2 Methods and results

The parameters have been changed by multiplying or dividing the values by 1.5. For every zone several nodes have been selected to calculate heads covering the entire zone-area. These points can be found on the map in Appendix D. The results have been compared with the reference heads of the base model. The results which gave the largest differences have been put in graphs, see figure 1 to 7 (Appendix D).

Changes in the topsystem
The following analysis have been done:
O: all drains $c_1 = 30$ days
P: all drains h_0 = drainage level - 0.5 m
S: all drains c_1 * 1.5
U: fenpeat h_0 = drainage level - 0.5 m.
The charaters O,P,S and U conform to the characters on abscisae in figures 1-7. As can be seen in figures 1-7 of Appendix D, the model is most sensitive to the drainage level, especially for the drainage level in the forest and the fenpeat.

Changes in effective precipitation
The effective precipitation was changed to 85% and 115% of the starting values. Figure 8 (Appendix D) shows a linear relation between changes in precipitation surplus and heads.

Changes in c_3 (resistance of the catotelm/clay aquitard) and T_3 (transmissivity of the till aquifer)

Figures 9 to 14 (Appendix D) show the most sensitive parameters. The tests include changing c_3 of HIGH BOG, BOG MARGIN and drains and changing T_3 of ESKER and MOUND.
A linear relation was found for changes in c_3 (drains) and T_3 (ESKER). Not linear is the change of c_3 (HIGH BOG) because other factors are involved.

The results of these tests are summarised in table 4.1.
table 4.1 sensitivity analysis

parameter changed	value in base model	% change	avg. difference of heads $h_{base}-h_{test}$ [m]	standard deviation (n = 34)
q1	0.79 -1.1 mm/d	+15	-0.162	0.141
		-15	0.185	0.142
c1 (drains)	50 d	-40	0.109	0.079
		+50	-0.091	0.097
h0 (drains)	surface level [m]	-0.5 m *[2]	0.203	0.131
h0 (fenpeat)	surface level [m]	-0.5 m *[2]	0.059	0.078
c3 (high bog)	40000-100000 d	-33	-0.053	0.164
		+50	0.029	0.058
c3 (ring)	10000-110000 d	-33	-0.041	0.061
		+50	0.035	0.054
c3 (fenp)	1000-20000 d	-33	0.006	0.049
		+50	0.006	0.042
c3 (for)	3000-20000 d	-33	0.006	0.024
		+50	-0.009	0.045
c3 (mound)	500-6000 d	-33	-0.012	0.064
		+50	0.032	0.077
c3 (drains)	10-110000 d	-33	-0.041	0.061
		+50	0.041	0.074
c3 (peat)*[1]	10000-110000 d	-33	-0.082	0.111
T3 (peat)	4-23 m^2/d	-33	-0.032	0.082
		+50	0.018	0.07
T3 (esker)	250-750 m^2/d	-33	-0.044	0.081
		+50	0.053	0.078
T3 (mound)	8-125 m^2/d	-33	-0.088	0.255
		+50	-0.053	0.264
T3 (fenpeat)	20-40 m^2/d	-33	-0.003	0.077
		+50	-0.026	0.075
T3 (till)	20-40 m^2/d	-33	0.009	0.051
		+50	-0.003	0.046
T3 (drains)	5-250 m^2/d	-33	0.012	0.041
		+50	-0.015	0.036

*[1] peat means HIGH BOG + BOG MARGIN + FOREST
*[2] means surface level - 0.5 m

The table also shows the standard deviation of the tests, defined as:

$$\text{Standard deviation (=RMS)} = \frac{1}{n}\left[\sum_{i=1}^{n}\left(h_b - h_s\right)_i^2\right]^{0.5}$$

Where: n = number of sensitivity values [-]
h_b = head in the base model [m]
h_s = simulated head [m]

From table 4.1 it is clear that most of the parameters have a similar standard deviation for both lowering and raising the value. The resistance of HIGH BOG shows a larger difference of the standard deviation on both sides. The transmissivity of the MOUND shows a large standard deviation.

Effects on the entire model
The residuals of the heads of the base model and the simulated heads have been plotted in a graph. See figure 15 to 18 (Appendix D). As can be seen in these figures the changed heads only occur in the area where the parameter has been changed. For example the lowering of h_0 - 0.5 in the fenpeat area has only effect on the fenpeat area itself.

4.3 Discussion

From the average differences listed in table 4.1 it is clear that most of the parameters show a linear relationship in changing the parametervalue. This means that the results of the sensitivity analysis can be used for further calibration. When the relationship is not linear, other factors may be involved which could make the calibration process more difficult. The differences of heads (base model minus sensitivity test) are small, so the heads in the model are not very sensitive to changes in the selected parameters. It is clear that the model is most sensitive to the changes in the topsystem (q_1, c_1 and h_0). The results found with this sensitivity analysis can be used for further calibration.

5. CALIBRATION

5.1 Introduction

The calibration was done to make the model as accurate as possible. In order to do this, observations of heads, fluxes or discharges are needed to compare the measured data with the calculated data of the model. Only measured heads were used to calibrate the model. To fit the model the values for the hydrological parameters must be adjusted (e.g. the resistance of the clay and the transmissivity of the till). These values must be acceptable in view of the real properties of the layers they represent.

5.2 Methods and results

In order to make a reliable model, observation points must be available to compare measured heads with calculated ones. In the Clara Bog region, piezometres, boreholes and (farmer)wells are found. The locations of these points are given in Appendix E.
From the piezometer data the hydraulic head of the first aquifer was used (this aquifer is only present on the bog) and from the boreholes and the wells the heads in the second aquifer were used. Only the filters of the piezometres are in the peat, the rest is in the till aquifer. In the model the average of the measurements from October 1991 to October 1992 is used. Because the heads were not measured from January till March, an interpolation was made for that period. Furthermore, to get more reference points, the heads from 1995-1998 of BH10-BH16 were extrapolated to the period 1991-1992. This was also done for the ABC-plots and the cobrapiezometers.
Because some data are interpolated and some are extrapolated, an error can occur. An error is also made when comparing data measured by different people. Therefor, the error estimated is 10-20 cm. The target of the calibration is set to a maximum deviation of 20 cm or less in all measured points.
Table 5.1 shows the results of the calibrated model. There are still some errors that cannot be solved. The measured reference levels of well03, well05, well08 and well09 show large deviations with the surface map so the levelling done there may be wrong. This is illustrated in Appendix E.
This is also the case for well16. The levels of the surface map are used in the model. The Cobra-drilling co4 also shows large differences. The average difference of the entire model is 0.41 m, and without the large errors this becomes 0.13 m. The infiltration over the aquitard from the bog is 14.9 mm/a. This value is still in the range of 5-15 mm/a (pers. com. S v.d. Schaaf).

table 5.1 calibration

observation point	filter in	measured head [m]	head in CLARA [m]	$h_{meas}-h_{clara}$ [m]
clbh2	till	57.6	57.3	+0.3
clbh3	till	57.8	57.7	+0.1
clbh4	till	57.1	57.0	+0.1
clbh5	till	55.0	55.0	0
clbh6	till	56.5	56.1	+0.4
clbh7	till	49.8	49.7	+0.1
clbh8	till	55.1	55.1	0
clbh9	till	56.9	56.8	+0.1
BH10	till	51.5	52.0	-0.5
BH11	till	53.3	52.8	+0.5
BH12	till	49.3	49.5	-0.2
BH13	till	53.0	53.1	-0.1
BH14	till	52.6	52.6	0
BH15	till	50.5	50.5	0
BH16	till	51.7	51.9	-0.2
well02	till	56.1	56.0	+0.1
well03	till	54.7	55.5	-0.8
well05	till	57.0	58.2	-1.2
well08	till	57.3	59.5	-2.2
well09	till	57.2	60.2	-3.0
well16	till	49.2	51.0	-1.8
well19	till	57.8	57.7	+0.1
well20	till	50.3	50.3	0
well21	till	57.1	57.0	+0.1
well22	till	53.0	53.0	0
co3	till	53.0	53.2	-0.2
co4	till	52.1	53.5	-1.4
co5	till	53.0	53.0	0
A	peat	59.9	59.9	0
B	peat	59.6	59.9	-0.3
C	peat	59.0	59.0	0
p89	peat	58.3	58.4	-0.1
p96	peat	60.7	60.7	0
p97	peat	60.7	60.9	-0.2

Figure 5.1 shows the hydraulic head in the till aquifer of the calibrated model.

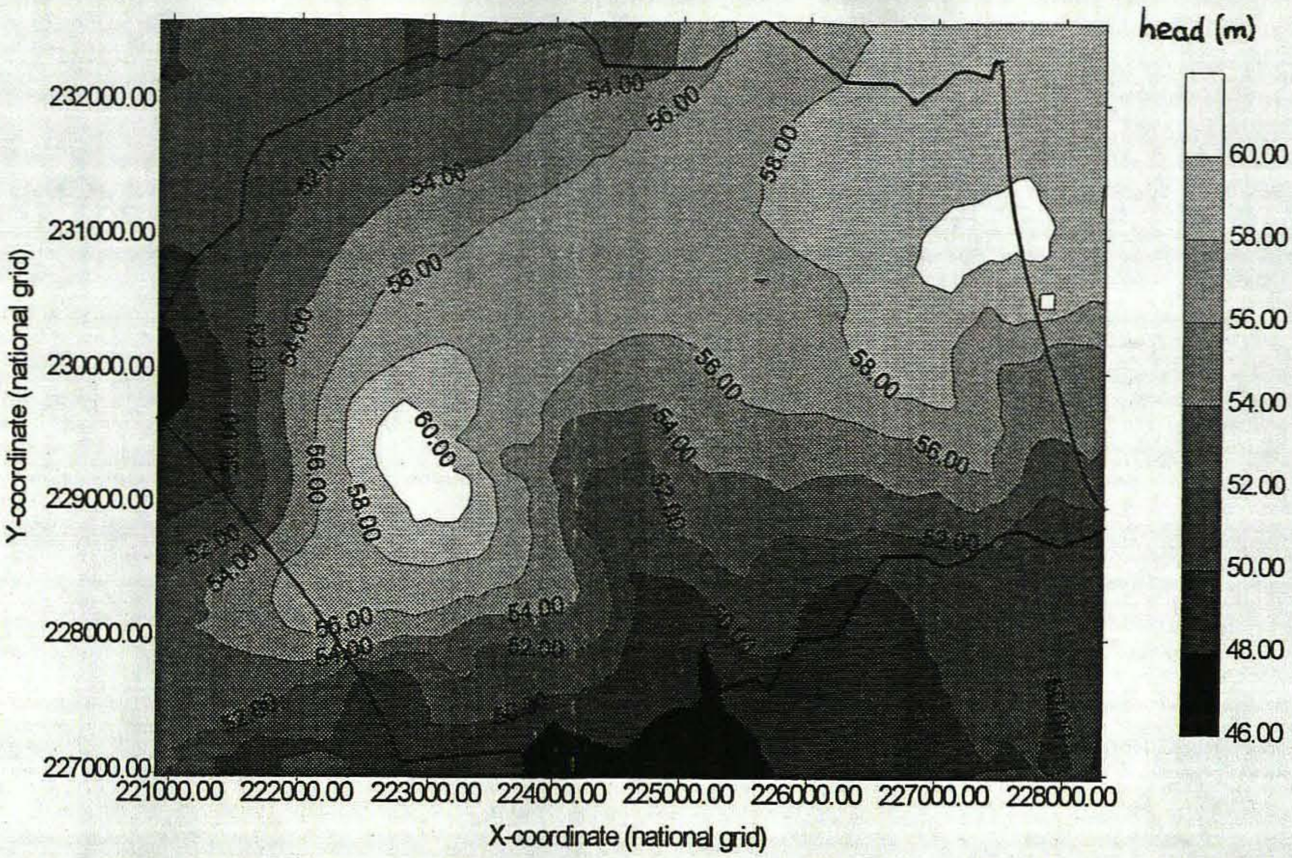

figure 5.1 hydraulic head in the till aquifer in the model

5.3 Verification

Another step in the modelling is to verify the model. This means another year's precipitation surplus is entered in the model and other measured data are compared with the outcome of the model. The period chosen for verification is August 1996-August 1997. The precipitation then was 848.2 mm. In Appendix E the results can be found. The same problems occur as in CLARA, the heads of wells 3, 5, 9, 16 are too high. The absolute average difference (over the observation points) is 0.49 m, and without the larger errors this is 0.21 m. The infiltration from the bog now becomes 16.06 mm/a. From the table in Appendix E it is clear that changes have occured on clbh5. (the measured head in 1991-1992 was 55.0 m and in 1996-1997 this was 53.9 m.) The reason for this lies in the fact that a deep drain is made for turfcutting near clbh5 (pers. obs.).

5.4 Discussion

The adjusting of the model lead to the final model CLARA. With this model the scenarios were calculated. There are still some errors but the overall accuracy of the model is as required. The most remarkable errors are the heads from wells 3,5,8,9 and 16. These are probably caused by wrong levelling as mentioned before. The same problem occured with co4: the level on the surface map didn't meet the level found by Moll & Peters (1996a).

6. SCENARIOS

6.1 Introduction

The second objective of the work was simulating scenarios with the model. The scenarios were entered into the calibrated model CLARA. The scenarios were (see also figure 6.1)
-blocking the drains along the road (scenario1, blue line)
-raising the waterlevel along the road to the height of the road (scenario 2, yellow line)
-building a dam across the road in the area of the forest (scenario 3, green line)
-blocking the drains south of the proposed dam alignment along the road (scenario 4, red line)

6.2 Methods and results

In this paragraph the scenarios will be dealt with separately. Contour maps of the differences in hydraulic heads can be found in Appendix F.

Scenario 1
In this scenario the drains along the Bog Road are blocked. This means that no water can discharge, except in periods of heavy rainfall. The drains are given a drainage level 0.5 m below the height of the road.
Comparing the hydraulic heads in the peat in the reference situation and the scenario doesn't show much effect. The difference in head is mostly in the order of 10^{-5} m.
The difference in the hydraulic heads in the till aquifer are more remarkable. In Appendix F the contourmap can be found. This map shows a gradual decrease of the difference with increasing distance of the drains.
In table 6.1 the seepage of the whole modelarea is related to the upward seepage of the reference model.

table 6.1 comparison of the upward seepages

Seepage	reference v (mm/d)	scenario 1 v (mm/d)
aquifer 1	1.035	1.035
aquifer 2	0.007	0.025
aquifer 3	0.007	0.008

The flux over the aquitard underneath the peat is 0.044 mm/d $\cong$ 16.06 mm/a.
There is no change in the pattern of the flow.

Scenario 2
This scenario includes the raising of the waterlevel along the road to the height of the road. This scenario looks like scenario 1 and the effects are the same. In Appendix F the differences in hydraulic heads in the till aquifer can be seen. The differences found here are larger (1.6m-1.8m) then in scenario 1 (1.2m-1.4m). The upward seepages can be found in table 6.2.

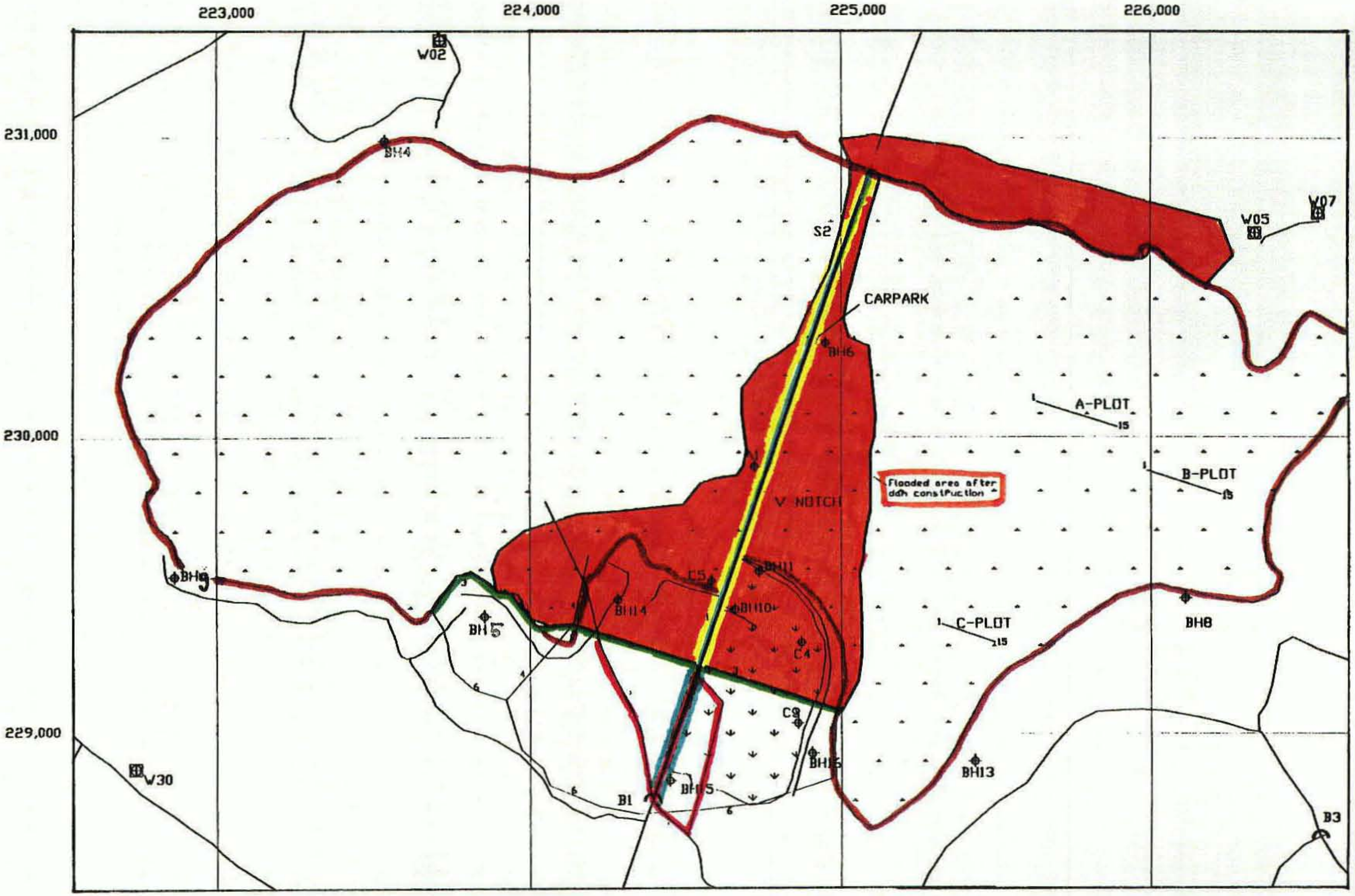

figure 6.1 scenarios

table 6.2. seepage of scenario 2 (entire area)

Seepage	scenario 2 v (mm/d)
aquifer 1	1.035
aquifer 2	0.005
aquifer 3	0.003

The flux over the aquitard underneath the peat is 0.048 mm/d ≅ 17.52 mm/a.
There is no change in the pattern of the flow.

Scenario 3

Scenario 3 contains the building of a dam perpendicular to the road in the area of the forest. The exact position is shown in figure 6.1. The design level should be 57.5 metres m OD. In this scenario two different levels were tried to see what the influence of the rising heads would be. These two heads were 56.5 maOD and 57.5 maOD, resp. scenario 3b and scenario 3d. The dam will cause a flooded area that is also shown in figure 6.1.
Behind the dam two zones were created to make it possible to measure the changing in up- or downward seepage (zone1 and zone 2). Also 32 points were selected to be able to measure the difference in waterheads, (r1 - r20 and s1 - s12). The zones and positions of the reference points can be found in Appendix F.

The following data were calculated:
- the difference in hydraulic heads.
- the difference in seepages.

Contourmaps were also constructed to show the differences in waterheads before and after the measure, see Appendix F. This map also shows how far the influence of the dam reaches.

table 6.3 damheight 56.5 m OD

	r2-r10	r16-r20	s2-s5
mean rise (m)	0.63	0.12	2.10
minimum (m)	0.04 (r2)	0.06 (r20)	1.20 (s5)
maximum (m)	1.38 (r5)	0.20 (r18)	2.94 (s3)

table 6.4 damheight 57.5 m OD

	r2-r10	r16-r20	s2-s5
mean rise (m)	1.01	0.16	2.10
minimum (m)	0.05 (r2)	0.09 (r20)	1.78 (s5)
maximum (m)	1.79 (r5)	0.26 (r18)	3.62 (s3)

The upward seepages:

For zone 1, just behind the dam, the seepage shows a change from downward seepage to upward seepage in the third layer (-0.08 mm/d to +0.77mm/d). For scenario 3d this upward seepage becomes much larger, compared to the last increase of one meter, up to 1.14 mm/d. Zone 2 already showed an upward seepage of 0.86 mm/d before building the

dam. After building the dam this seepage increased to 1.41 mm/d and 1.61 mm/d for resp. scenario 3b and 3d.
The seepages can be found in figure 6.2.

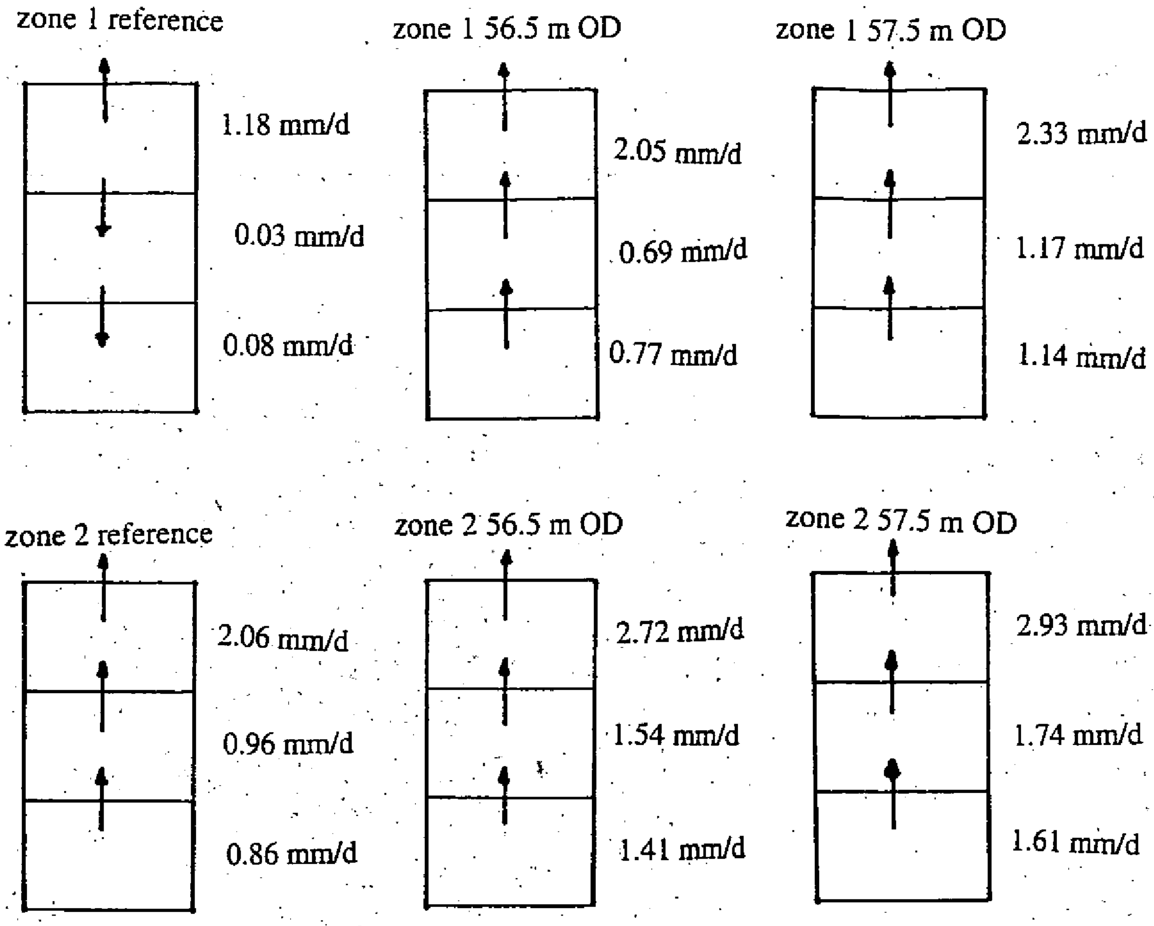

figure 6.2 seepages of the area behind the dam

Scenario 4
This scenario involves blocking the drains south of the proposed dam alignment along the road (figure 6.1, red lines). The drainage resistance was removed and the heads were calculated. The results of comparing the reference heads with these heads can be found in Appendix F. This is only done for the heads in the till aquifer, the differences in the peat aquifer were very small. The seepages of the area can be found in table 6.5

table 6.5 seepages of scenario 4 (entire area)

Seepage	scenario 4 v (mm/d)
aquifer 1	1.035
aquifer 2	0.005
aquifer 3	0.001

As can be seen in table 6.5 the seepage doesn't differ much from the reference values. The flux over the aquitard underneath the peat is 0.046 mm/d ≅ 16.70 mm/a.

This scenario is entered in a model based on data of October 1991 - October 1992. This means that changes in e.g. drains were not taken into account. The drain most to the west has now been enlarged for turfcutting (pers. obs.) so this will have an effect on the new situation, as already can be seen from the last data of borehole 5 (more than one metre lowering). Expected is an influence of heads in the high bog.

6.3 Conclusions

Scenario 1 and 2 show very small effects on the bog area, and the effects that can be found only have influence in the nearest surroundings of the blocked drains.
Scenario 3 implies a marked increase in the waterlevel. The effect this rise has on the bog area can be found in Appendix F, more than three quarter of the bog area is affected by an increase in hydraulic head in the till aquifer.
Behind the dam, the largest effects in rising heads can be found in the lowest parts of the surrounding, these are the places where the heads in front of the dam have risen the most. At the eastern side of the dam the rising of the heads is larger than the western side. This is probably caused by the less deep flooded area at the west side.

7. MODEL LIMITATIONS

7.1 Introduction

This section states the limitations of the model and the assumptions made in the modelling. It is important to know to what extent the model approximates the truth, especially when large changes have to be modelled. E.g. scenario 3 (building a dam) involves a large change in hydraulic head.

7.2 Limitations and reliability of the model

From the sensitivity analysis it can be found that the model is very sensitive to changes in the transmissivities in the till aquifer. During the calibration these transmissivities have been changed with factors up to 3. The drainage resistance (toplayer) has been changed from 50 days to 10 days. It must be clear that for these values the range of realistic values is very large because it is not kown for each drain how deep it cuts into the different layers. Thus is it very difficult to estimate the values.

The transmissivities of the Mound were never measured, so one should take a security range of at least a factor 2 for the entered values. The transmissivities and the resistances of the peat body have been measured well in the past and there is no real doubt about these values. For the esker it is not well known how far different layers reach and what the variation in transmissivies exactly is.

After verification of the model it has become clear that for other years and other precipitation surplus the model also shows realistic results. This gives a confidence in the reliability of the model.

7.3 Degree of uncertainty in the scenarios

In the scenarios mostly use has been made of zones in which differences in head and seepage have been calculated. For very small spots, e.g. behind the dam, these differences might be larger than the overall results, especially when there are till outcomings in these neighbourhoods. The swelling of the catotelm, which could possibly happen as a result of a scenario has not been modelled. But it is expected that the catotelm transmissivities may become considerably larger.

7.4 Use of modelling results

When using modelling results one should take into account that a model never will represent the whole reality. Calculated scenarios with a model also need a critical view, before using the results. This report tells nothing about dam constructions or the soilmechanical theory about them, so before using the scenarioresults be sure about these things. This model involves a very large area and shows the effects of the scenarios on a bigger scale. To show the effects near the dam and surrounding a more detailed model should be made, which only deals with the effects really close to the dam. Also the effects of raising catotelm could be modelled better in this way.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The conclusions and recommendations only deal with the hydrological model and the calculated scenarios:

- The most sensitive parameters of the model are the drainage resistances and the transmissivities.

- Some wells possibly have not been levelled correctly, there are considerable differences between the digital levelchart we used and the some of the levelled wells.

- The model boundaries are located far enough away from the area of interest now, no boundary effects are found anymore in the dam area.

- The infiltration over the aquitard beneath the bog (clay and catotelm) is 14.9 mm/a in the final model, which is still in the range of 5-15 mm/a (pers. com.S v.d. Schaaf).

- Scenario 3 (building the dam across the road) gives the largest effects on the hydraulic heads in the peatbody and the surroundings.

- Blocking the drains near the road (scenario 1 and 2) does not yield the required effects, neither does blocking the drains south of the proposed dam-site (scenario 4).

- A better drain inventory might give better results in the north west area of the model.

8.2 Recommendations

- This model represents a large area in and around Clara Bog. It should be used to simulate the effects on phreatic and piezometric levels caused by different scenarios in the bog and its near surroundings caused by different scenarios. To simulate local effects in and near planned dams and other scenarios a more detailed model should be constructed, based on the described model.

- The swelling of the catotelm has not been modelled, it would be advisable to test what the effects of swelling catotelm are for the dam area. Relationships of the hydraulic conductivity and volume fraction of solid matter in the peat as developed by Moll & Peters (1996a) should be used.

- It would be advisable to test more scenarios, e.g. more dam positions could be entered to see what the effects are.

- This report does not deal with soilmechanical problems. Further investigation is necessary.

- More attention should be given to the upward seepage behind the dam. This must be done to see if agriculture is still possible in that area.

- The new drain near clbh5 should be entered in scenario 4 to test what its effect will be.

9. LITERATURE

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APPENDICES

CLBH4 17-Dec-97
Discharge 23 s/2l

Time (s)	level (m)	drawdown (m)
0	2.110	0.000
10	2.190	0.080
19	2.200	0.090
65	2.210	0.100
540	2.210	0.100
900	2.210	0.100

Drawdown in rock tube: 1.5 cm

CLBH5 16-Dec-97
Discharge 22 s/2l

Time (s)	level (m)	drawdown (m)
0	0.750	0.000
40	0.950	0.200
60	0.980	0.230
91	0.990	0.240
140	1.000	0.250
185	1.010	0.260
277	1.020	0.270
430	1.030	0.280
543	1.040	0.290
630	1.050	0.300
785	1.060	0.310
990	1.065	0.315
1147	1.070	0.320

17-Dec-97
Discharge 25 s/2l

Time (s)	level (m)	drawdown (m)
0	2.080	0.000
10	2.150	0.070
19	2.190	0.110
25	2.200	0.120
80	2.210	0.130
180	2.220	0.140
307	2.230	0.150
960	2.230	0.150

CLBH14 17-Dec-97
Discharge 40 s/2l.

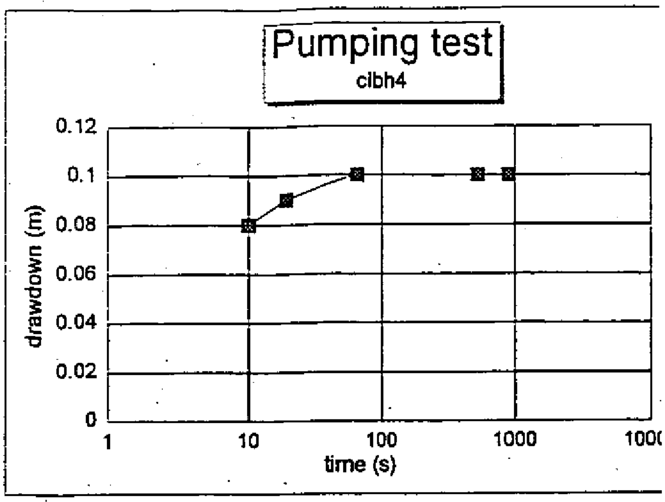
Time (s)	level (m)	drawdown (	Time per 2 l of discharg
0	0.700	0.000	
5	0.860	0.160	
10	0.990	0.290	
13	1.100	0.400	
17	1.250	0.550	
21	1.310	0.610	
25	1.390	0.690	
31	1.450	0.750	
35	1.530	0.830	
40	1.690	0.990	
50	1.800	1.100	32 s
55	1.890	1.190	
60	1.900	1.200	
65	1.940	1.240	
81	2.060	1.360	
96	2.120	1.420	
106	2.220	1.520	
345	3.510	2.810	45 s
375	3.500	2.800	
409	3.470	2.770	
420	3.460	2.760	43 s
555	3.470	2.770	
560	3.480	2.780	
600	3.490	2.790	
780	3.480	2.780	
815	3.440	2.740	42 s
840	3.460	2.760	
890	3.450	2.750	
945	3.410	2.710	
990	3.400	2.700	
1030	3.380	2.680	41 s
1170	3.300	2.600	
1210	3.260	2.560	
1250	3.250	2.550	
1265	3.240	2.540	
1305	3.230	2.530	
1350	3.210	2.510	
1403	3.200	2.500	43 s
1560	3.230	2.530	
1579	3.250	2.550	
1599	3.270	2.570	39 s
1630	3.260	2.560	
1680	3.240	2.540	40 s
1780	3.220	2.520	

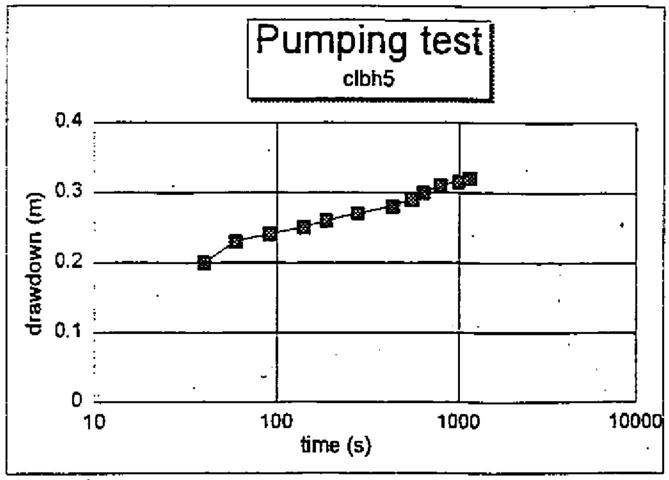
Drawdown in rock tube: 2 cm

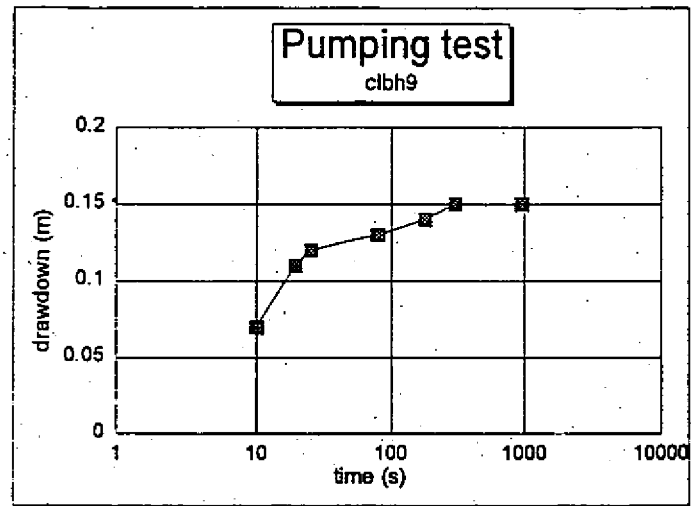
CLBH16 16-Dec-97
Discharge 20.5 s/2 l.

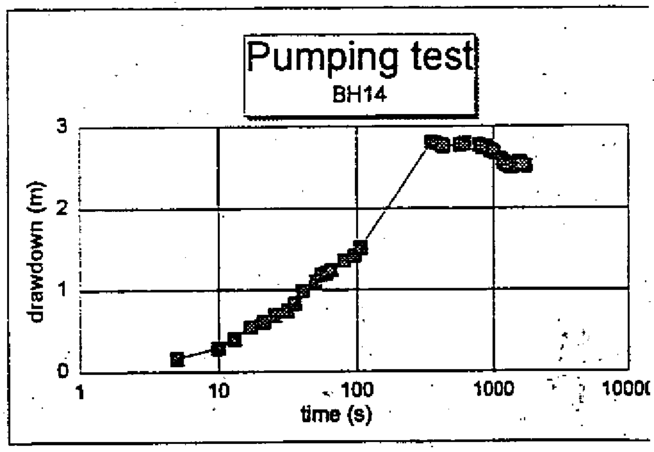
Time (s)	level (m)	drawdown (m)
0	0.130	0.000
5	0.170	0.040
15	0.200	0.070
25	0.230	0.100
46	0.240	0.110
57	0.250	0.120
70	0.260	0.130
83	0.270	0.140
93	0.280	0.150
110	0.290	0.160
140	0.300	0.170
165	0.310	0.180
191	0.320	0.190
225	0.330	0.200
268	0.340	0.210
317	0.350	0.220
388	0.360	0.230
440	0.370	0.240
690	0.390	0.260
815	0.400	0.270
1000	0.410	0.280
1185	0.420	0.290
1560	0.420	0.290

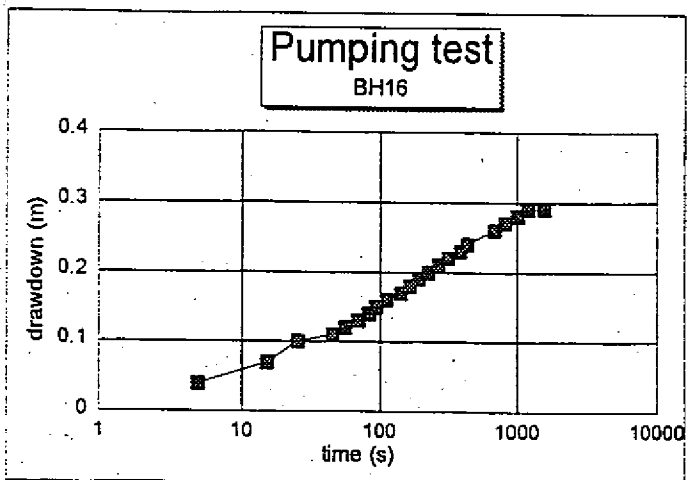
Drawdown in rock tube about the same as in till tube

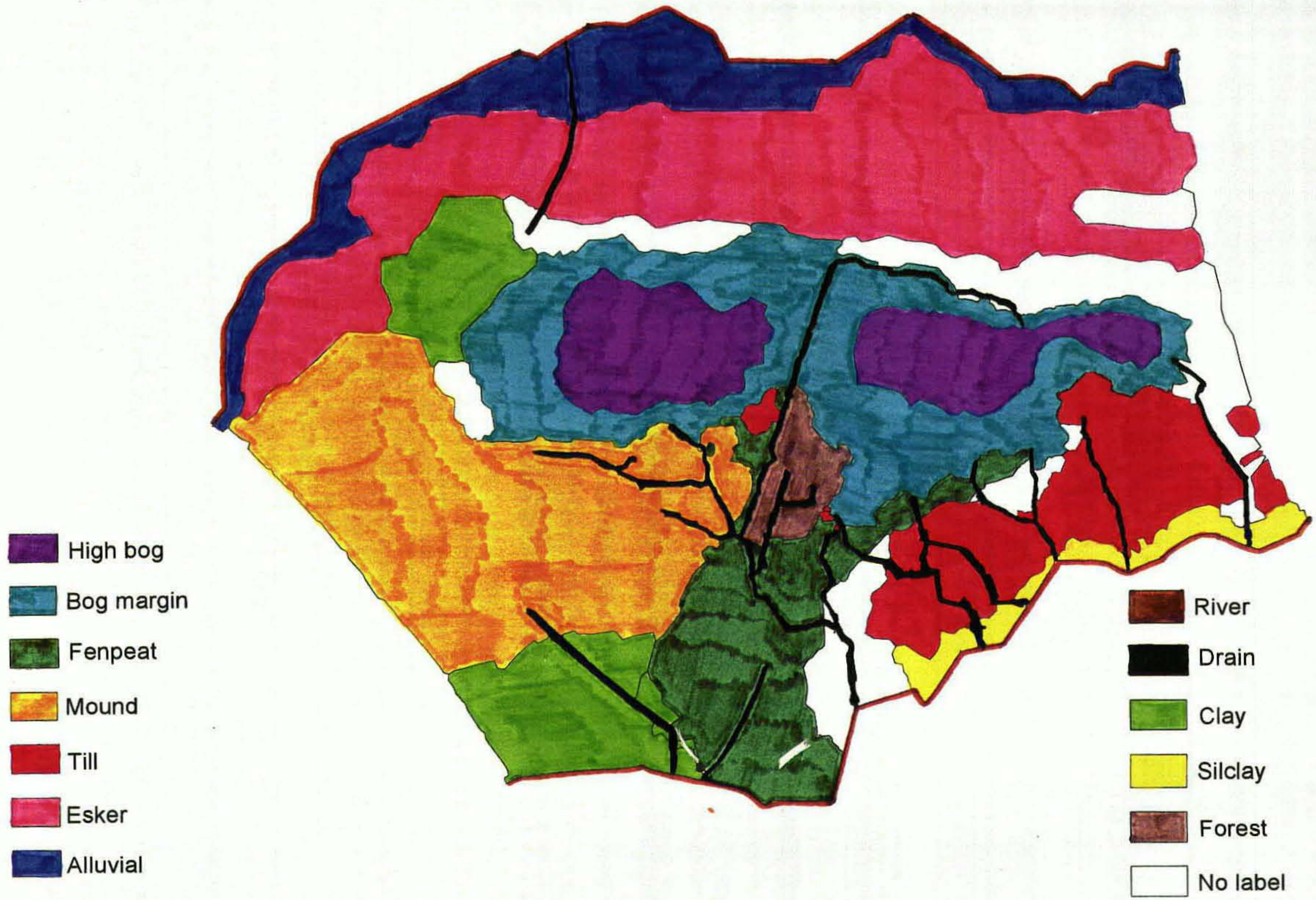

Pumping test
clbh4
drawdown (m)
time (s)


Pumping test
clbh5
drawdown (m)
time (s)

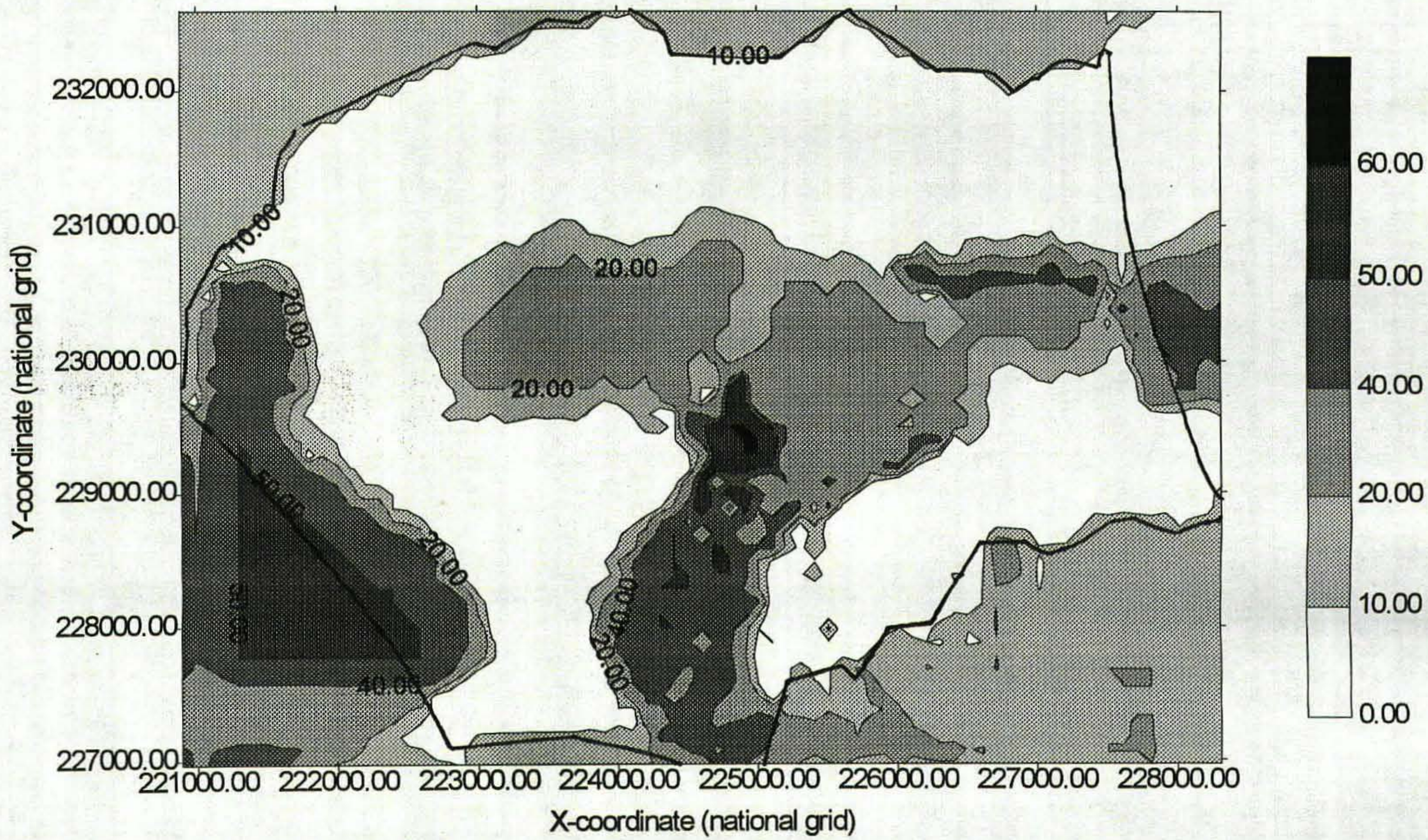

Pumping test
clbh9
drawdown (m)
time (s)


Pumping test
BH14
drawdown (m)
time (s)

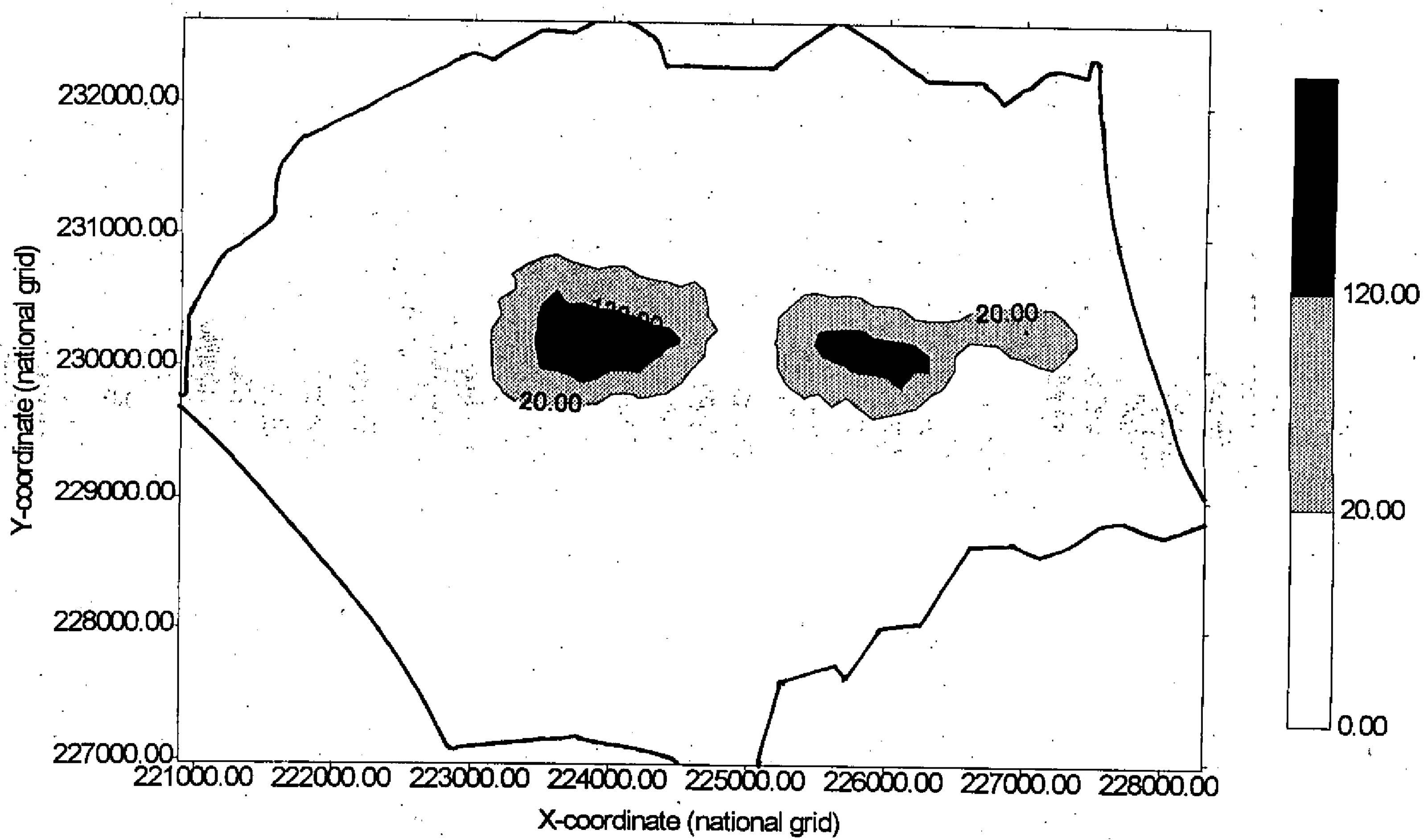

Pumping test
BH16
drawdown (m)
time (s)


High bog
Bog margin
Fenpeat
Mound
Till
Esker
Alluvial
River
Drain
Clay
Silclay
Forest
No label

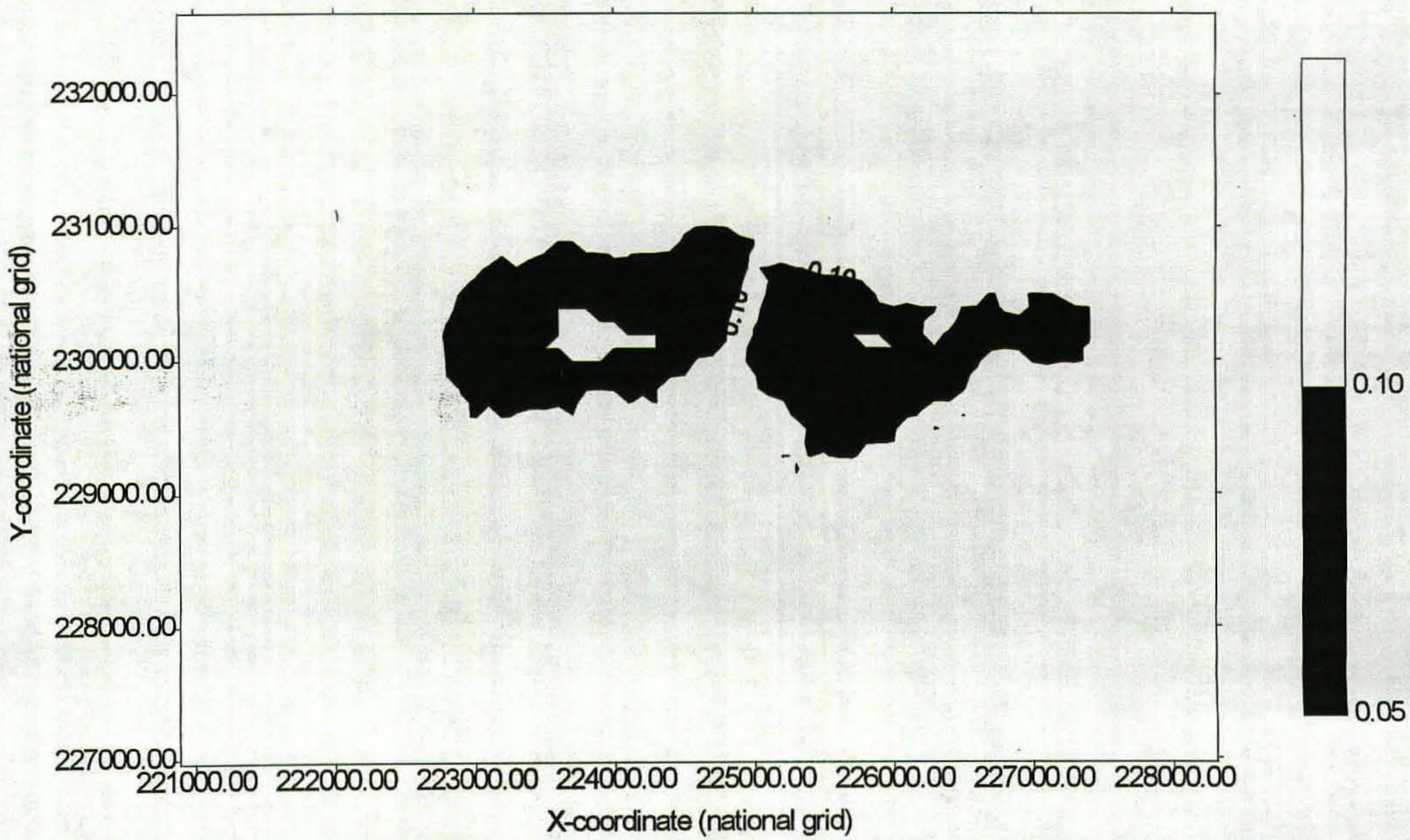
Drainage resistance c1 (d)



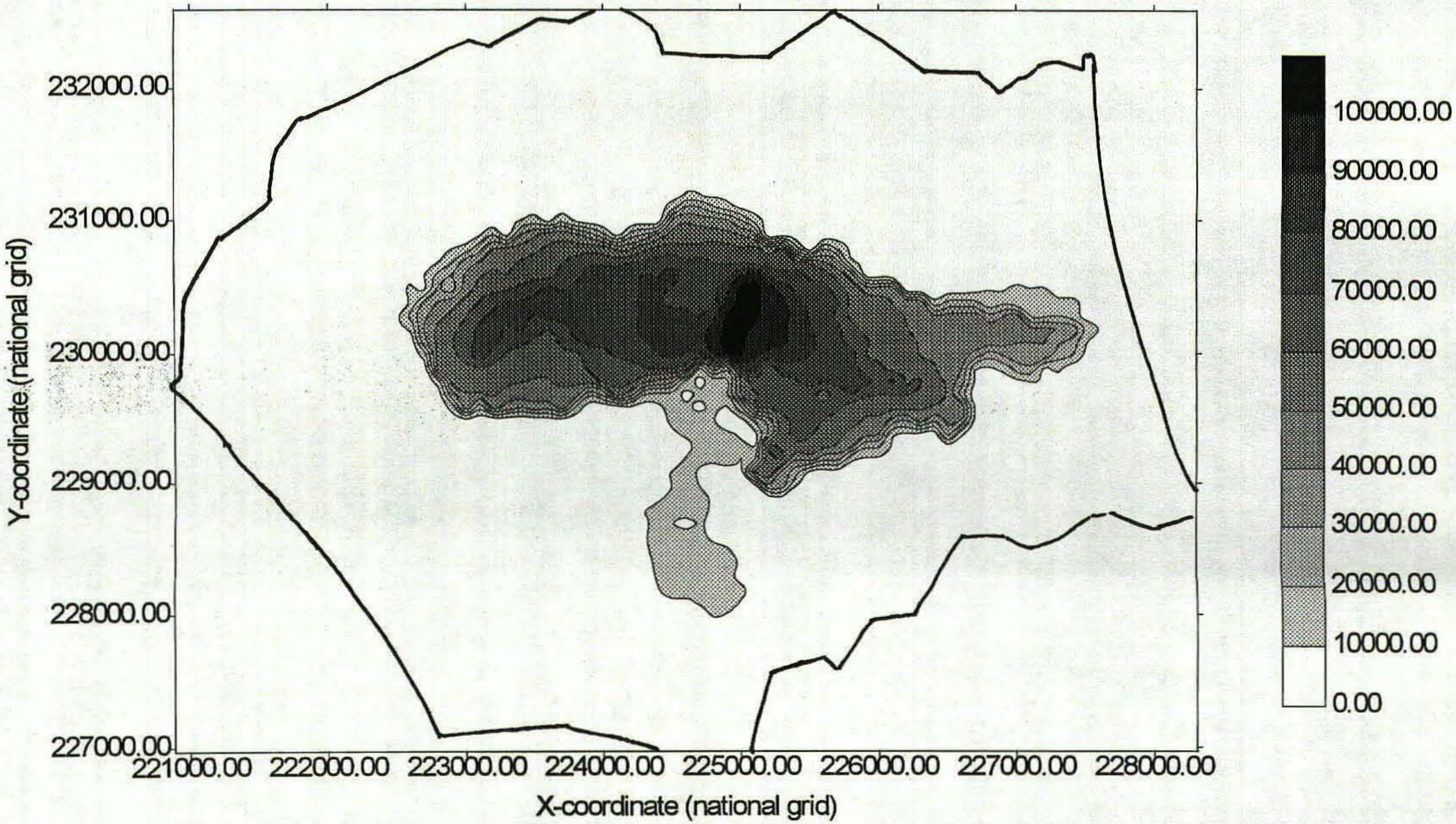
Transmissivity acrotelm T1 (m2/d)



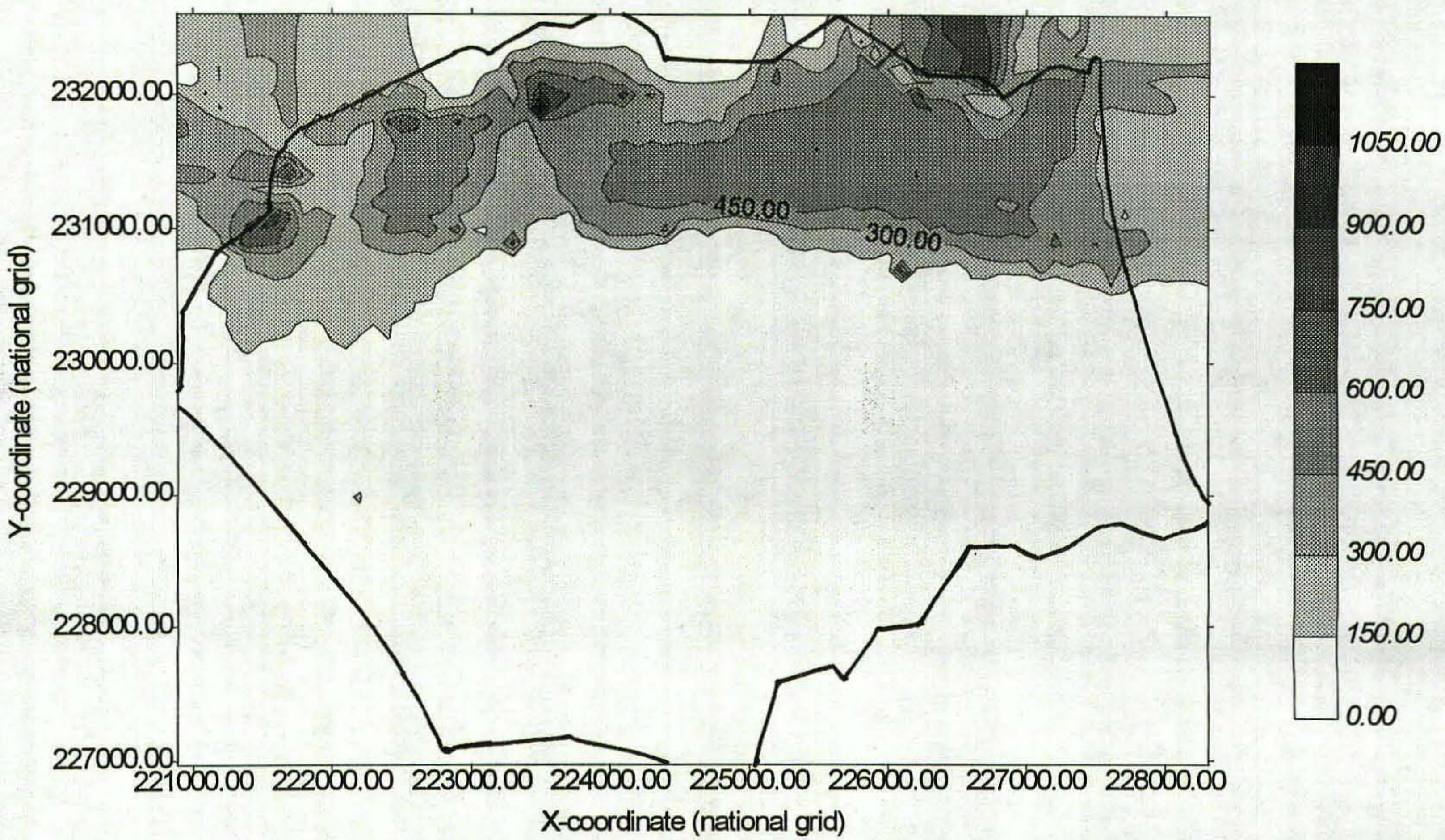
Transmissivity catotelm T2 (m2/d)



Resistance catotelm/clay aquitard c3 (d)

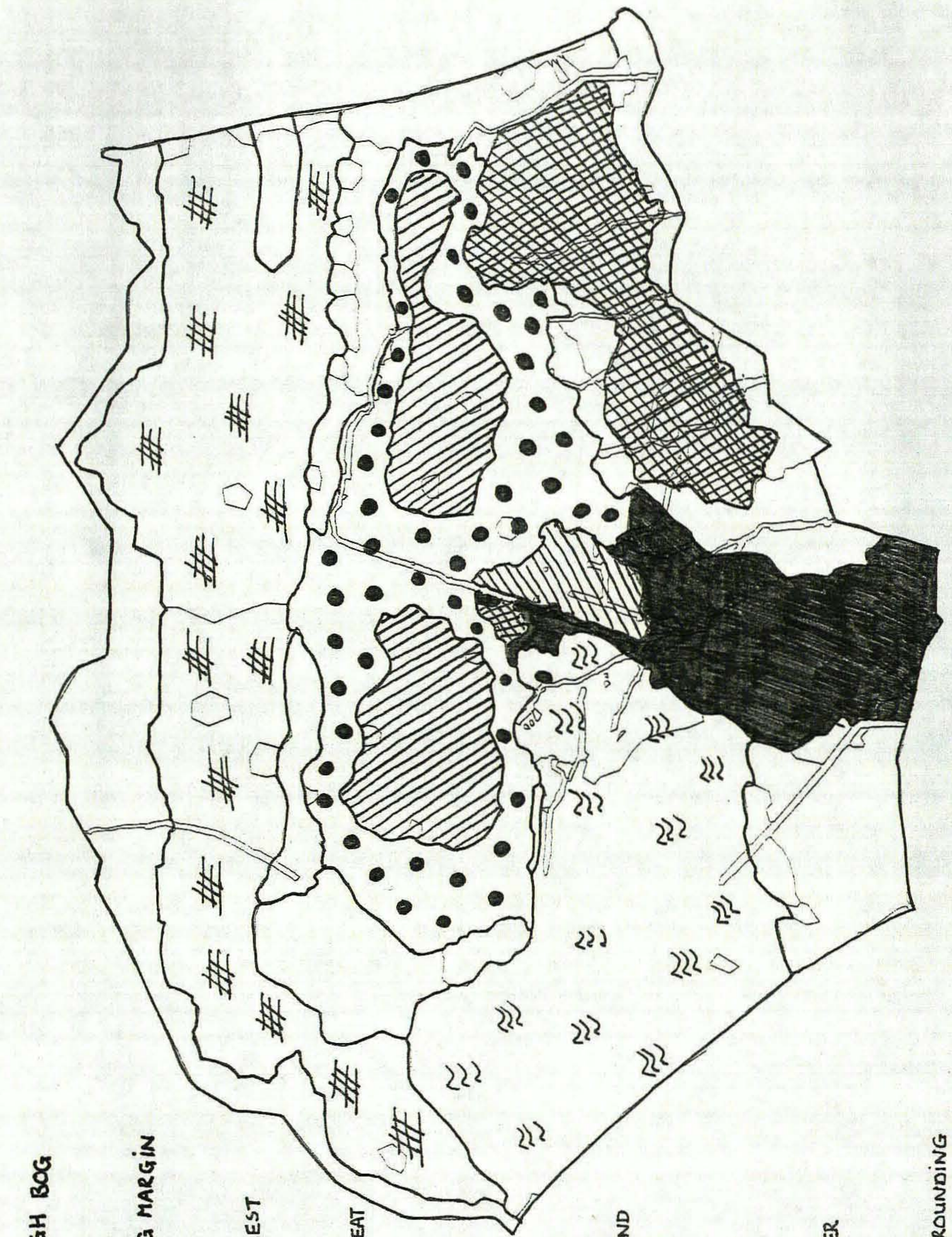


Transmissivity in esker/till aquifer T3 (m2/d)

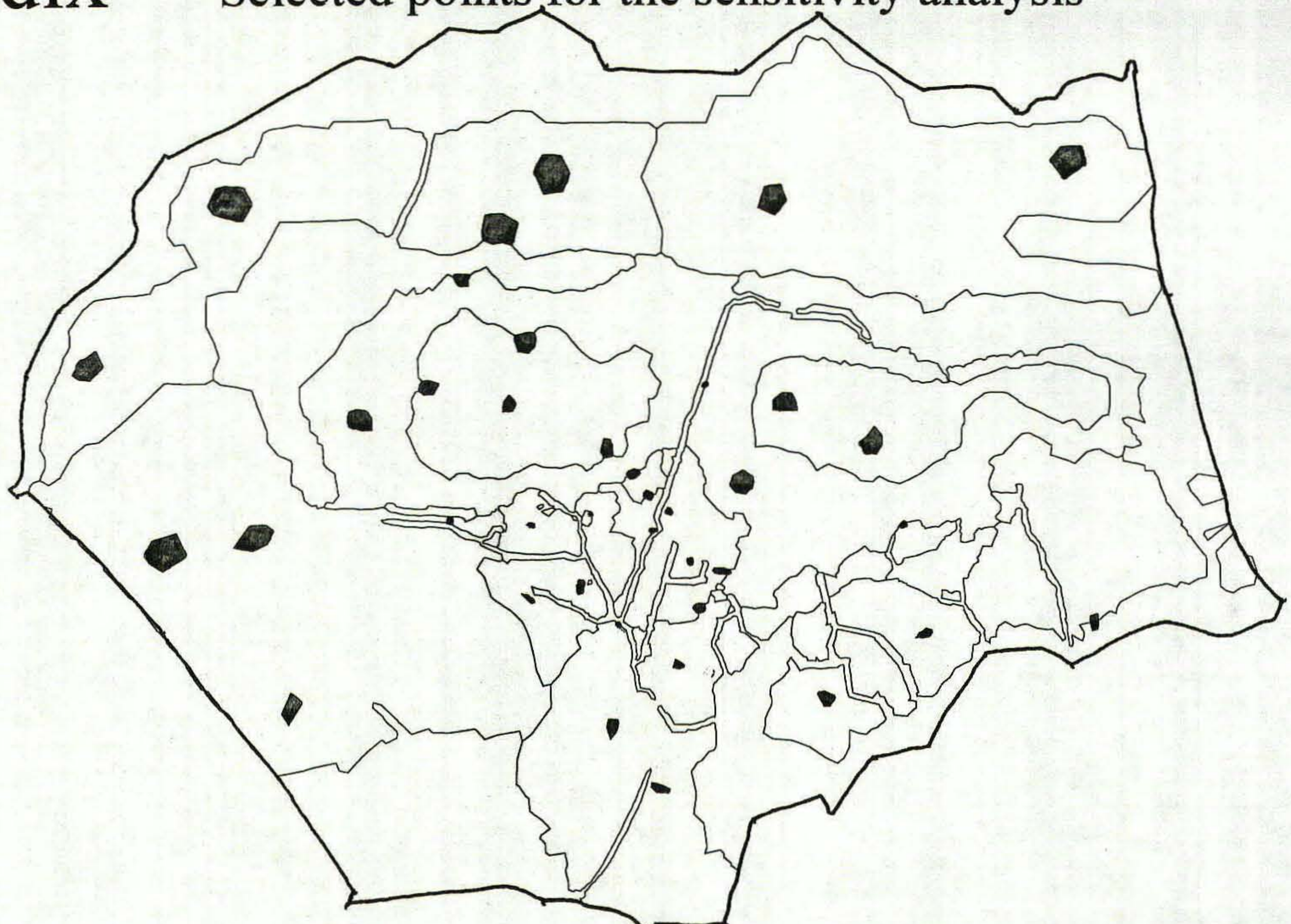


Appendix C PARAMETER VALUES

parameter	value		parameter	value
q_1 (entire bog)	0.79 mm/d		c_3 (high bog)	40000-100000 d
q_1 (grass)	1.10 mm/d		c_3 (bog margin)	10000-110000 d
q_1 (forest)	1.00 mm/d		c_3 (forest)	3000-20000 d
			c_3 (fenpeat)	1000-20000 d
h_0 (drains)	drainage level		c_3 (mound)	500-6000 d
h_0 (rest of model)	surface level			
c_1 (drains)	10 d		c_3 (till)	500 d
c_1 (rivers)	20 d		c_3 (drains)	10-110000 d
c_1 (entire bog)	20 d		c_3 (silklei)	3000 d
c_1 (fenpeat)	50 d		c_3 (alluvial)	2000 d
c_1 (diffuse)	50 d		c_3 (rest of model)	1 d
c_1 (rest of model)	0 d			
			T_3 (entire bog)	4-23 m^2/d
T_1 (high bog)	125 m^2/d		T_3 (forest)	4-23 m^2/d
T_1 (bog margin)	10 m^2/d		T_3 (fenpeat)	20-40 m^2/d
T_1 (rest of model)	1 m^2/d		T_3 (mound)	8-125 m^2/d
			T_3 (till)	20-40 m^2/d
c_2 (entire bog)	1 d		T_3 (esker)	250-750 m^2/d
c_2 (forest)	1 d		T_3 (drains)	5-250 m^2/d
c_2 (fenpeat)	1 d		T_3 (Silver)	18-40 m^2/d
c_2 (rest of model)	1 d		T_3 (Brosna)	18-400 m^2/d
			T_3 (alluvial)	20-700 m^2/d
T_2 (high bog)	0.1 m^2/d		T_3 (silklei)	10-20 m^2/d
T_2 (bog margin)	0.05 m^2/d		T_3 (clay)	100-250 m^2/d
T_2 (rest of model)	1 m^2/d		T_3 (rest of model)	20-500 m^2/d
q_2 (model)	0 mm/d		q_3 (model)	0 mm/d


HIGH BOG
BOG MARGIN
FOREST
FENPEAT
MOUND
TILL
ESKER
SURROUNDING

Appendix Selected points for the sensitivity analysis



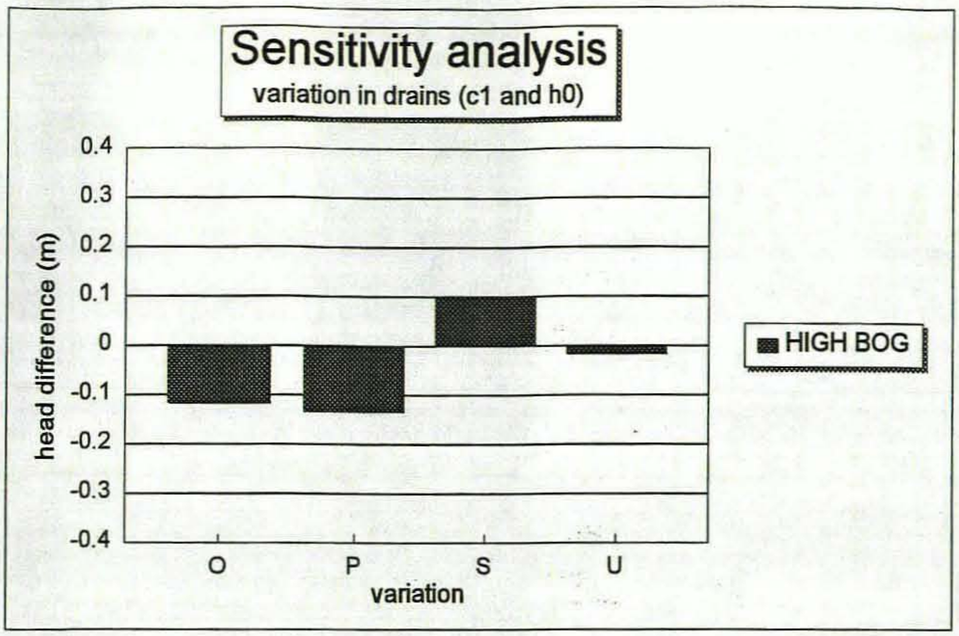


figure 1

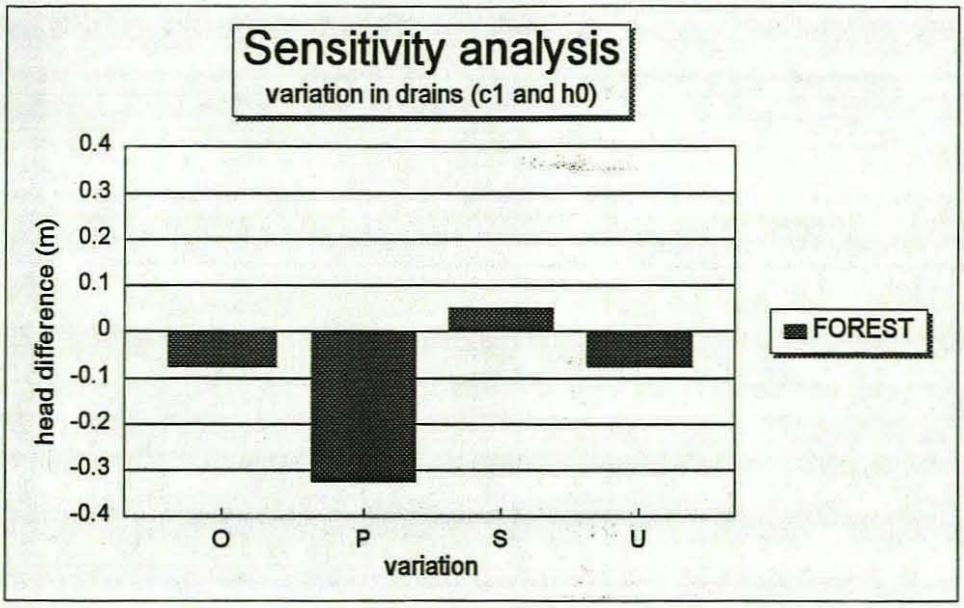


figure 2

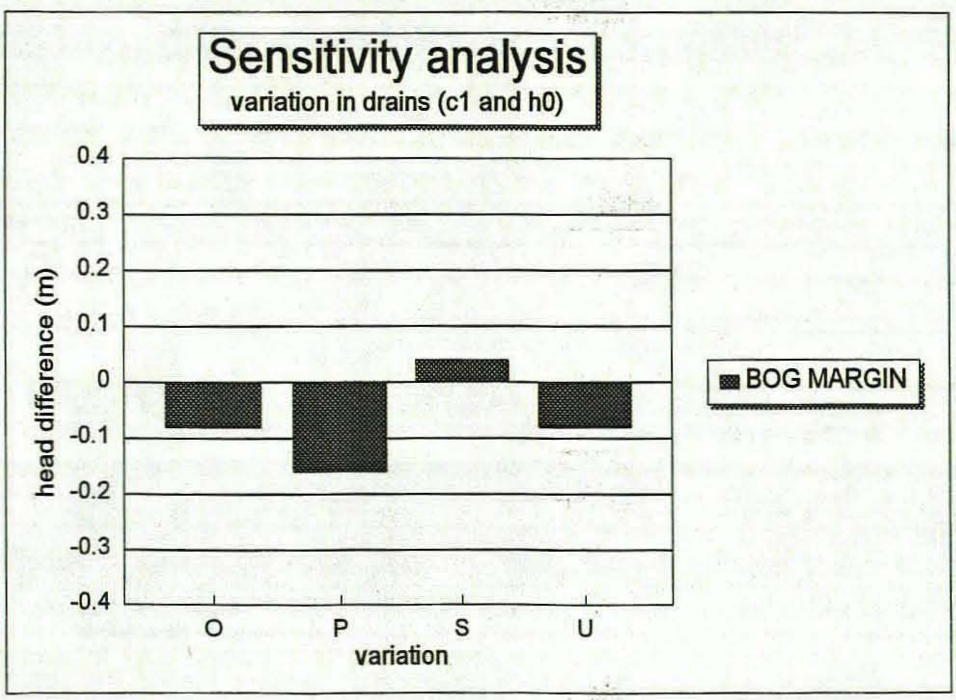


figure 3

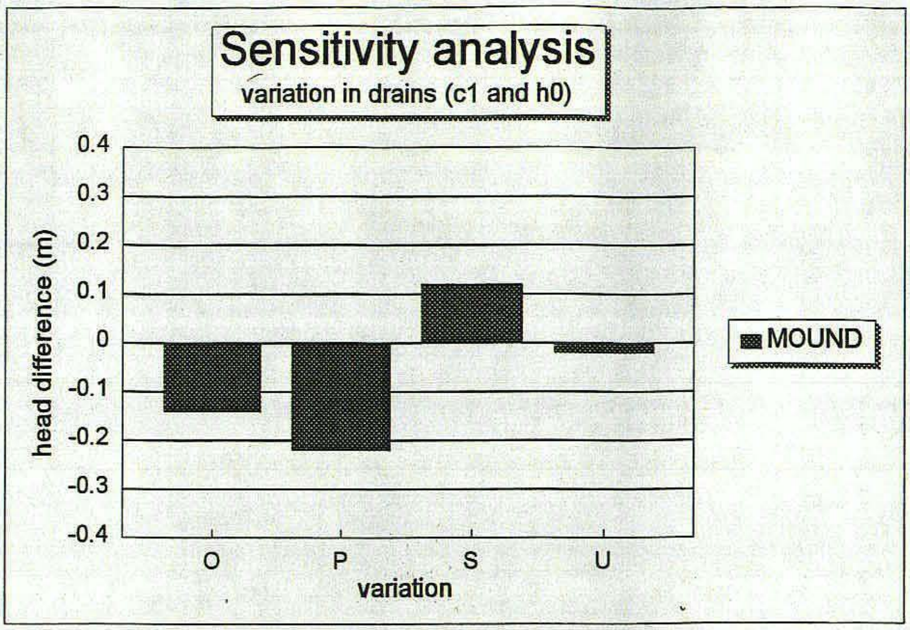


figure 4

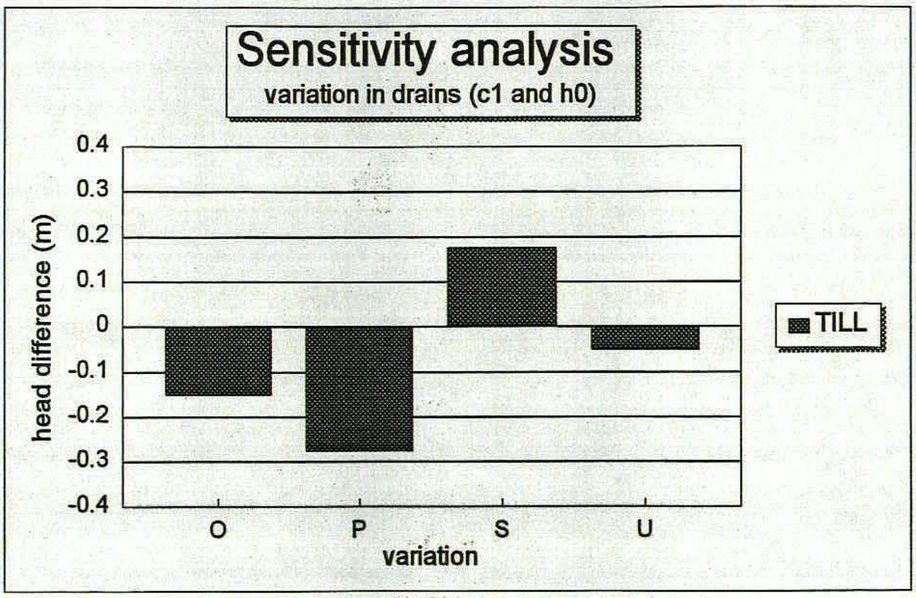


figure 5

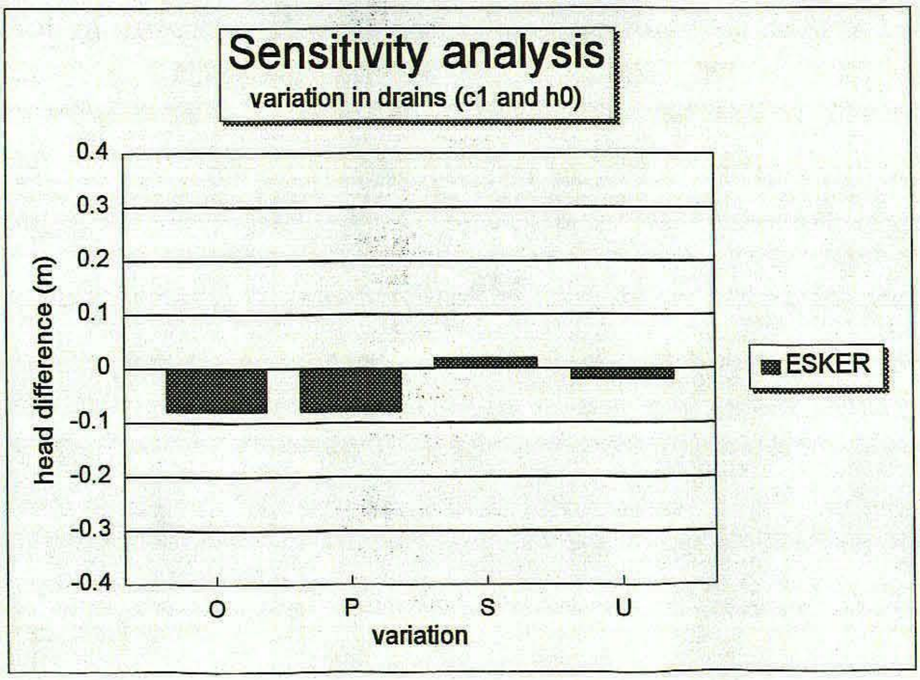


figure 6

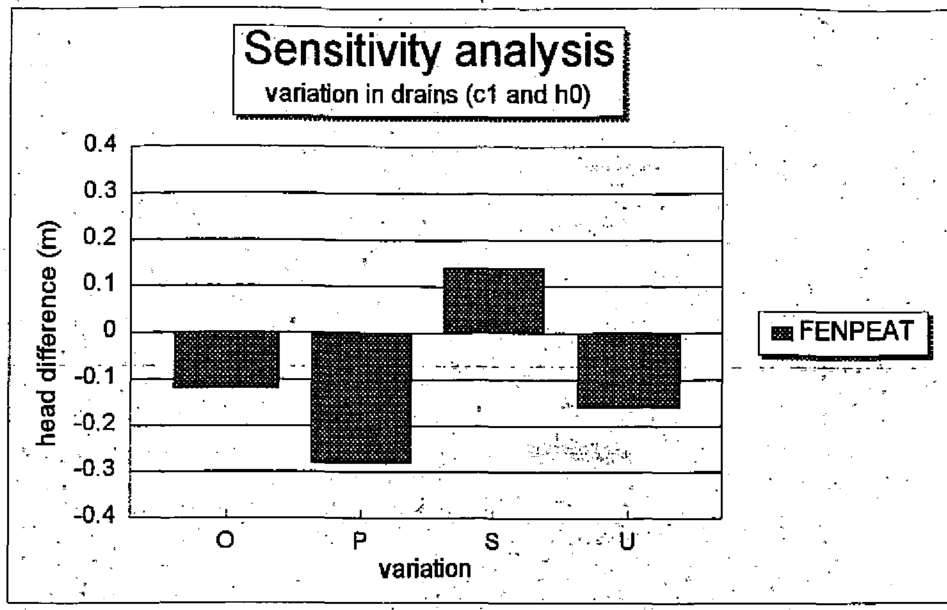


figure 7

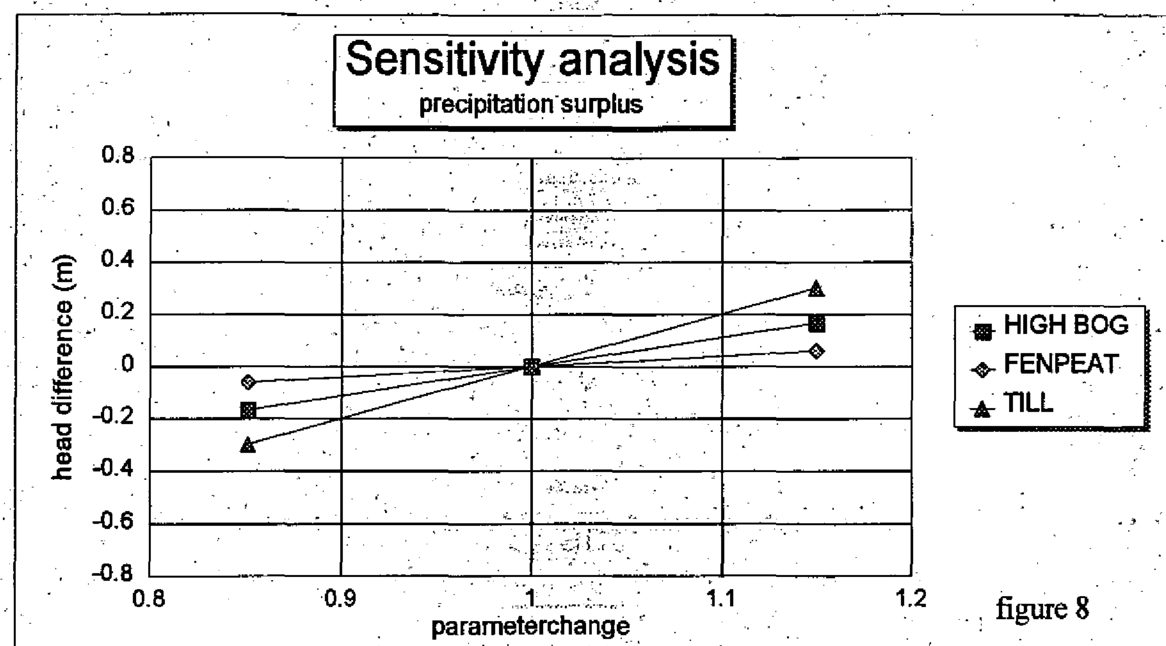


figure 8

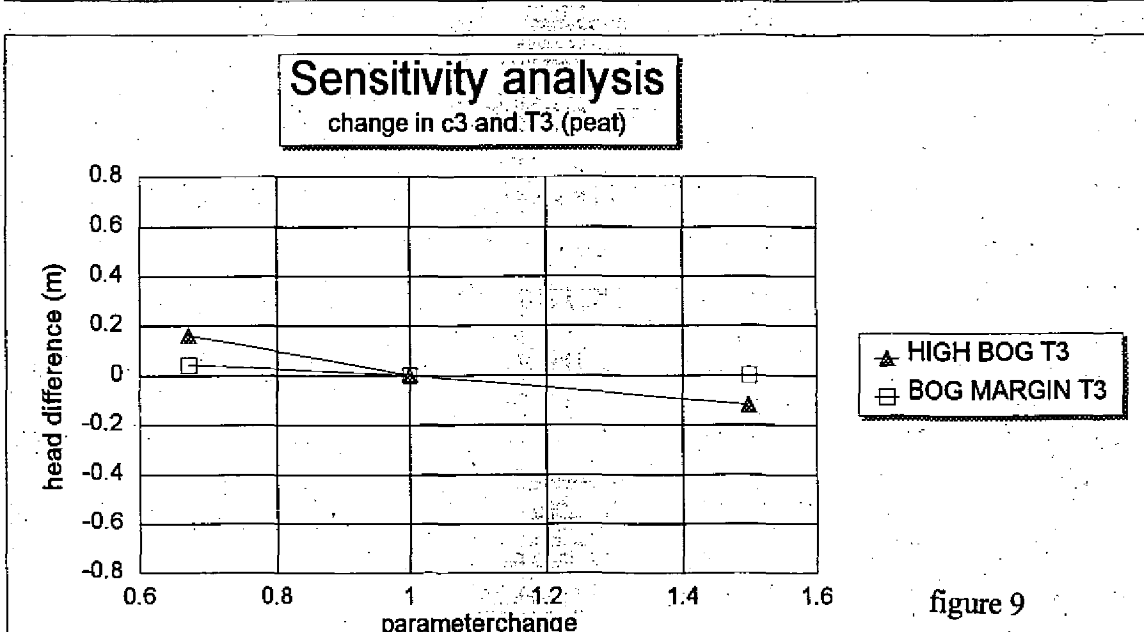


figure 9

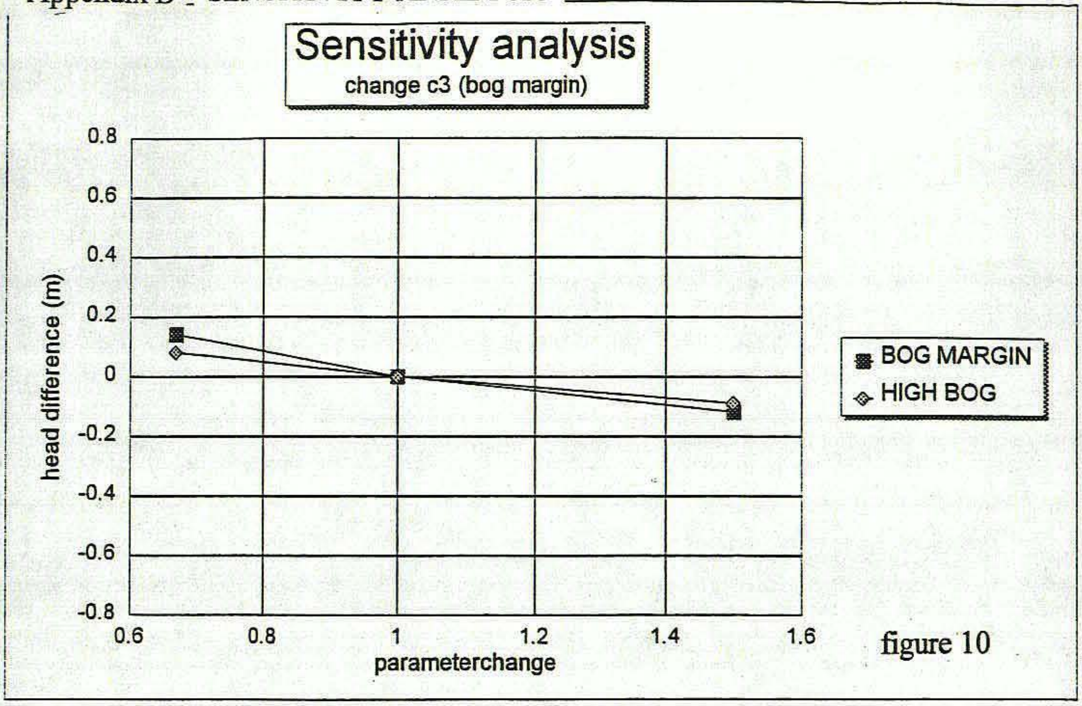


figure 10

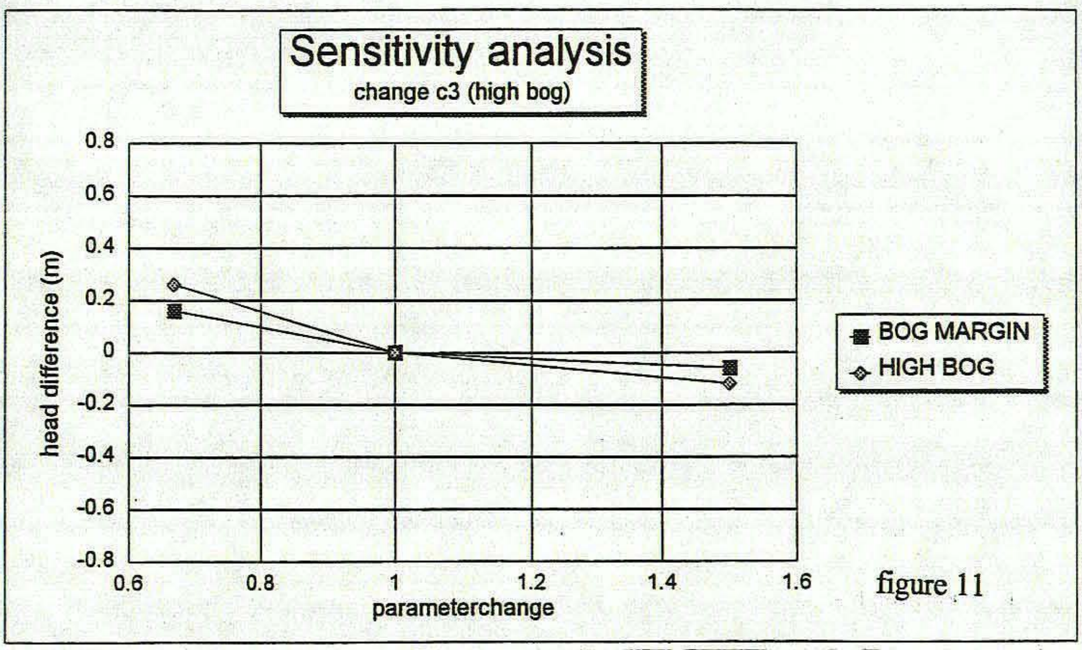


figure 11

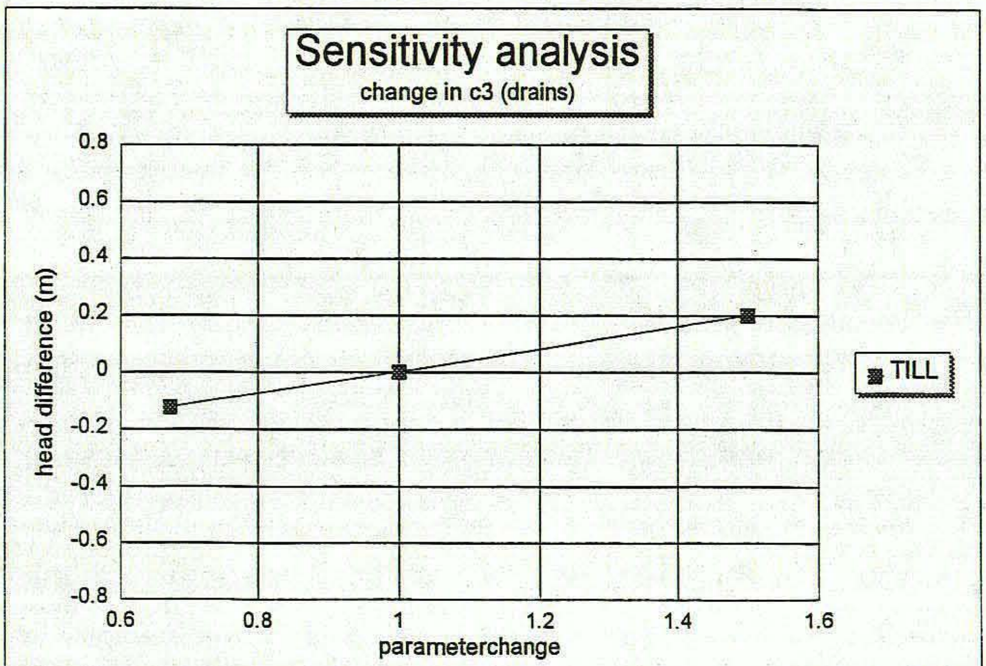


figure 12

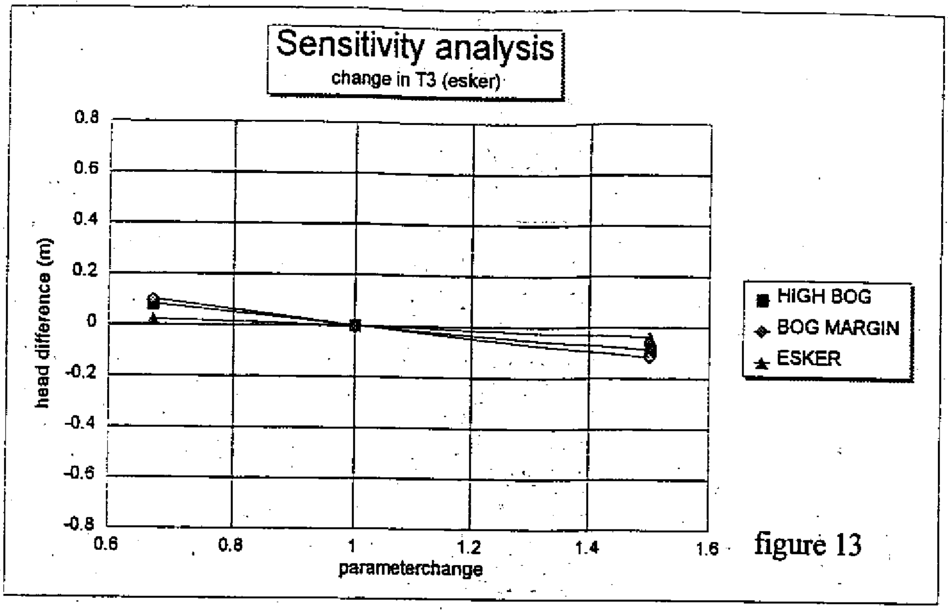


figure 13

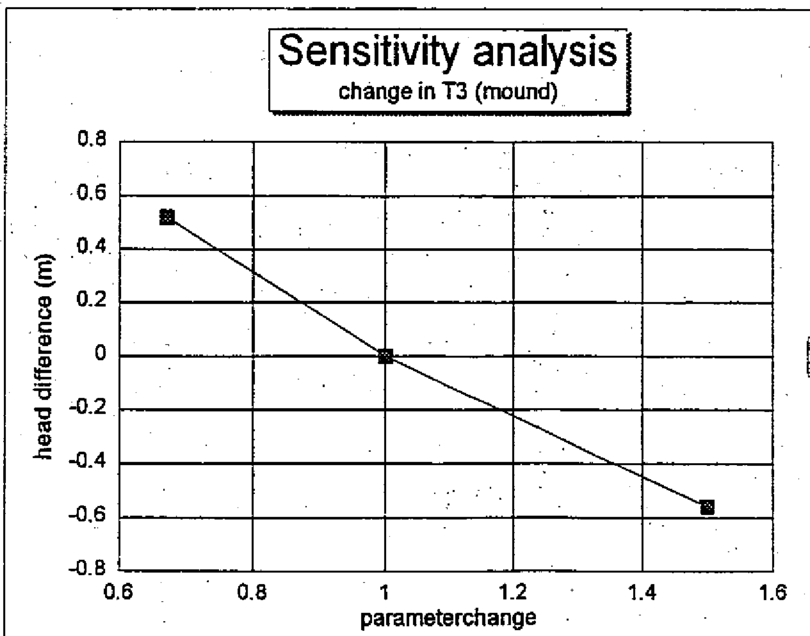


figure 14

Q1*1.15 interval=0.15

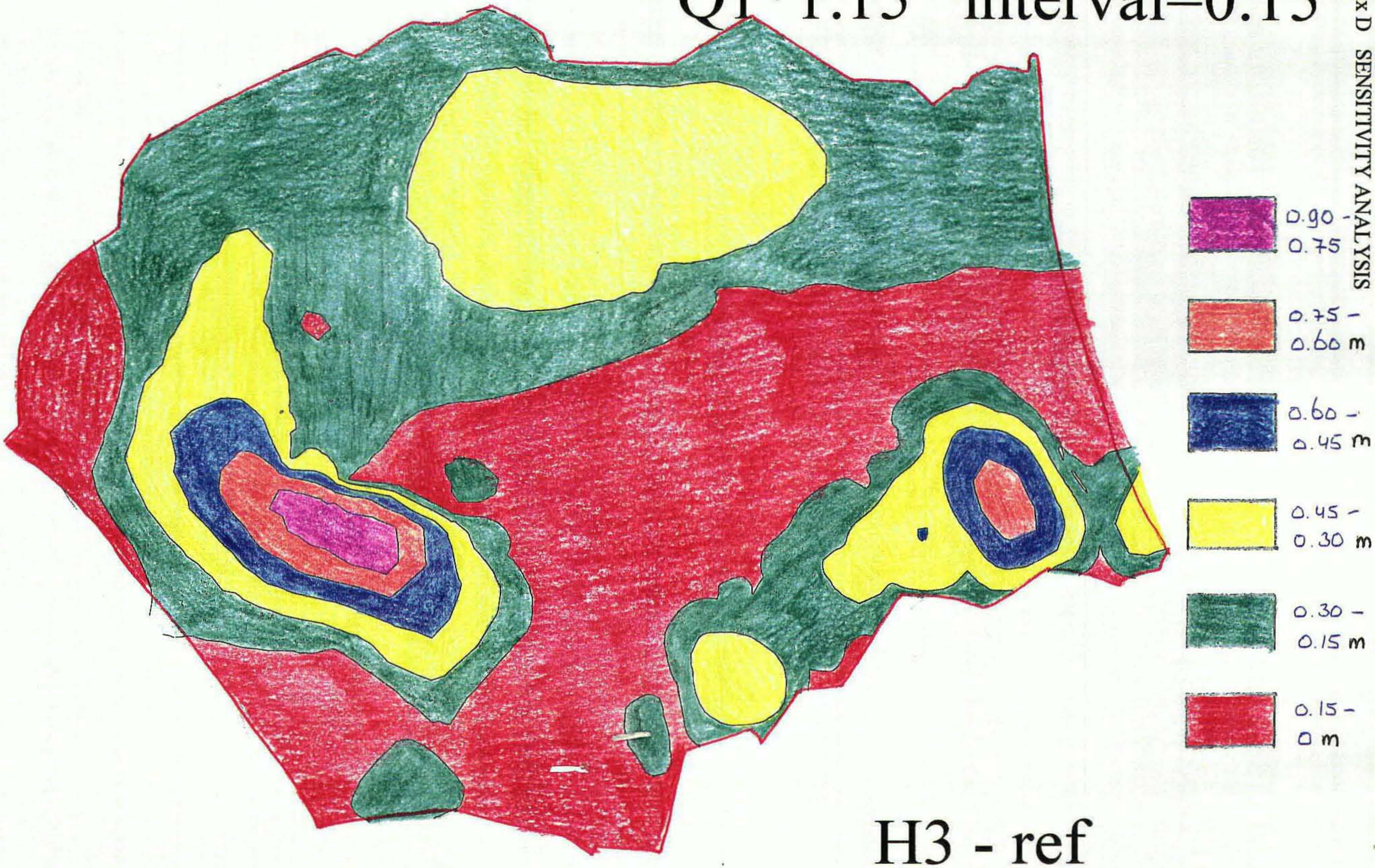


figure 15

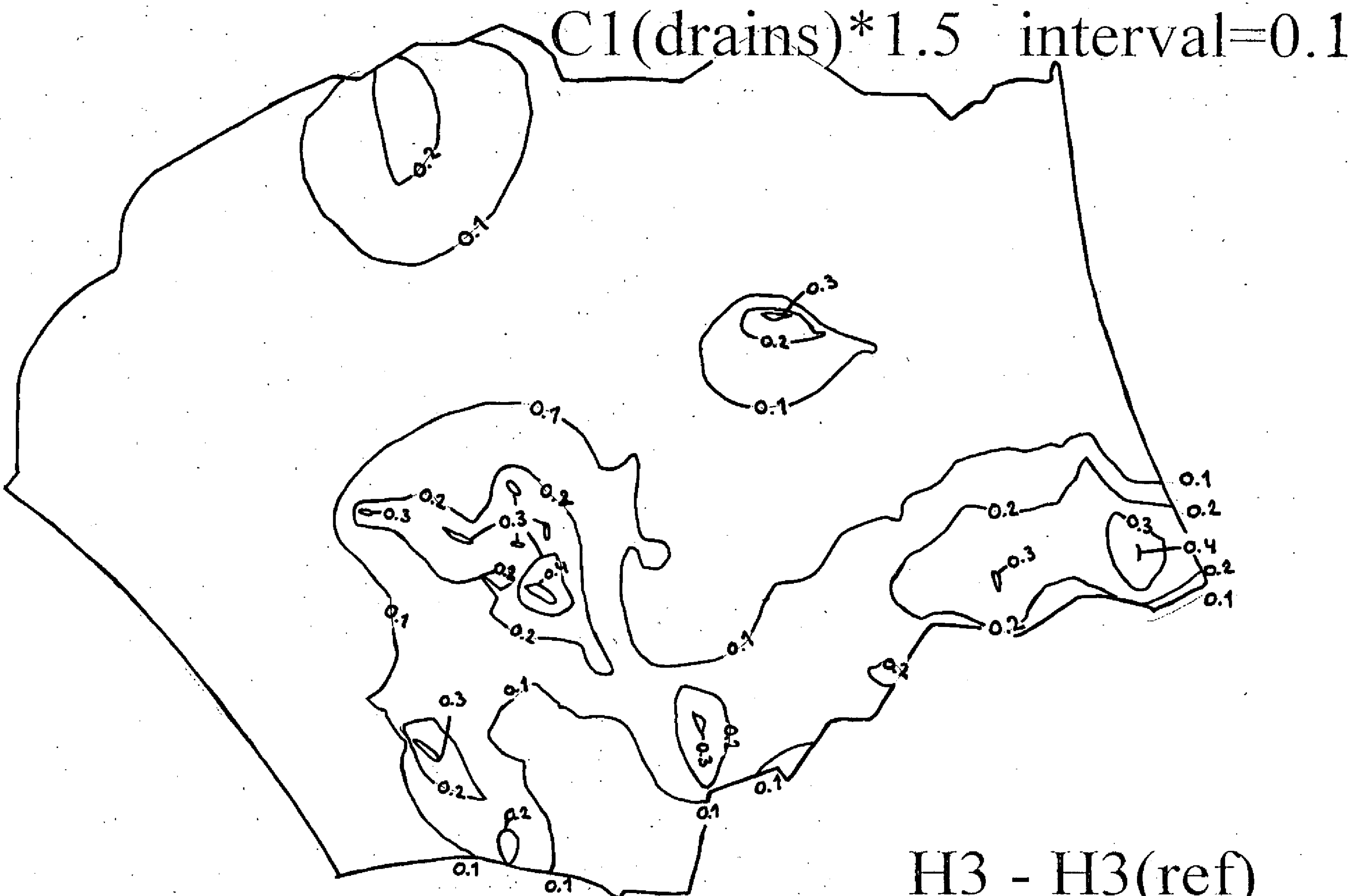
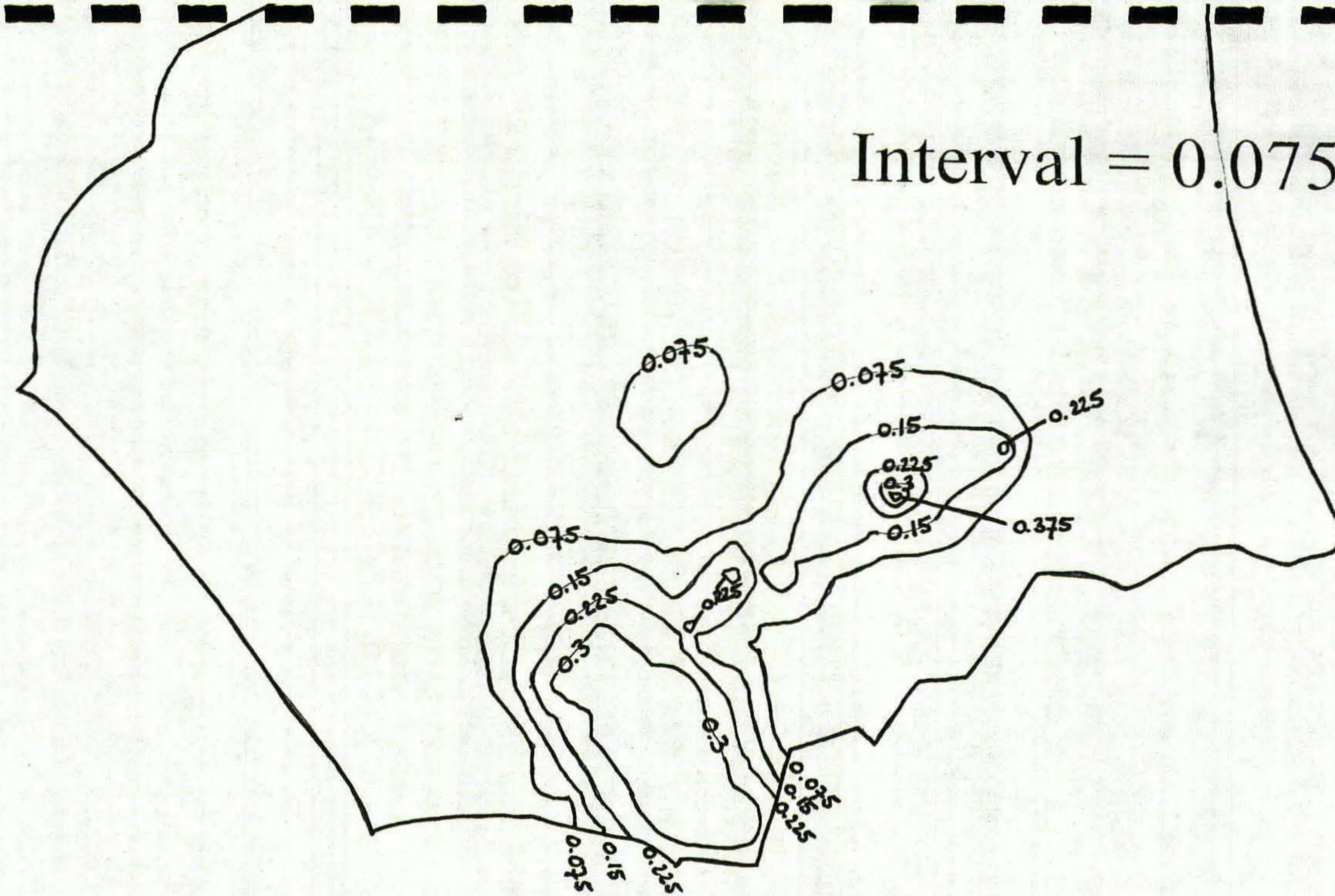


figure 16



H3-H3(ref)

Fenpeat H0-0.5m

figure 17

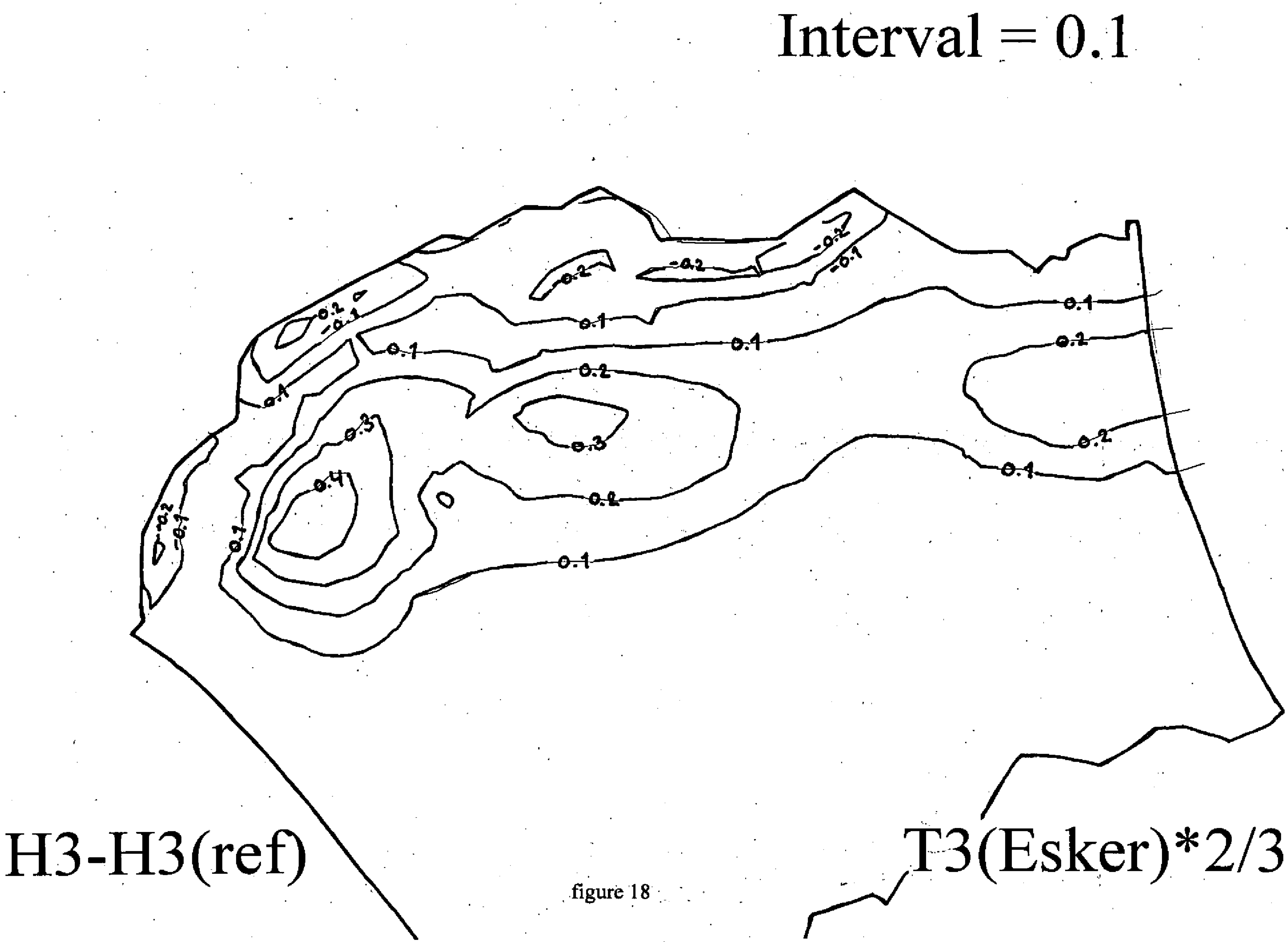
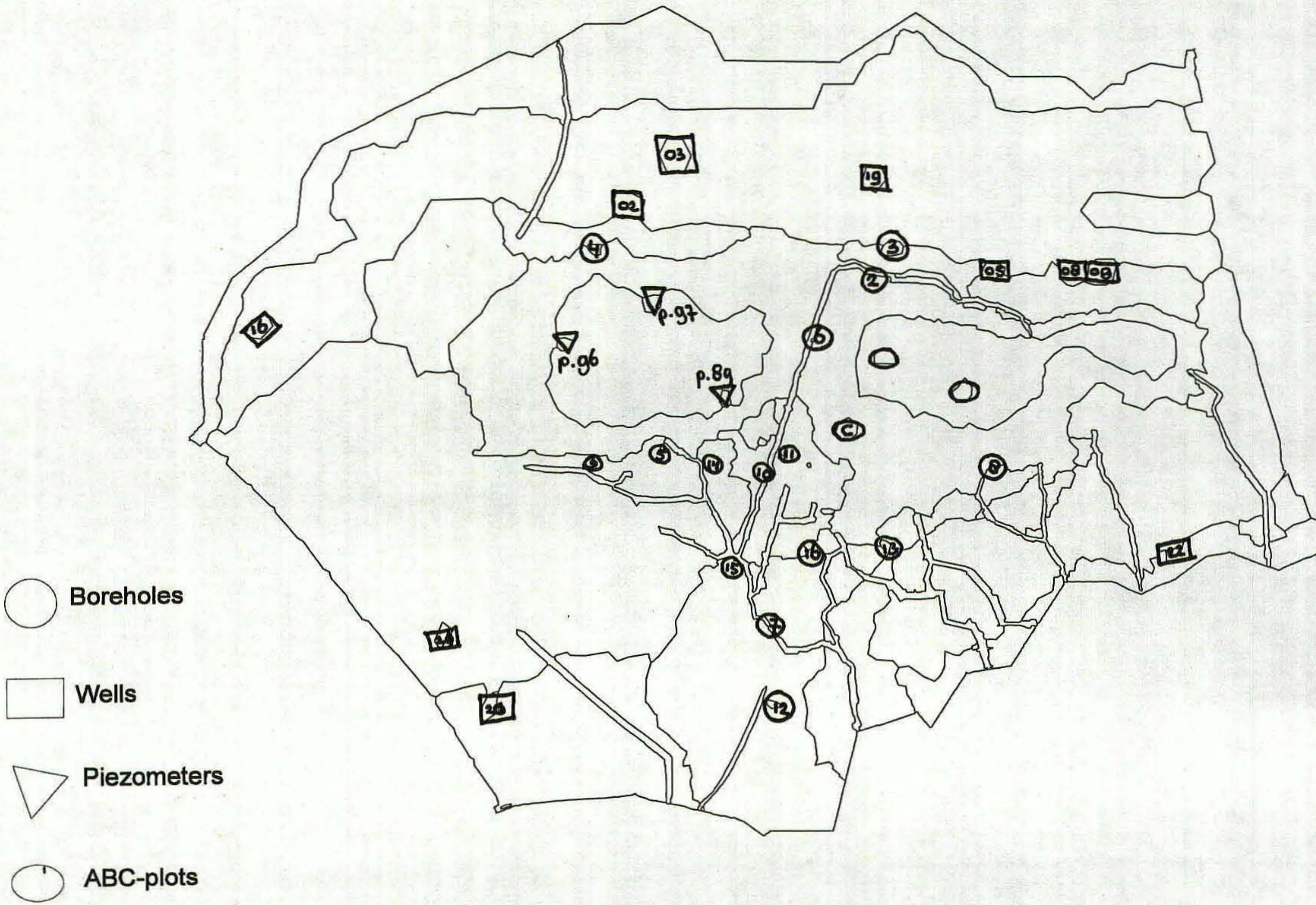


figure 18

Location of boreholes, wells, piezometers and ABC-plots



differences in levelings

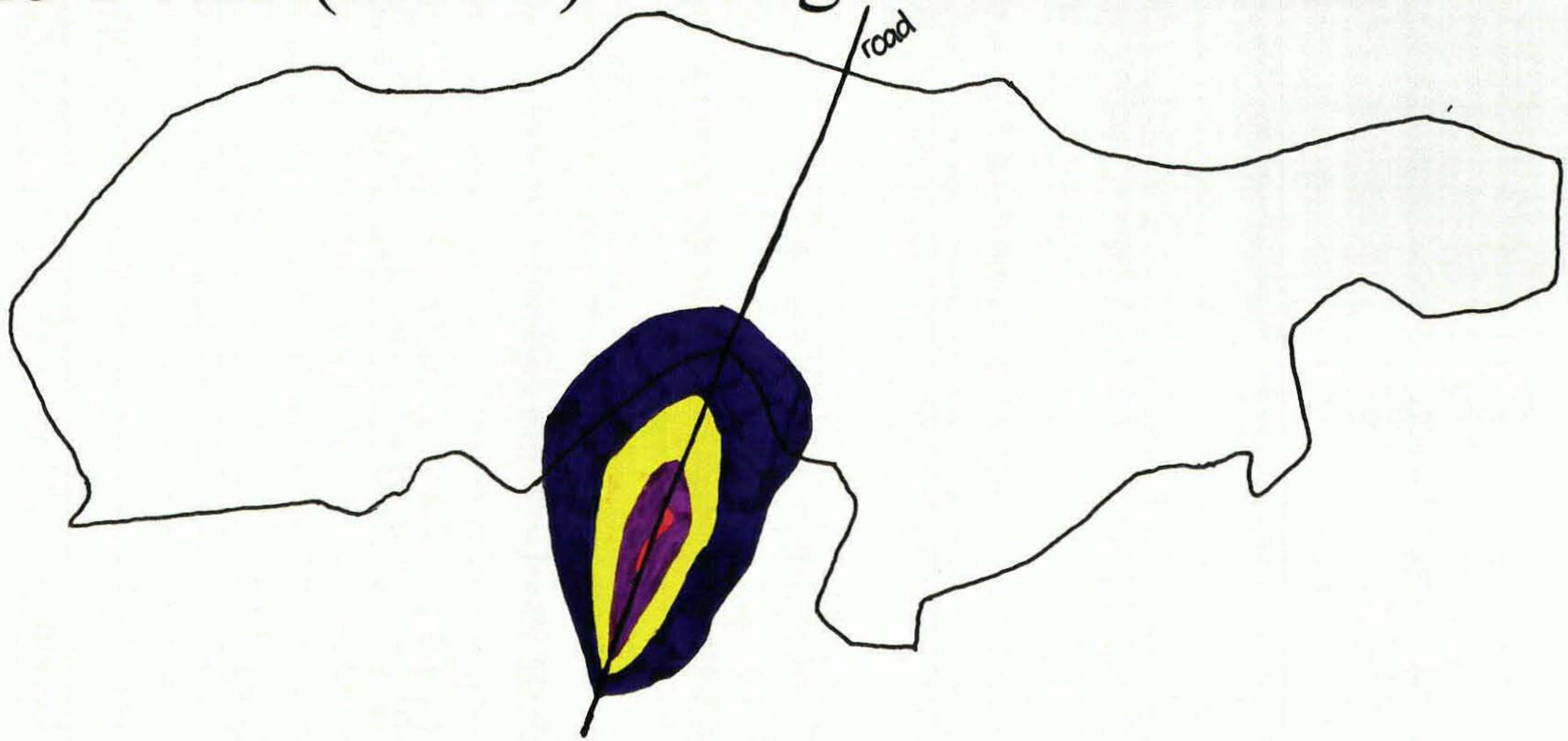
well	level Boogaard (1993) [m OD]	surface map OPW [m OD]	difference (level-map) [m]
well03	57.7	61.3	-3.6
well05	60.4	61.2	-0.8
well08	60.9	63.4	-2.5
well09	60.4	66.8	-6.4

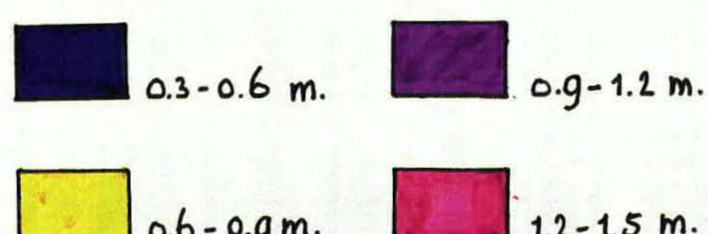
Appendix E CALIBRATION

VERIFICATION

observation point	filter in	measured head [m]	head in VERIFIC [m]	$h_{meas}-h_{verific}$ [m]
clbh4	till	57.4	57.1	+0.3
clbh5	till	53.9	55.0	-1.1
clbh6	till	56.4	56.1	+0.3
clbh7	till	49.8	49.8	0
clbh9	till	57.1	56.8	+0.3
BH11	till	53.4	52.8	+0.6
BH12	till	49.4	49.5	-0.1
BH13	till	53.0	53.1	-0.1
BH14	till	52.6	52.6	0
BH15	till	50.5	50.5	0
BH16	till	51.7	51.9	-0.2
well02	till	56.0	56.0	0
well03	till	54.6	55.6	-1.0
well05	till	56.7	58.2	-1.5
well09	till	56.9	60.2	-3.3
well16	till	49.3	51.0	-1.7
well20	till	50.4	50.3	+0.1
well21	till	57.2	57.0	+0.2
well22	till	52.9	53.1	-0.2
co3	till	52.9	53.3	-0.4
co4	till	52.1	53.5	-1.4
co5	till	53.0	53.0	0
A	peat	59.9	59.9	0
B	peat	59.6	59.9	-0.3
C	peat	59.3	59.0	+0.3
p89	peat	58.3	58.4	-0.1
p96	peat	60.7	60.7	0
p97	peat	60.7	60.9	-0.2

Scenario 1 : h0 (drains) = height road - 0.5 m

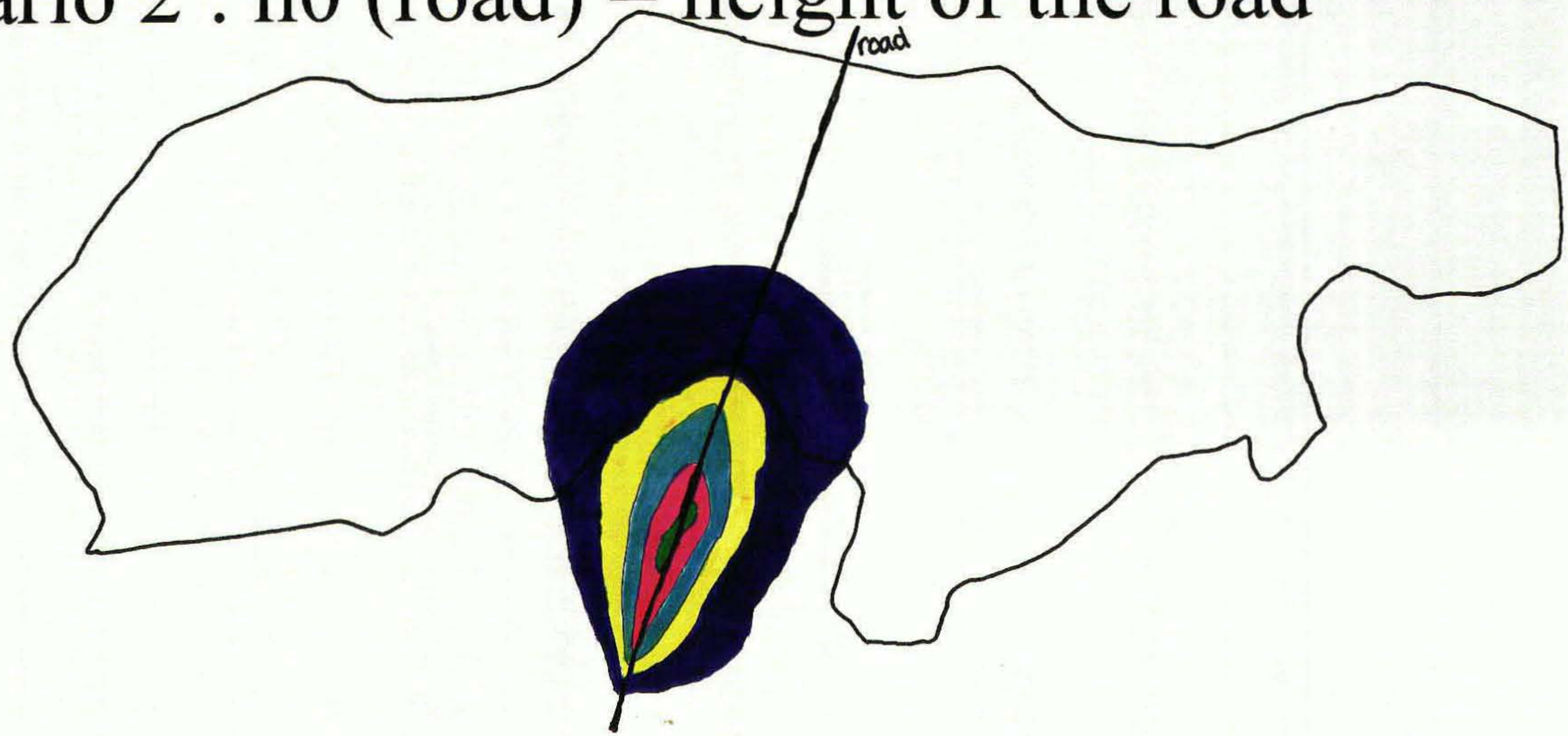


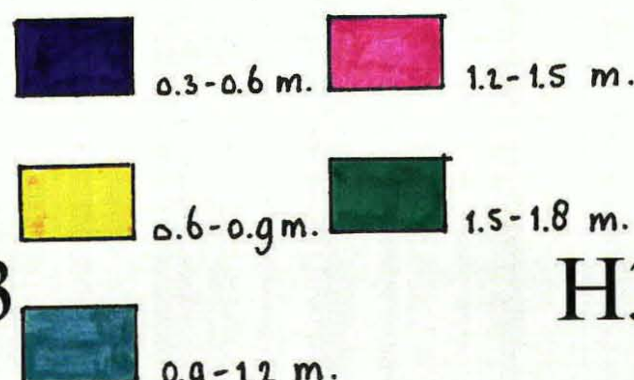


h3 - h3 (ref)

Interval = 0.3

Scenario 2 : h0 (road) = height of the road

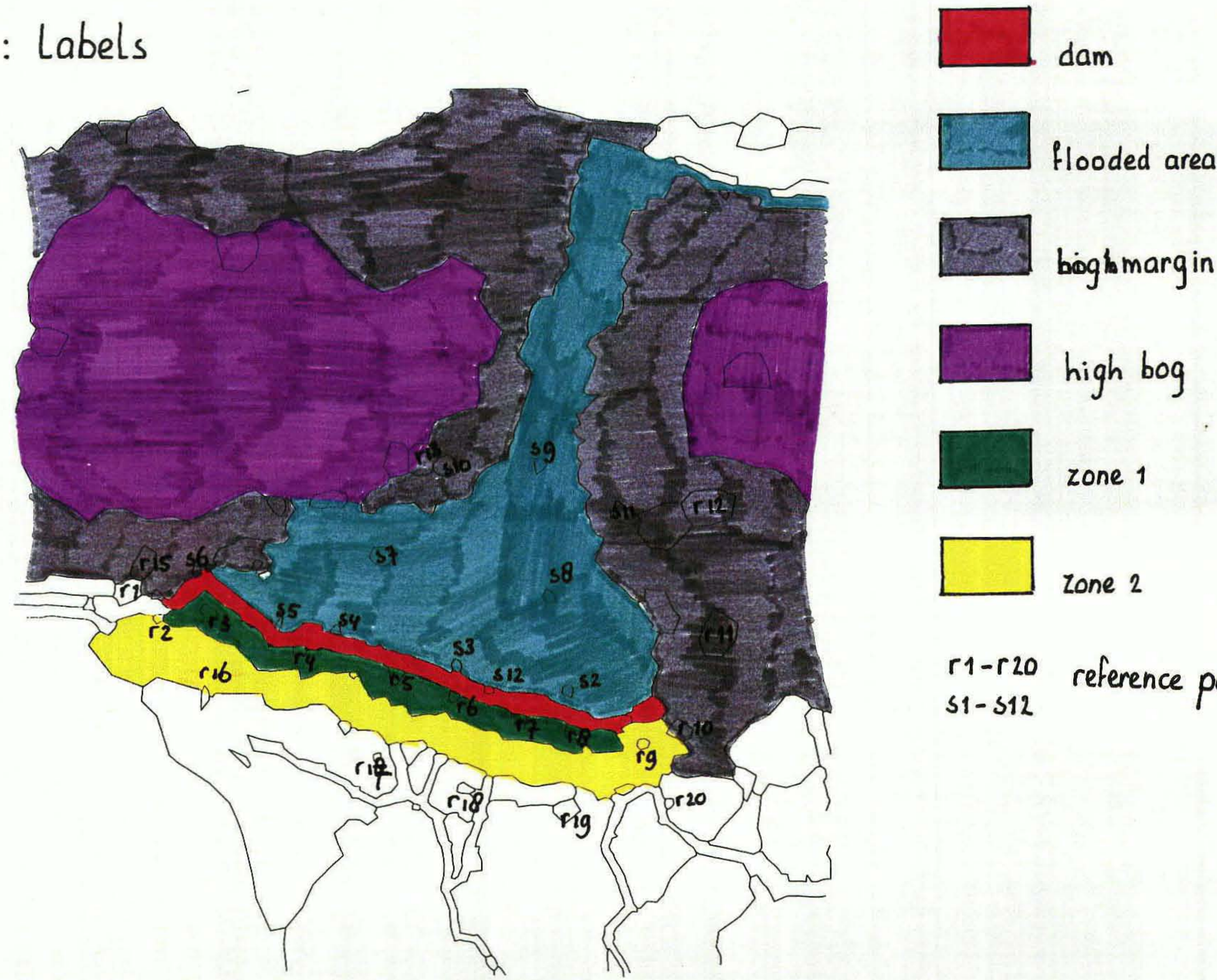




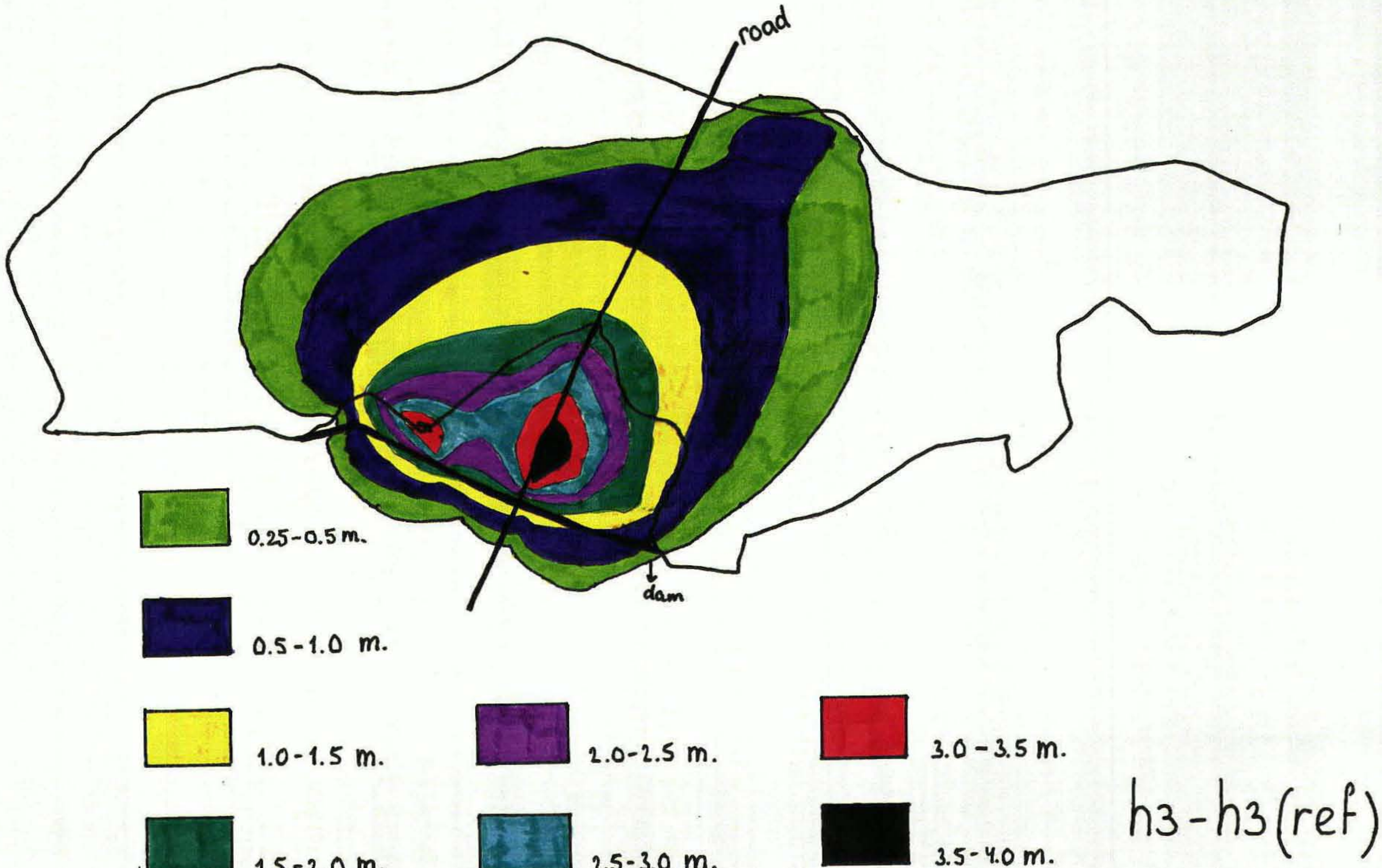
Interval = 0.3

H3 - H3 (reference)

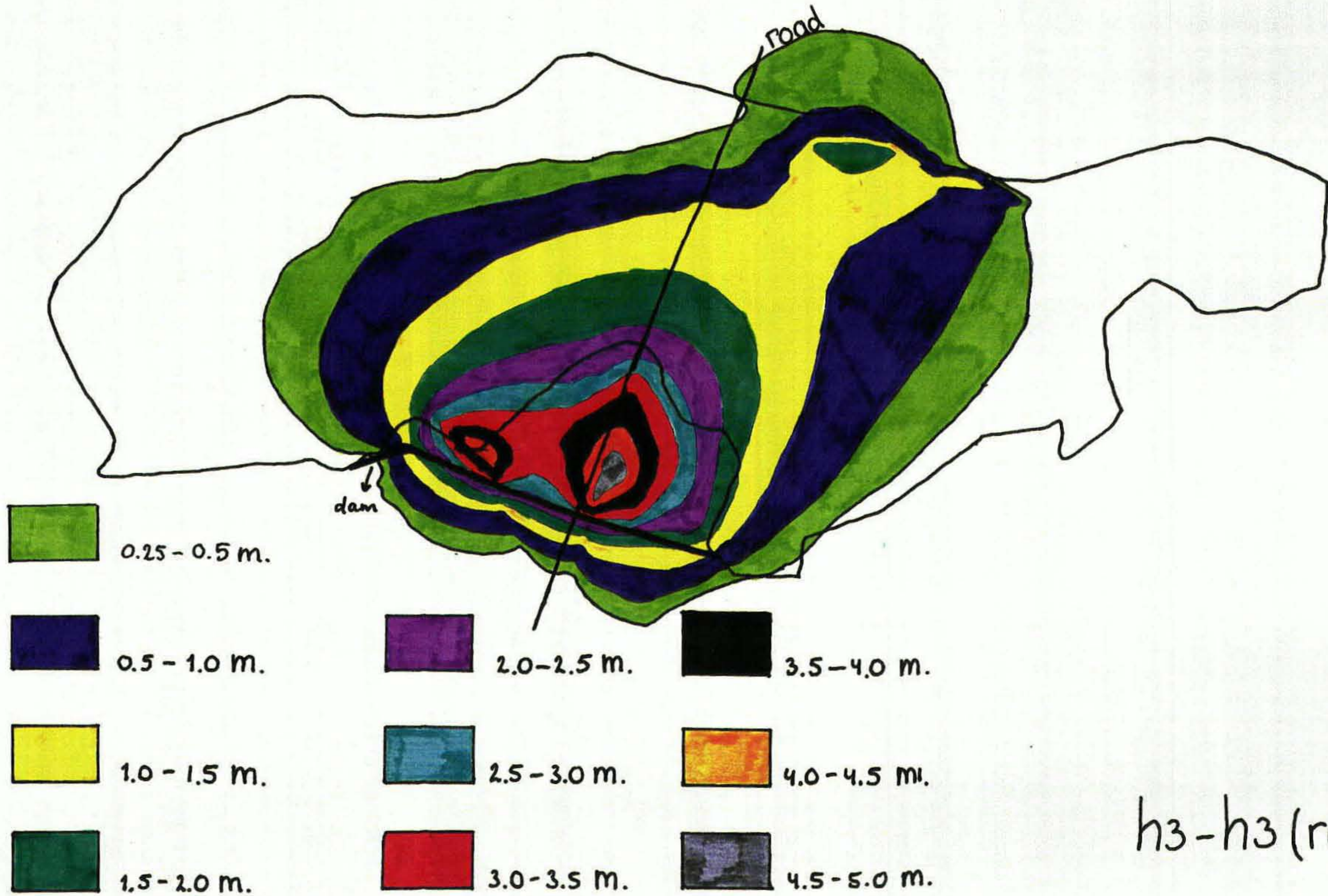
Scenario 3: Labels



Scenario 3 : Dam across the road (water level height : 56.5 ma OD)

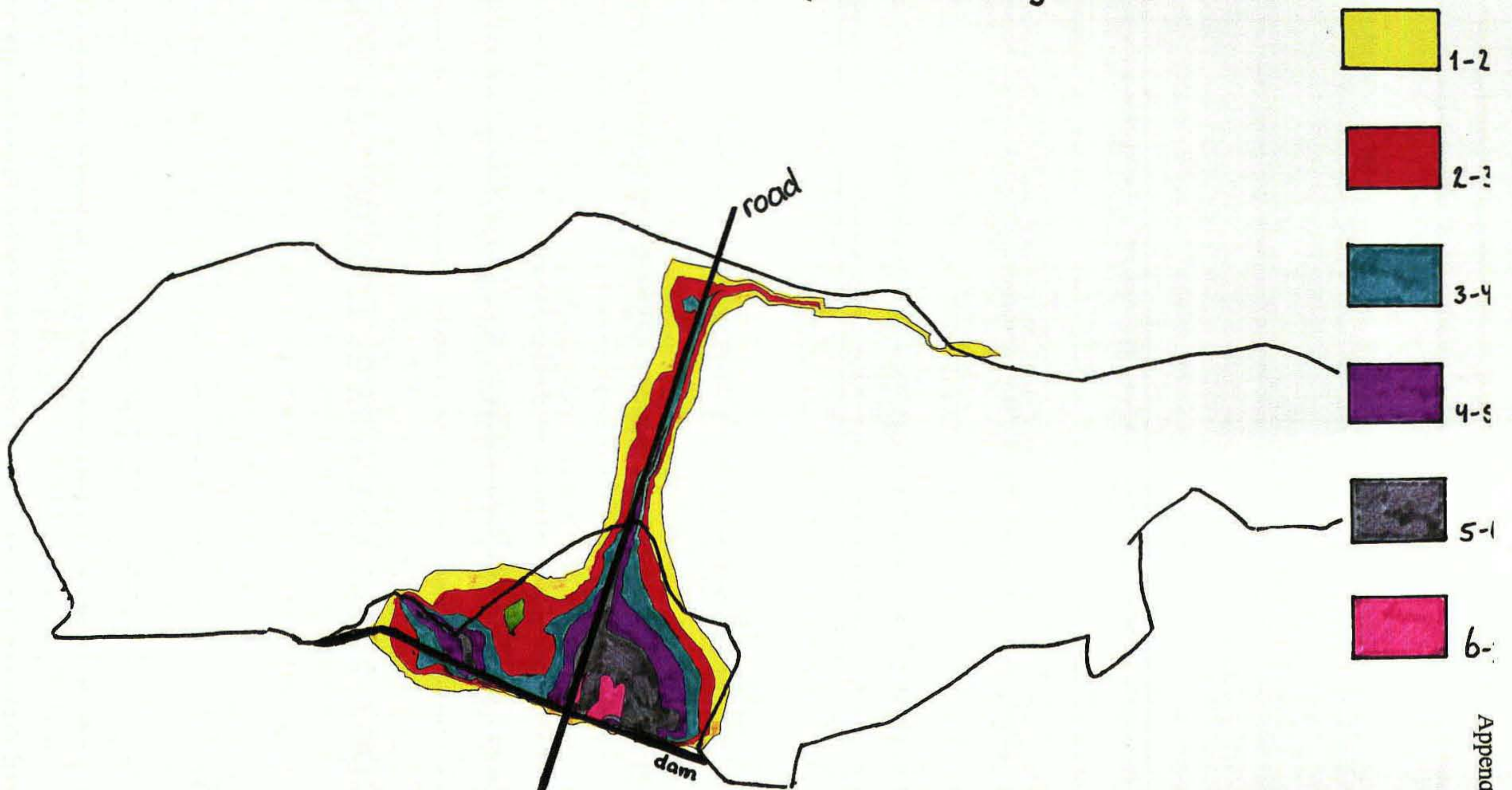


Scenario 3: Dam across the road (water level height : 57.5 ma OD)



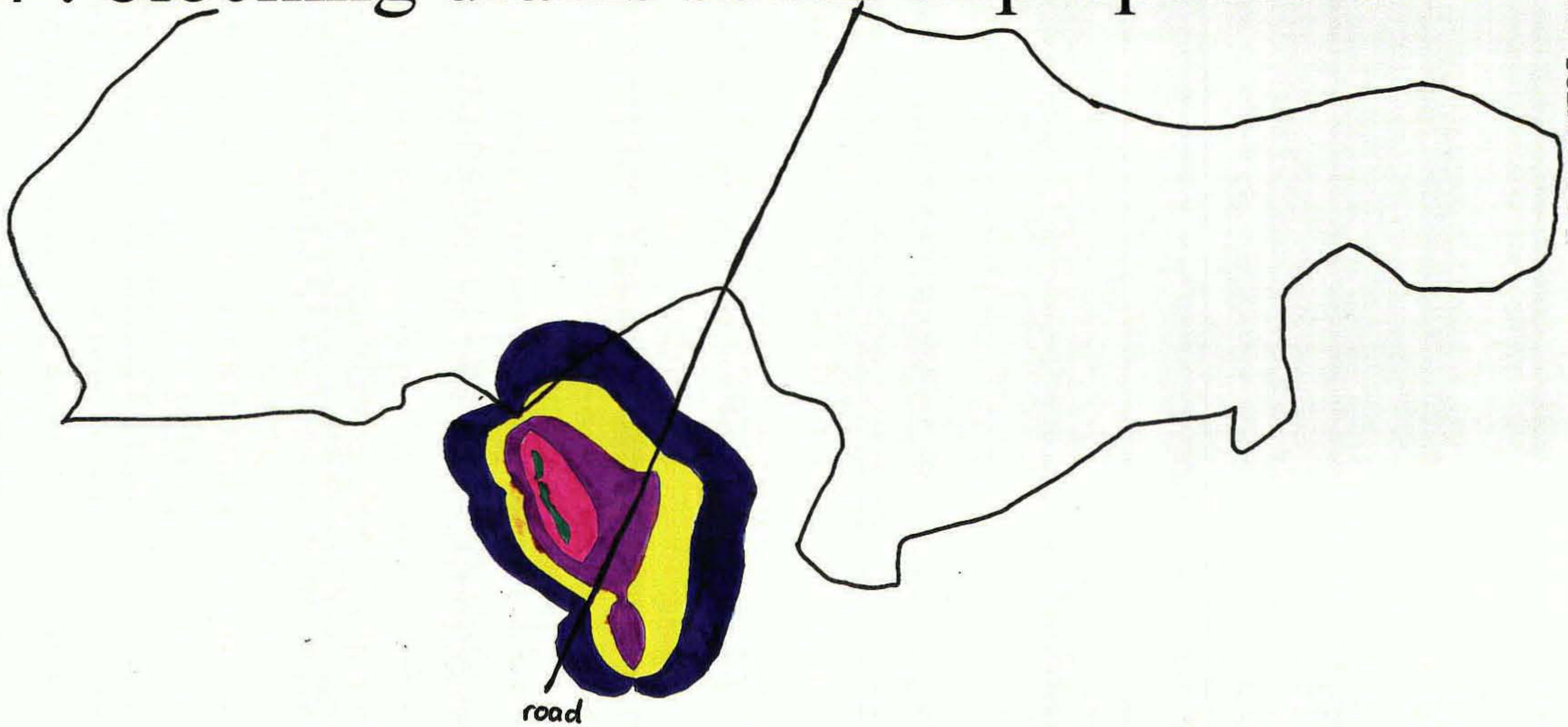
h3 - h3 (ref)

Scenario 3 : Dam across the road (water level height : 57.5 ma OD)



h2 - h2 (ref)

Scenario 4 : blocking drains south of proposed dam



0.3 - 0.6 m.

0.6 - 0.9 m.

1.2 - 1.5 m.

h3 - h3 (ref)

0.9 - 1.2 m.

1.5 - 1.8 m.

Interval = 0.3