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Water management in the *Groote Peel* bog reserve and surrounding agricultural area

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Water management in the *Groote Peel* bog reserve and surrounding agricultural area

Simulation and optimization

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ABSTRACT

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The *Groote Peel* is a bog reserve that is considered to be of great value. Goals have been formulated for the partial regeneration of the original bog-forming vegetation. Various water management measures have been suggested to achieve this end, both inside the *Groote Peel* ('internal measures') and in the surrounding area ('external measures'). To evaluate these measures the simulation model SIMGRO has been set up. For the external measures also a simplified model has been developed that can be used in combination with optimization (Linear Programming). Scenarios generated with the simplified model can be verified with the simulation model. Results from both models can be analyzed using an interactive graphical display system. The combined use of simulation and optimization is shown to yield scenarios that are more 'efficient' than scenarios obtained through straightforward specification. Such scenarios can provide opportunities for reaching a compromise between nature conservation and agriculture.

Keywords: bog reserve, wetland, hydrology, water management, simulation, optimization, Linear Programming, decision support system

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PREFACE

The Winand Staring Centre was asked to research the water management measures inside the *Groote Peel* bog reserve ('internal measures') as well as those in the surrounding area ('external measures'). The investigation of the internal measures was done for the Ministry of Agriculture, Nature Management and Fisheries; that of the external measures for the Provinces of North-Brabant and Limburg.

The procedure for translating hydrologic effects to ecological effects (Section 3.1) was a joint effort of the author and J.H.J. Joosten (University of Utrecht).

During the work on the external measures the assistance of C.C.P. van Mourik was of great value (period 1-9-1989 till 1-6-1990).

SUMMARY

Introduction

The *Groote Peel* (1340 ha) is a so-called bog reserve that is considered to be of great value. For this reason in 1985 the procedure for making it into a national park was initiated. Apart from containing rare types of vegetation it is an important breeding area for birds. Thus in 1986 it was designated to become a 'special protection area' under the EC Birds Directive.

As a consequence of the water-transmitting properties of the subsoil, a controversy has arisen between nature conservationists on the one hand and farmers on the other. Farmers blame the water conservation measures that have been taken inside the *Groote Peel* for the increased waterlogging of their lands due to increased upward seepage stemming from the bog reserve. Conversely, nature conservationists blame the farmers for increasing the downward seepage from the *Groote Peel* by installing subsurface drainage in the surrounding area.

Various measures have been put forward to protect the *Groote Peel* from losing its present ecological value and if possible to regenerate the bog-forming vegetation. The potential internal measures (i.e. inside the *Groote Peel* itself) that have been suggested are as follows:
- constructing reservoirs for storing the winter outflow and re-using the stored water during the following summer;
- altering the drainage base;

Potential external measures were:
- regulating the subsurface drainage of agricultural lands;
- regulating the sprinkling of agricultural lands, from groundwater and/or surface water;
- modifying the surface water level management, with or without supply of water from external sources;
- regulating the pumping of groundwater for public water supply.

A number of other studies preceded the work reported here, e.g. Joosten & Bakker (1987) concerning the past and present ecology of the nature reserve, and Poelman (1987) concerning the regional hydrology. Poelman implemented the model SIMGRO (Querner & Van Bakel, 1989) using results of geohydrologic field investigations performed by Wit (1986) and the Netherlands Geological Survey. A review of policy options was made by the Government Service for Land and Water Use (*Landinrichtingsdienst*, 1988).

The Winand Staring Centre was asked to research both internal and external measures, in support of regional decision making. Since groundwater for public water supply is pumped from very deep aquifers, the effects transcend the regional scale. These measures were therefore only investigated to a limited extent. This report contains a description of used data and calculation methods; some results are included for illustrative purposes only. A full overview of computational results can be found in *Projectgroep de Groote Peel* (1990) for the internal measures, and Van Walsum (1990) for the external measures.

Simulation of the regional hydrologic system

Both the internal and external measures involve changes of the hydrologic system that are not constant in time. Storage of the winter outflow in reservoirs and re-use during the following summer obviously involves a time dimension. The same holds for the influence of the external measures, which are typically of an intermittent nature:

- in periods with a plentiful rainfall, subsurface drains become active when the groundwater level rises above the threshold level of the drainage system;
- in periods with a lack of rainfall the soil moisture depletion (of the lands used for agriculture) is counteracted in many places by means of sprinkler irrigation.

Since these impacts vary temporally, they can only be adequately modelled using an unsteady model. For this reason the hydrological calculations were carried out using the regional model SIMGRO (Querner & Van Bakel, 1989). The focus of SIMGRO is on modelling the saturated groundwater flow and the integrating role it plays on a regional scale. Groundwater flow is modelled using a so-called quasi three-dimensional geohydrologic schematization, i.e. a schematization into a two-dimensional horizontal flow through aquifers and a one-dimensional vertical flow through aquitards. The finite-element method is used for the horizontal flow; the numerical scheme is repeated for each of the aquifers involved in the geohydrologic schematization.

SIMGRO was chiefly developed with the characteristics of agricultural areas in mind. A certain degree of general applicability was attempted, by for instance allowing for a flexible definition of the 'technologies' (types of land-use) that the model can be run with. However, because the hydrology of a bog reserve is so very different from that of an agricultural area, a straightforward application of SIMGRO was not possible. This mainly concerned the modelling of surface water, which in the *Groote Peel* covers roughly 25% of the area.

To achieve a better fit between model and reality the so-called hybrid water-level concept was introduced into SIMGRO. This concept circumvents the difficulty of modelling the complex geometry of small pools by taking a macroscopic view. Instead of explicitly trying to model the presence of surface water, most of the surface water is treated as 'additional storage' of groundwater. Implementation of this concept mainly consists of deriving a composite curve for the storage coefficient of surface water and groundwater in a subregion.

The way in which the surface water management takes places in nature areas differs from that in agricultural areas in various ways. In agricultural areas the surface water level control tends to 'follow' the soil surface, whereas in nature areas this is usually not the case. Thus in the standard version of SIMGRO the surface water level within a subregion is treated as a level below the soil surface. The surface water level is per nodal point converted to a level in absolute terms (i.e. relative to the datum plane of the hydraulic head) before using it for computing the interaction with the groundwater. Since this manner of modelling was not deemed applicable to all situations in the bog reserve, SIMGRO was extended with an option for defining the surface water level control in absolute terms, and not as a level below soil surface.

Another aspect in which the bog reserve differs from agricultural areas is the importance of water conservation measures. The internal management of bog reserves is usually aimed at holding on to the water as long as possible, by reducing the depth of the drainage base and by directing drainage outflow from one hydrological unit ('compartment') to the other. Conversely, in agricultural areas, drainage water outflow is usually transferred as quickly as possible to the larger drainage channels, thus minimizing the further interaction with the groundwater system. In the standard version of SIMGRO this is simply modelled by allowing the surface water outflow of a subregion to 'disappear'. In the adapted version for bog reserves the possibility has been created to let a certain percentage of the outflow pass to the surface water reservoir of another subregion.

Most of the parameters needed for implementing SIMGRO were obtained directly from physical information about the region, the exception being the vertical resistances of the top aquitard within the *Groote Peel.* The availability of discharge measurements made it possible to calibrate and verify these resistances using a water balance method. Water-level measurements were available for a great many sites, both inside the bog reserve and in the surrounding area. However, the high spatial variability of conditions inside the *Groote Peel* limited the practical use of these data. With respect to locations in the surrounding area the difficulty was also that of representativeness, yet in a different way: most of the locations are near ditches and farmhouses, and not in the middle of fields as should ideally be the case. Nevertheless, it can be concluded that the model simulates the dynamics of real conditions reasonably well.

Effects on nature

On the occasion of designating it to become a national park, a number of ecological goals were formulated for the *Groote Peel.* The central theme is the regeneration of the original bog-forming vegetation, dominated by *Sphagnum* moss of which there is less than 1 ha left. Apart from remnants of the bog vegetation, the 1340 ha *Groote Peel* contains a number of other water-depending vegetations that cover an area of roughly 170 ha.

Of the rare species in the Groote Peel, *Sphagnum* is the most demanding in terms of the hydrologic conditions: it requires the water-level to remain within 20 cm of the ground level. Practical observations in similar areas show that for the prevailing climatological conditions the water-level constraint implies that the long-term average of the downward seepage should not be more than between 30 and 50 $mm.yr^{-1}$. From the water balances made with the measured data (discharges) and model calculations (evapotranspiration), it appeared that (averaged over a subregion) the long-term downward seepage is currently at least 110 $mm.yr^{-1}$.

This could lead one to believe that in the current situation the bog-forming vegetation does not stand any chance at all; in that case there is also no impact of external measures on the ecological value of the area. However, this way of reasoning overlooks two things:

- within the bog reserve there is a high spatial variability of the thickness of the humified peat. This humified peat has a high flow resistance, therefore the downward seepage is very low where the peat is relatively thick;
- apart from some patches with living moss, the *Groote Peel* contains other species that are less demanding hydrologically, but nonetheless of importance from a nature conservation point of view.

A method has been developed that takes account of the high spatial variability of the thickness of the (remaining) peat and thus of the downward seepage. In this way a relationship could be derived between the change of the total downward seepage and the change of the 'potential bog area'. Furthermore it is argued that the percentage change of this potential area is indicative of the change of potential area of other species.

Effects on agriculture

Agricultural production can be negatively influenced by conditions that are too wet or too dry. Though the relationships between hydrologic conditions and agricultural output are very hard to quantify, methods have been developed that have achieved a wide degree of acceptance.

For the computation of the production loss caused by too wet conditions use is made of HELP-method (*Landinrichtingsdienst*, 1987). The production loss caused by too dry conditions is computed from the difference between the potential and the actual evapotranspiration.

Evaluation of internal measures

The evaluated alterations of the drainage base were in the first place an assessment of the water conservation measures completed in 1987. These measures have raised the average water level in a subregion, which in the model is simulated by raising the drainage base. The higher water levels inside the *Groote Peel* have increased the average downward seepage; this in turn has led to an increase of the upward seepage in parts of the surrounding agricultural area, accompanied by a rise of water levels. However, from runs with SIMGRO it appears that this rise is minimal, thus hardly leading to any loss of agricultural production. And then there is also the fact that the summer groundwater levels are also raised, thus causing a slight increase of the agricultural production through an increase of the capillary rise. This reduces the net damage caused to agriculture by the water conservation measures inside the *Groote Peel* even further.

Apart from measures directed towards raising the drainage base, in some situations it is interesting to do exactly the opposite – to lower the drainage base. The central lakes of the *Groote Peel* are examples of this. That is because they have been created by damming the low-lying central part of the *Groote Peel*. Yet it is just this low elevation that would make the land, now covered by lakes, suitable for the growth of *Sphagnum* moss. A computational experiment involving the lowering of the drainage base in one of the central lakes showed that stable water levels could be obtained across an area of some 30 ha.

Basically, it should be possible to store part of the winter outflow in storage reservoirs and to use it during the summer months for infiltration via a network of shallow trenches. Various alternatives have been formulated involving one or more storage reservoirs. To simulate such a hypothetical situation the model had to be adapted for:

- the manner in which the discharged surface water is collected during the winter months;
- the manner in which the stored water is used during the summer months, i.e. the operational strategy.

The simulated operational strategy during the summer months depended on the type of question that was put to the model; two questions had to be answered:

- what is the maximum size of the area that at all times could be supplied with enough water such that the water level requirements of bog-forming vegetation are fulfilled ?
- what could be achieved if the available water is spread over a large part of the *Groote Peel* at the start of the summer season ?

The first question relates to the so-called concentration strategy, because it involves supplying water to a relatively small part of the *Groote Peel*; the second question concerns what has been called the spreading strategy, because it involves spreading the available water over a rather large part of the bog reserve. In the latter case it would of course not be possible to maintain hydrological conditions that are optimal for the growth of bog-forming vegetation: in this case the idea of supplying water is to provide a general upgrading of hydrological conditions.

Answering questions concerning the concentration strategy involved iterative running of the simulation model in order to determine the area that could just be supplied with enough water. For most of the formulated alternatives this area was found to be in the order of 100 ha. Evaluation of the spreading strategy consisted of running the model with a fixed number of nodal points that are intended to be supplied with water – no iterative running was required in this case. The results, that were fully reported in *Projectgroep de Groote Peel* (1990), showed that the raising of water levels would not amount to much. The main reasons for the rather disappointing effects of the proposed internal measures are that:

- in the current situation it often happens that a year goes by without any discharge at all; and the mean yearly outflow that can be stored is only about 45 mm (see Table 5), though re-cycling would slightly increase it;
- re-use of winter outflow induces more downward seepage (owing to raised water levels) and also some extra evapotranspiration.

The investigation of the possible water quality complications that could occur if winter outflow is re-used during the summer was not included in the work reported here (see *Projectgroep de Groote Peel*, 1990).

Decision support system for external measures

For reasons of simplicity, it is assumed that the regional water management is in the hands of one (imaginary) regional authority. The design of a future state of a region has been conceived as consisting of two separate stages with corresponding elements of the decision support system (Fig. 42; Orlovski et al., 1986):

- identification of the future possibilities for a region using the scenario generating system (SGS);
- analysis of potential water management measures using the policy analysis system (PAS).

The scenario generating system can be used by the regional authority to obtain scenarios that meet certain requirements pertaining to the well-being of the different water users. This well-being is quantified in terms of two indicator values, the ecological value of the *Groote Peel* and the economic performance of the surrounding area. In a sense, the SGS generates a reference scenario of future regional development that could be achieved if all the water users would behave in the way the authority wants.

The need for a policy analysis system (PAS) stems from the desire to predict the effects of certain policy measures without actually having to try them out. If it appears that the reference scenario (identified by the SGS) is not reached, the authority can either try another policy or else lower its ambitions. The behavioral responses of farmers (and other water users) are, however, hard to predict from mathematical models. That leaves common sense for predicting the reactions of water users to various measures. Since the PAS does not involve the use of models, attention is focused on the scenario generating system.

The model SIMGRO provides a relatively detailed description of the relevant processes and is therefore called a comprehensive model. The disadvantage of such a model is that because of its complex mathematical form it is not possible to couple it to an algorithm for the screening of scenarios in an automated way. This type of coupling is needed for finding – within an acceptable period of time – scenarios that are so-called Pareto-optimal; such scenarios are also called 'efficient'. An 'efficient' scenario cannot be improved upon with respect to one of the conflicting interests without damaging the other. In other words, the physical possibilities of the regional system are fully exploited. For finding efficient scenarios simplified models are more suitable. Because such simplified models are a relatively crude approximation to reality, however, comprehensive models will always be needed for verification and more accurate estimation of scenarios that seem promising.

An overview of the scenario generating system and its components is given in the flowchart of Fig. 43. A 'User interface and color graphical display' (Van Walsum, 1991) is included. Such a system is necessary for analyzing and interpreting the large numbers of input and output data of the models.

Prior to deriving a simplified model, an analysis was made of the potential developments with respect to the various activities that influence the regional hydrology: subsurface drainage, sprinkling, surface water management and buying of agricultural land. The latter implies the virtual swamping of the land, with the dual purpose of indirectly benefiting the *Groote Peel*, and also the creation of 'new' nature in a wet buffer zone. The partial potential developments mentioned were combined to form a set of 16 possible combinatory developments. Derivation of a simplified model was performed with the so-called response matrix approach. To this end, for each of the combinatory developments a 'spatial' sensitivity analysis was made in the following manner:

- a reference run was made with the comprehensive simulation model;
- a certain water management option was subsequently introduced in each of the subregions and for each of these 'traveling option' scenarios a simulation run was made;
- the results obtained for the reference run were subtracted from the results obtained for the separate 'traveling option' scenarios, thus yielding 'responses'.

The responses were collected in the response matrix after applying a procedure for translating one-year effects to long-term averages. This translation, consisting of simple multiplication by a factor, was necessary because the sensitivity analysis had to be performed with one-year runs. (Otherwise the required computer resources would have been excessive.) The method for evaluating the ecological effects of hydrological changes was based on the long-term average of the downward seepage; so the gap had to be closed with the mentioned translation procedure.

The computational implementation of the simplified model was done as a Linear Programming problem, using GEMINI (Lebedev, 1984) for the pre-processing and MINOS (Murtagh and Saunders, 1985) for the optimization. The LP-formulation was extended with procedures for dealing with:
- the discreteness of certain variables;
- the multi-objectivity.

The discreteness of certain variables was handled with the following cyclic procedure:
- a scenario was obtained using LP, with all the variables as continuous ones on the interval [0;1]
- each of the discrete variables that had not been set to either 0 or 1 by the LP-algorithm was set to one of these values, depending on which was the nearest.

This procedure was repeated until the desired type of optimized scenario was obtained.

The so-called constraint method was used for dealing with the multi-objectivity. The method consisted of the following two steps:
- the setting of a lower (or upper) bound on one of the two objective functions;
- optimization of the remaining objective function.

An example of an optimized water supply scenario is given in Fig. 48a. As reported in Van Walsum (1990), the optimized scenarios were found to make 20% better use of externally supplied surface water than scenarios that were specified in an off-hand manner. The usefulness of the simplified model is also demonstrated by Fig. 48b, which gives the subregions that could be drained without it appearing to harm the *Groote Peel* (except perhaps the bird-foraging function of the surrounding area). That this is possible is due to a judicious combination of surface water supply and extra subsurface drainage.

Concluding remarks

A survey has been given of the modeling undertaken for providing decision support with respect to water management in the area surrounding the *Groote Peel*. The computational results having being reported elsewhere, attention could be focused on the used algorithms, including results only by way of illustration.

The model SIMGRO as described in Querner & Van Bakel (1989), although essentially ripe for application to a wide range of situations in both agricultural areas and nature areas, required several adaptations to make it suitable for application to the *Groote Peel* and its surroundings. When using the model for the type of region considered and the kinds of questions that were to be answered, it became apparent on many occasions how vital it is to take the temporal variability of the regional hydrology into account. Furthermore, it was found that there is simply no substitute for making multi-year runs covering at least a ten year simulation period. Modelling approaches involving a 'representative year' are thus doomed to misrepresent reality unless backed up by multi-year simulation runs.

The way in which the simulation model SIMGRO was implemented has various shortcomings. Partly this was due to the non-availability of GIS-procedures for setting the model up, and partly to the limited validation of the model. Lack of data (detailed water balances of the surrounding area) was a problem, but also the difficulty of bridging the gap between the model – which computes water levels that are representative for the whole 'influence areas' of nodes – and the point gaugings of the water levels. These point gaugings are rarely representative for larger areas. An accurate interpretation of water level data therefore requires being able to 'zoom in' with the model, using an explicit representation of the surface water system. By the latter is meant that the tertiary and secondary water courses should not simply be represented by 'drainage resistances' that apply to a whole nodal influence area of several hectares, but only by the entry resistance of the water courses themselves. The part of the resistance that is due to radial and horizontal flow in the vicinity of the water courses has then to be modeled through a very fine network of finite-elements.

The availability of a zoom-in facility would not only be of great help in validating the model, but would also be of use in helping to bridge the gap between the regional modelling on the one hand and the very local scale of ecological impacts on the other. In this study the latter problem has been circumvented by using a macroscopic approach for translating the spatial variability of the peat thickness to the 'potential bog area'. This method is certainly open for improvement, though it will probably continue to be necessary to have a special procedure for bridging the gap between regional hydrologic modelling and local ecological effects.

The developed simplified model served the purpose of finding scenarios that are more efficient than scenarios specified without the help of mathematical programming. The found scenarios make efficient use of available resources – for instance the surface water supply from external sources. Furthermore, the simplified model showed that a substantial area of agricultural land can be drained in the vicinity of the bog reserve without appearing to do much harm (except perhaps to the bird-foraging function of undrained lands). Such scenarios provide opportunities for reaching a compromise between nature conservation and agriculture.

Shortcomings of the simplified modeling were partly due to as yet unsolved methodological problems and partly to the lack of available CPU-power for deriving the coefficients of the response matrices. At the root of the methodological problems is the fact that the regional hydrologic system is non-linear, involving many types of feedback mechanisms. A shortcoming of the computational implementation of the simplified model is the use of a heuristic (ad hoc) method for treating discrete variables. Whether this led to a lower efficacy in the search for scenarios remains yet to be investigated.

Finally it should be stated that the developed simplified model is still a working prototype; so much of this software still lacks the flexibility of easy application to other regions.

1 INTRODUCTION

The *Groote Peel* (1340 ha) is a so-called bog reserve – it is one of the few remnants of a 'living bog' that once covered some 30 000 ha. The top layer of such a 'living bog' consists of bog-forming vegetation (in the *Groote Peel* dominated by *Sphagnum* moss), the layers underneath of peat that is humified to a varying degree. In the area surrounding the *Groote Peel* the peat and the covering layer of moss have almost everywhere been completely removed, revealing the sandy subsoil. The *Groote Peel* itself has been subjected to partial removal of the peat, which has created a very irregular pattern of pools, lakes, peaty areas, and patches of sandy soil. Even though the *Groote Peel* is a disturbed bog with very little of the original vegetation still intact, its remaining 'wetland' values and its relative extensiveness (in comparison to other bog reserves in the Netherlands) were reasons for the government to initiate the procedure for making it into a national park. Apart from containing rare types of vegetation, it is an important breeding area for many species of birds. Thus in 1986 it was designated to become a 'special protection area' under the EC Birds Directive.

The water-bearing properties of the subsoil of the region have given rise to controversies between nature conservationists on the one hand and the agricultural community on the other. Nature conservationists see subsurface drainage in the surroundings of the *Groote Peel* as a threat to the ecological values of the bog reserve, because it causes lowering of the groundwater level. This lowering is transmitted to the nature area by the regional aquifer. Extraction of groundwater for sprinkling (and for public water supply) is seen as a threat for just the same reason.

Conversely, the agricultural community has pointed to the water conservation measures that have been implemented within the *Groote Peel* during the past 5 years. These measures consisted of constructing levees and of raising weir crests. Both types of measures have raised the water levels inside the bog reserve, which in turn has increased the water pressure in the regional aquifers; this has resulted in an increase of the upward seepage in the low-lying parts of the surrounding area. The farmers say that this has caused more water-logging problems, thus forcing them to improve the subsurface drainage of their lands.

Various measures have been put forward to protect the *Groote Peel* from losing its current ecological value and to try to achieve a certain degree of regeneration of the bog-forming vegetation. The suggested measures can be divided into:
- internal measures, i.e. within the *Groote Peel* itself;
- external measures in the surrounding area.

The following potential internal measures have been suggested:
- constructing reservoirs for storing the winter outflow and reusing the stored water during the ensuing summer;
- several types of measures involving the altering of the drainage base.

External measures concerned:
- regulating the subsurface drainage of agricultural lands;
- regulating the sprinkling of agricultural lands, from groundwater and/or surface water;
- modifying the surface water level management, with or without surface water supply;
- regulating the groundwater pumping for public water supply.

A number of other studies preceded the work reported here, e.g. Joosten & Bakker (1987) concerning the past and present ecology and of the nature area, and Poelman (1987) concerning the regional hydrology. Poelman implemented the model SIMGRO (Querner & Van Bakel, 1989) using geohydrological field investigations done by Wit (1986) and the Netherlands Geological Survey. A review of policy options was made by the Government Service for Land and Water Use (*Landinrichtingsdienst*, 1988).

The research that the Winand Staring Centre was asked to do concerned both the internal and external measures in support of regional decision making. Since groundwater is pumped for public water supply from very deep aquifers, the effects transcend the regional scale. Therefore these measures were only investigated in a very limited manner. In this report a description is given of the calculation methods used, including some results for illustrative purposes only. A complete overview of computational results can be found in *Projectgroep de Groote Peel* (1990) for the internal measures, and Van Walsum (1990) for the external measures.

In the next chapter a description is given of how the simulation model SIMGRO has been adapted and applied to the *Groote Peel* and its surroundings, followed by descriptions of the methods used for translating hydrological changes to ecological and economic effects in chapter 3. In chapter 4 the calculation methods for evaluating the suggested internal measures are described, followed by a description of the decision support system for the external measures in chapter 5. Some concluding remarks are made in chapter 6.

2 SIMULATION OF THE REGIONAL HYDROLOGIC SYSTEM

2.1 Introduction

The boundaries of the study region and its location in the Netherlands are shown in Fig. 1. The east boundary coincides with a major tectonic fault – the *Peelrand* fault – that marks the transition between a graben (to the west) and a horst (to the east), respectively the Central Graben and the Peelhorst. The south and west borders of the region coincide with major canals: the *Noordervaart* to the south and the *Zuid-Willemsvaart* to the west. The northern boundary does not coincide with any special geologic or topographic feature – it has been drawn at roughly the same distance from the boundary of the *Groote Peel* as the other boundaries.

Only one of the boundaries coincides with the water divide of a catchment: the *Noordervaart* forms part of the divide of the *Aa*, which to the east of the *Zuid-Willemsvaart* follows its course to the north, to the confluence with the *Voordeldonksche Broekloop* coming from the east (Fig. 1). This divide pertains only to surface water and shallow groundwater; the divides of the deeper aquifers follow a quite different pattern.

The study region has a slightly undulating topography, with a mild downward trend in the north-west direction: the elevation difference between the point midway along the south border and the point in the north-west corner is just seven meters. The mild topography leads to shallow watertables and a significant interaction between the saturated and the unsaturated zone: on average, roughly 20% of the crop moisture supply is obtained through capillary rise from the water table to the root zone. (This amount of course varies from year to year, depending on the weather conditions.) The surface water system is characterized by a dense network of small channels that are only water-bearing during part of the year and some larger channels and canals that never run dry; to a certain extent this is due to water supply from external sources (the river Meuse) during the summer season. The hydrology of the bog reserve is characterized by large expanses of surface water and permanent downward seepage. The type of region considered, and the kind of water management measures that are to be evaluated, calls for the use of an unsteady regional model, covering water quantity processes in the saturated zone, the unsaturated zone, and surface water.

The (potential) internal measures involving the storage of winter outflow and reuse during the summer period can clearly only be modeled with an unsteady model. Most of the external measures also have a temporal component, since they are typically of an intermittent nature:

- in periods with a rainfall excess subsurface drains become active when the groundwater level rises above the threshold level of the drainage system;
- in periods with a lack of rainfall the soil moisture depletion (in the soils used for agriculture) is in some places counteracted by means of sprinkler irrigation.

But also measures that of themselves are 'steady', like the extraction for public water supply, can cause hydrologic effects that vary in time – during a period with a high precipitation excess the influence of a steady groundwater extraction on the water level in the nature area will be very small because there is anyhow a water surplus that is

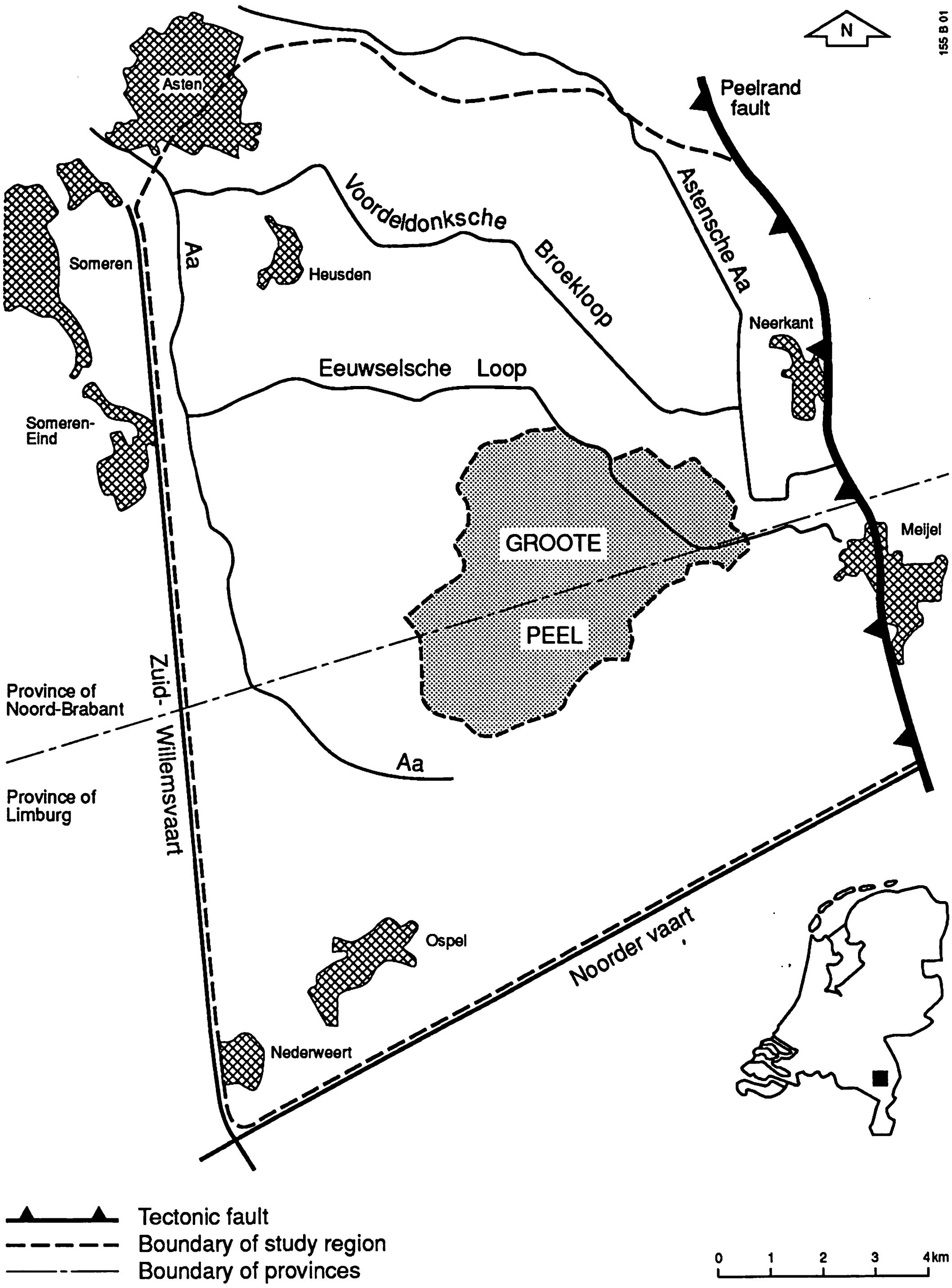


Fig. 1 The study region and its location in the Netherlands, showing some major topographic features.

drained away; during long droughts the situation is completely different and the effects of groundwater pumping are much bigger.

A further justification for the use of an unsteady model is that continuous downward seepage is a dominant feature of the hydrology of the *Groote Peel.* During periods with a lack of rainfall, the combination of high evapotranspiration and downward seepage leads to a heavy storage depletion. The large storage fluctuations imply that the system has a relatively long 'memory', because it can take a long time for it to reach saturation again. This long memory can lead to a cumulation of external effects on the nature area, for instance the effect of groundwater pumping during summer and the effect of subsurface drainage during the ensuing winter. Only an unsteady model can be of use in predicting the total effect on the nature area and the point in time when the maximum effect can be expected.

Since SIMGRO is an unsteady model that covers most of the relevant processes, it is well suited for modelling the hydrology of the region concerned. However, because it was originally developed with mainly agricultural land-use in mind, a number of adaptations had to be made for the specific hydrologic characteristics of bog-reserves. In the subsequent section 2.2 a short overview is given of the unadapted version of the model; for a technical description of the used calculation methods the reader is referred to Querner & Van Bakel (1989). In Section 2.3 the manner in which SIMGRO has been adapted for bog reserves is discussed. In the description of the implementation of SIMGRO in Section 2.4 frequent reference will be made to the modelling work of Poelman (1987) that preceded this study. A certain amount of repetition of earlier published material was deemed inevitable in order to provide a comprehensive overview.

2.2 General description of SIMGRO (Querner & Van Bakel, 1989)

The focus of SIMGRO is on the modelling of saturated groundwater flow and the integrating role it plays on a regional scale. Groundwater flow is modelled using a so-called quasi three-dimensional geohydrologic schematization, i.e. a schematization into two-dimensional horizontal flow through aquifers and one-dimensional vertical flow through aquitards. The finite-element method is used for the horizontal flow; the numerical scheme is repeated for each of the aquifers involved in the geohydrologic schematization. Coupling of the numerical schemes is through simple 'leakage' equations for each of the nodal points of the finite-element network.

Since the model mainly focuses on describing the groundwater flow, the submodels for surface water and soil moisture have been kept relatively simple. For modelling these processes the concept of a subregion has been introduced. A subregion consists of a number of nodal points of the finite-element scheme that are relatively homogeneous with respect to soil physical properties and hydrologic conditions.

An overview of the processes modelled in SIMGRO is given in Fig. 2. In the overview a geohydrologic schematization of four layers has been used, starting with an aquitard in the top layer.

The surface water system, which in reality is a network of channels with a complex geometry, is schematized into four classes of water courses (Fig. 3):
- trenches;
- tertiary water courses;
- secondary water courses;
- canals.

Per nodal point a characterization of the four classes must be given in terms of two parameters:
- the level of the drainage base (m below soil surface);
- the drainage resistance (d).

(In the case of 'canals' the drainage resistance is actually specified differently, in terms of the length of canal in a nodal area and the parameters of the 'entry resistance' and the 'radial resistance'. Since this option has not been used in this study, the interested reader is referred to Quemer & Van Bakel, 1990)

The level of the drainage base acts as a threshold for the intermittent functioning of the type of water course concerned. The discharge of groundwater to the surface water system is assumed to be proportional to the reciprocal value of the drainage resistance and directly proportional to the hydraulic head difference between groundwater and surface water. Such a method of parameterization circumvents the need to explicitly specify the geometry of the surface water system in the model – the drainage resistance is an abstract description of this geometry. It should be realized, however, that this parameterization is only valid if the average distance between the channels is smaller than the diameter of a nodal area.

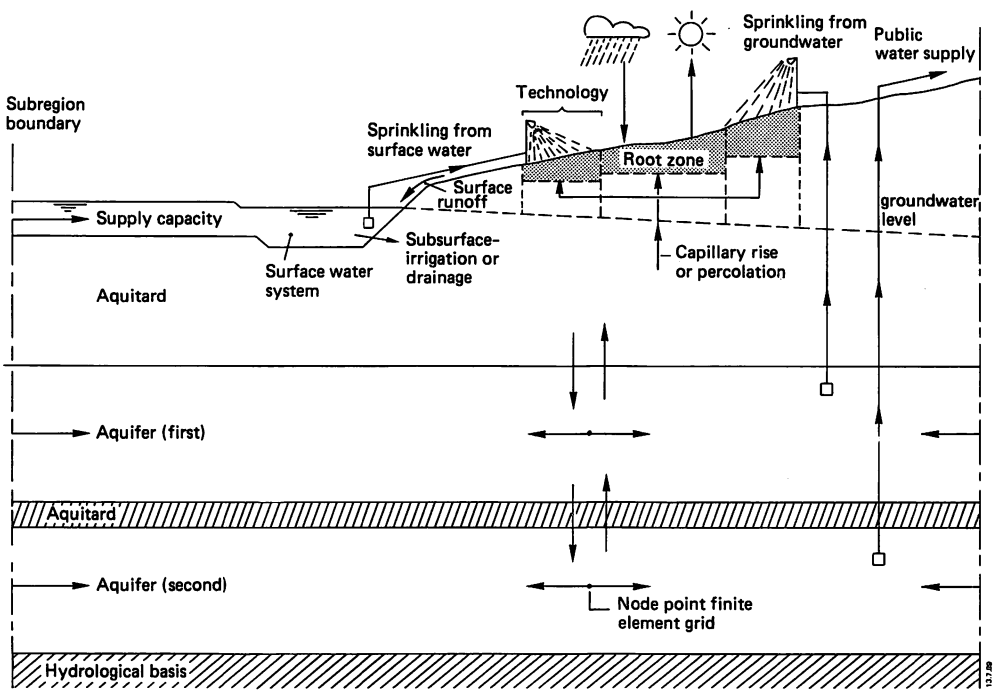


***Fig. 2** Overview of the schematization of the hydrologic system within a subregion of SIMGRO, involving groundwater flow, surface water flow and soil moisture processes. The term 'technology' is used for a type of land use.*

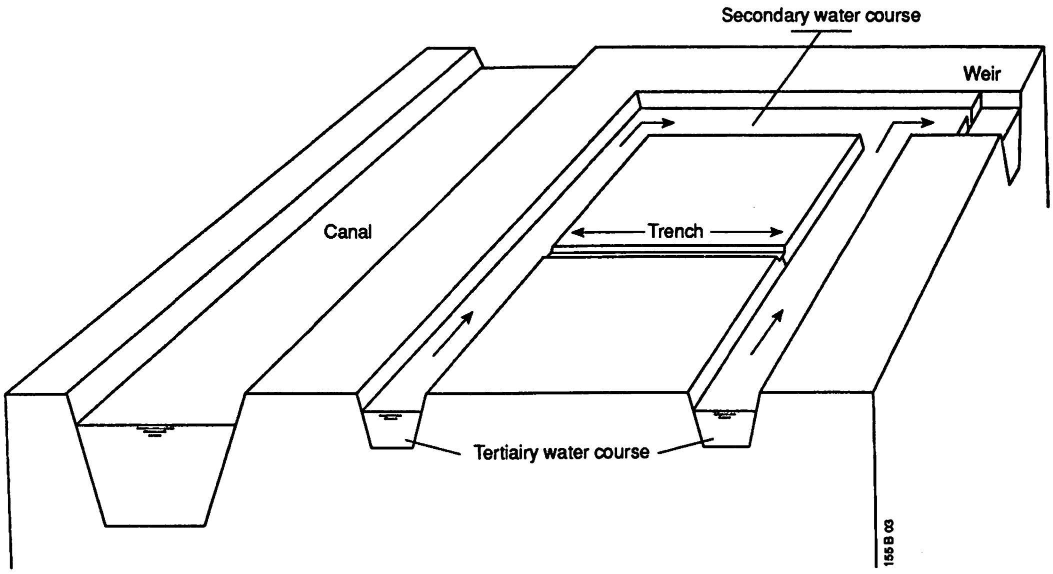


Fig. 3 Schematization of the surface water system in SIMGRO

The surface water system itself is modelled as a single reservoir for which a water balance is computed per subregion. The surface-water level control is simulated using a scheme that relates the target level to the groundwater level. This scheme has two extremes:
- the highest target level, which is only allowed in the summer season, and then only when the groundwater level has dropped below a certain depth;
- the lowest target level.

The complete scheme involves a number of intermediate situations. The surface-water target level has been made dependent on the groundwater level in order to reduce the risk of water-logging agricultural lands.

Soil moisture is also modelled by means of a reservoir. Per subregion and per type of land use the water balance of such a reservoir is computed for each time-step of the groundwater submodel. Capillary rise of moisture from the groundwater table towards the root-zone is computed using relationships derived from the steady-state soil moisture model CAPSEV (Wesseling, 1991).

2.3 Adaptation of SIMGRO for bog reserves

SIMGRO was developed with mainly the characteristics of agricultural areas in mind. A certain degree of general applicability was strived for, by for instance making possible a flexible definition of the 'technologies' that the model can be run with. Application to 'nature' areas was deemed possible by defining a separate technology with specific hydrologic characteristics. However, the hydrology of bog reserves is so much different from that of agricultural areas that straightforward application of SIMGRO was considered to be questionable. The specific characteristics of bog reserves that can not be described by simply choosing appropriate input parameters mainly concern the modelling of surface water.

In a bog reserve surface water may have a dominant presence – in the *Groote Peel* roughly 25% of the area is covered by it. Agricultural areas can of course also be interspersed by large tracts of surface water. In the standard version of SIMGRO, an expanse of surface water can be modelled as a subregion, completely covered by the technology 'open water'. Appropriate parameters have to be chosen for the 'soil physical unit', e.g. by specifying that the storage coefficient is equal to 1.0 under all circumstances. Surface water is thus treated as phreatic groundwater, having similar interactions with the deeper aquifers. This way of modelling the surface water in bog reserves is, however, only feasible for the larger lakes. In bog reserves peat-mining activities can have left behind a great many isolated pits, some having only an area of a few square meters. The geometry of the small pools and lakes is far too complex to be described in terms of separate subregions and finite elements. Another complicating factor is the spatial variability of the resistance to lateral flow between surface water and groundwater.

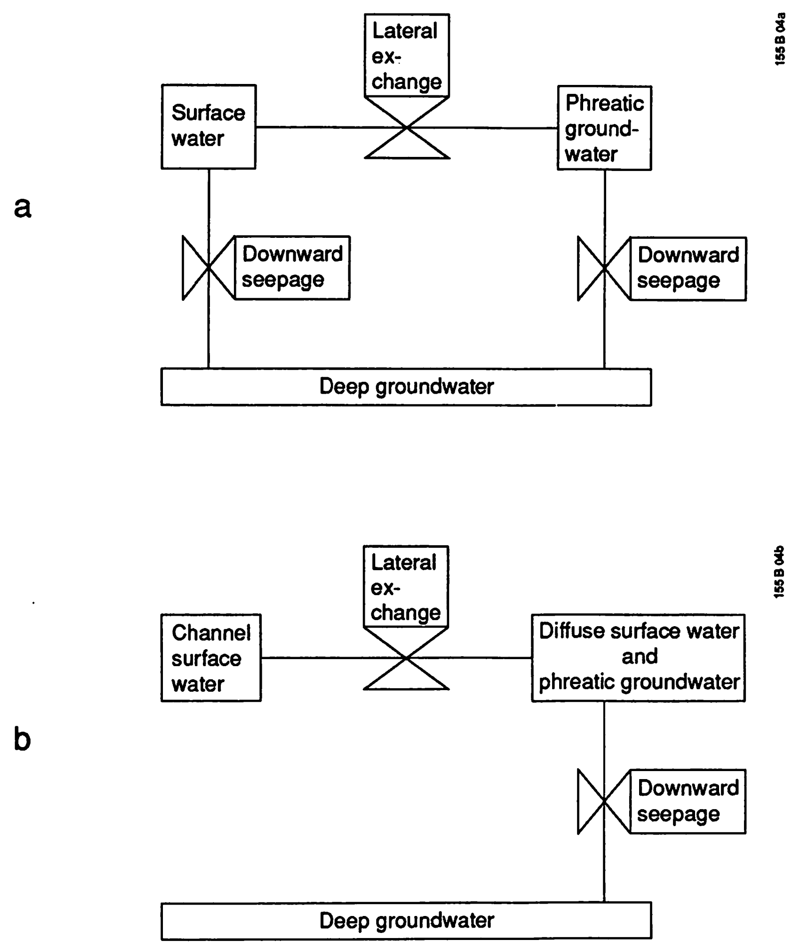


Fig. 4 Schematic diagram of flow resistances in a bog reserve (a) and in the further schematization by means of the hybrid water-level concept (b)

Since a detailed modelling of the physical reality is not in any way feasible, a very simple macroscopic modelling concept has been introduced for modelling the presence of surface water in a bog reserve. In this approach a distinction is made between the 'diffuse' surface water – that in the first place has a storage function – and the 'channel' surface water – that in the first place plays a role in removing water from the area. For modelling the diffuse surface water, SIMGRO has been adapted in a manner that – implicitly – the flow resistance between the diffuse surface water and groundwater is set to zero. This method leads to the computation of a 'hybrid water-level' for surface water and groundwater. The leaving out of a flow resistance that in reality is present between the diffuse surface water and the groundwater, has to be compensated by increasing the flow resistance of the first aquitard. This is illustrated by the diagrams shown in Fig. 4. Implementation of the hybrid water-level concept in the model is fairly straightforward, consisting mainly of some extra pre-processing steps.

The first step is the derivation of a storage curve for the diffuse surface water. This is done from field observations of the relationship between the observed expanse of surface water and the water level: the higher the level, the larger the area that is inundated. The dashed line in Fig. 5a is an example of the dimensionless form of such a relationship. The soil that falls dry due to the dropping of the surface water level also has a storage coefficient; a value of 0.20 has been used in the example of Fig. 5a.

For groundwater the storage coefficient has a trend opposite to that of diffuse surface water: the lower the level, the higher the coefficient becomes (cf. Fig. 5b). The exception to this is the trajectory near the soil surface. In SIMGRO the elevation of the soil surface is for each node of the finite-element scheme assumed to be a mean value. In reality there will always be a certain amount of variation. When the groundwater level rises to a very high level, approaching the average elevation, certain parts of the area represented by a node will become inundated. In the model this is reflected by the assumed trajectory of the storage coefficient from a depth of 20 cm to the soil surface: in this trajectory the storage coefficient is assumed to increase from the value obtained with the steady state model for unsaturated flow to a value of unity. This incidental inundation due to extremely high groundwater levels is distinguished from the more permanent inundation by the diffuse surface water with respect to the assumed degree of vegetational cover: the assumption being that if the soil inundated by diffuse surface water falls dry, this will occur well into the summer season, leaving too little time for the development of a full vegetational cover. This leads to a lower evapotranspiration rate (i.e. that of 'bare soil') and a lower storage coefficient.

The second pre-processing step consists of calculating a composite curve from the two curves for the storage coefficient of diffuse surface water and groundwater, to be used in the model for computing the changes of the hybrid water-level. The composite curve is obtained by simply calculating the weighted mean of the storage coefficient, for a number of depths below the soil surface. An example of such a curve is given in Fig. 5c.

Whereas the standard version of SIMGRO applied to a bog reserve overemphasizes the role of the phreatic groundwater level as the driving force behind the downward seepage, the hybrid water-level method overemphasizes that of open water. The latter overemphasis is due to the fact that open water has a storage coefficient of 1.0 and phreatic groundwater a value in the order of 0.25. So the open water has a relatively larger influence on the hybrid storage coefficient than the groundwater. This leads to the computation of a hybrid water-level that is disproportionately close to the head of open water. In order to minimize this kind of misrepresentation of reality, large lakes should as much as possible be modelled as separate subregions. For subregions that are completely covered by open water, this yields the same results as when the standard version of SIMGRO is applied in the manner described above (i.e. through defining a special soil physical unit).

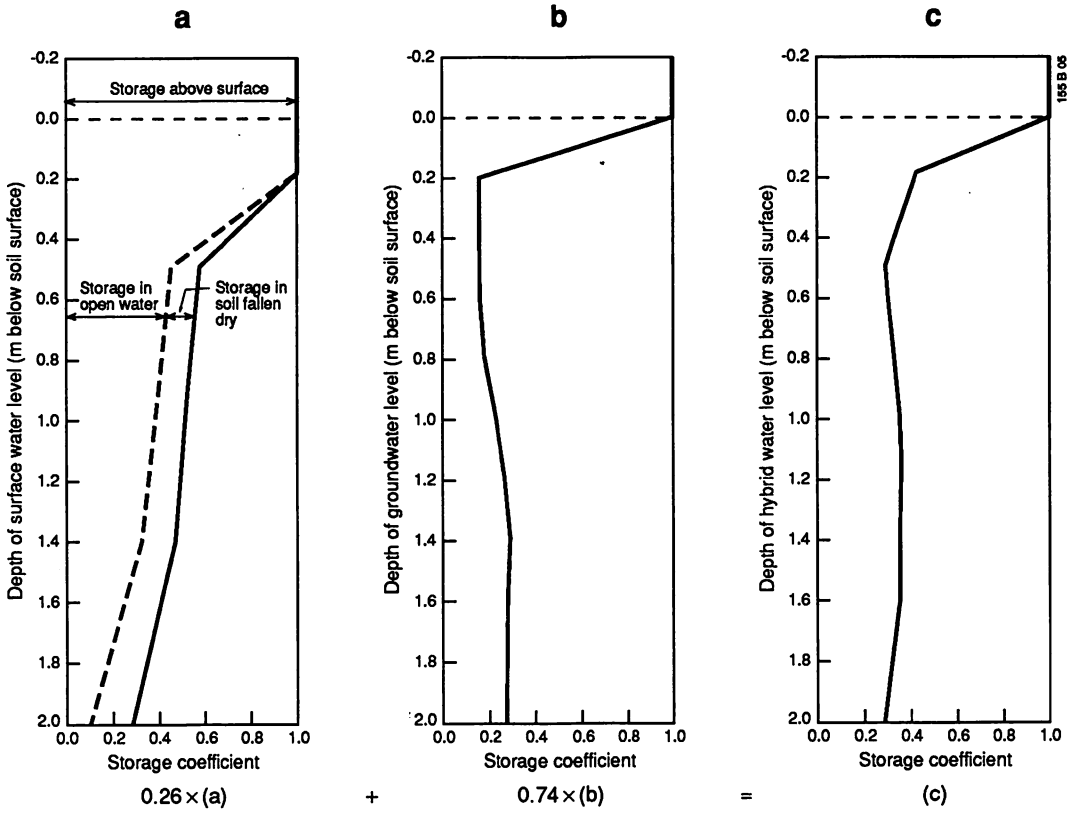


***Fig. 5** Calculation of a composite storage coefficient for the 'hybrid water-level' of diffuse surface water and groundwater. The storage curve for the diffuse surface water (a) has two components: the open water (dashed line) and the 'bare soil' that falls dry due to a dropping water level. The storage curve for the groundwater (b) is derived from steady-state calculations for groundwater levels deeper than 20 cm below soil surface. The composite curve (c) is obtained by calculating the weighted mean of the curves, with the weights taken as the relative expanses of diffuse surface water and phreatic groundwater.*

The evapotranspiration of the diffuse surface water has been set at 1.26 times the reference-crop evapotranspiration according to Makkink (derived as an average from data given in De Bruin, 1987). The part of the diffuse surface water that falls dry with the dropping of the water level (trajectory with a storage coefficient less than unity in Fig. 5a) is assumed to become 'bare soil', with a relatively low level of evaporation, due to the mulch effect of the upper soil crust. The manner of calculating the bare soil evaporation is the same as in the standard version of SIMGRO.

The 'channel' part of the surface water that mainly serves to discharge water from the area can also not be modelled using the standard options of SIMGRO. The reason being that in bog reserves the surface water level control usually does not follow the soil surface as closely as in most agricultural areas. That in agricultural areas this level tends to follow the soil surface is because a prolonged process of optimizing the water management has been gone through, with a view to maximizing agricultural production. In the standard version of SIMGRO this is reflected by treating the surface water level within a subregion as a level below soil surface. Per nodal point within a subregion, the surface water level is converted to a level in absolute terms (i.e. relative to the datum plane of the hydraulic head) before using it for computing the interaction with the groundwater. Since this manner of modelling was not deemed to apply to all situations in bog reserves, SIMGRO was extended with an option for defining the surface water level control relative to the average soil surface elevation in a subregion. Since the conversion to a level in absolute terms (the hydraulic head) is the same for all the nodal points in a subregion, this is effectively equivalent to defining the water level control itself in absolute terms.

Another aspect in which bog reserves differ from agricultural areas is the importance of water conservation measures. The internal management of bog reserves is usually directed towards holding on to the water as long as possible, by reducing the depth of the drainage base and by leading drainage outflow from one subregion to another. In situations that a downstream subregion has a relatively high seepage loss to the subsoil, the water coming from an upstream subregion can have a mitigating effect on the storage depletion. In agricultural areas, on the other hand, drainage water outflow is usually directed as quickly as possible towards the larger drainage channels, thus minimizing further interaction with the groundwater system. In the standard version of SIMGRO this is simply modelled by letting surface water outflow of a subregion 'disappear'. In the adapted version for bog reserves it has been made possible to let a certain percentage of the outflow pass to the surface water reservoir of another subregion. The remaining percentage 'disappears' like in the standard version. More than one subregion can drain to certain downstream subregion.

2.4 Model implementation

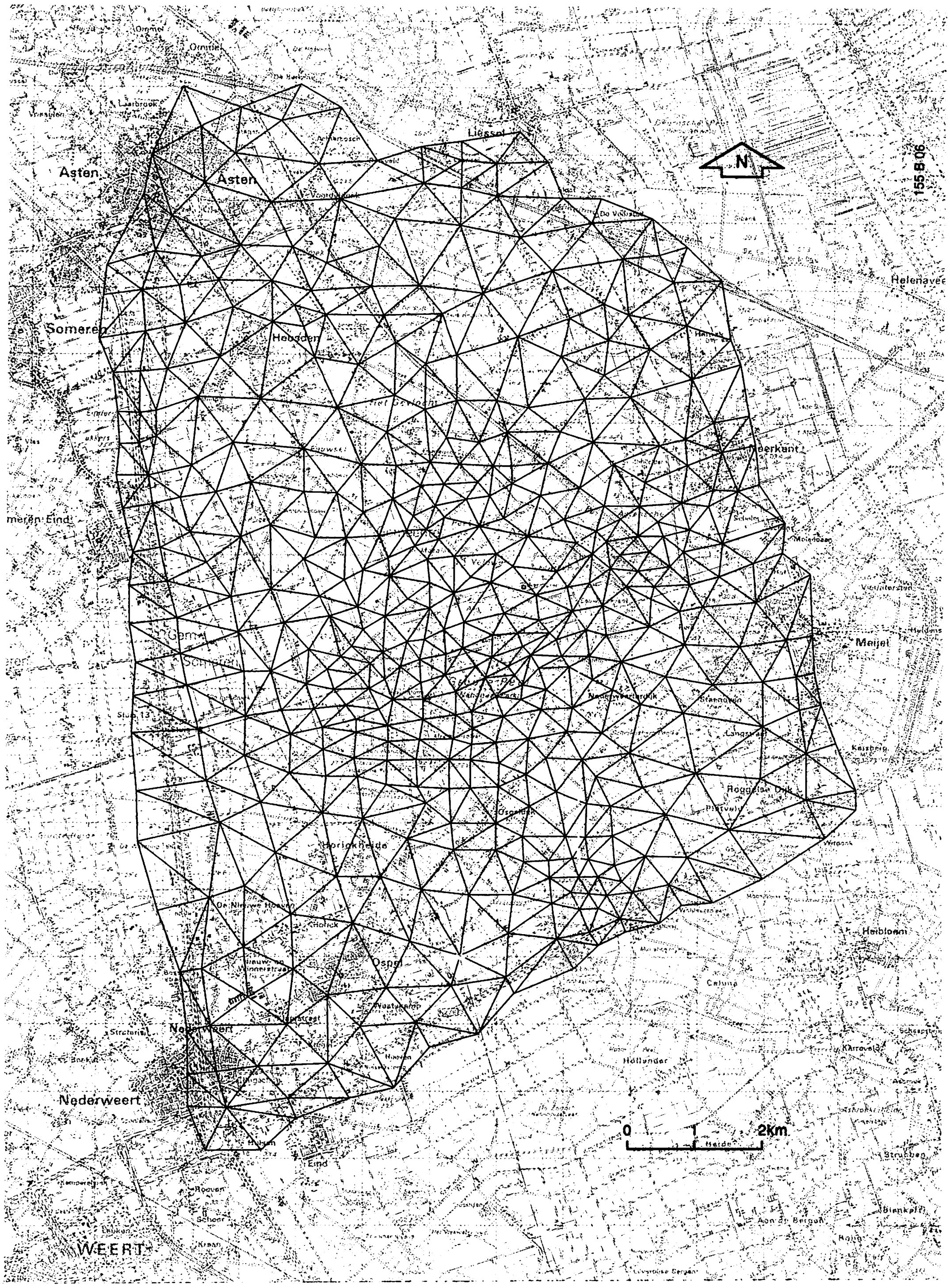
A regional model like SIMGRO requires a large number of input parameters. These parameters can be grouped into:
- parameters that can be obtained directly from existing sources of data;
- parameters for which only initial guesses are available and that can only be determined indirectly through calibration of the model.

Most of the data used for implementing the model were taken directly from the study of Poelman (1987). In the following, frequent reference will be made to this source. For a concise overview of the data that were modified in the course of the present study, the reader is referred to Van Walsum (1990). Part of the data borrowed from Poelman were originally obtained through calibration; in the following these data are discussed along with the other data that have been obtained directly from existing sources.

2.4.1 Directly obtained parameters

Finite-element scheme and division into subregions

Triangular finite elements have been used for the spatial discretization. The constructed scheme of roughly 450 nodal points is shown in Fig. 6. Through geometric construction,



Topography: Topografische Dienst

Fig. 6 Finite-element scheme for the study region (from Poelman, 1987)

the 'influence areas' of the nodal points are obtained. (In the model, the hydraulic head at a nodal point is treated as a representative value for the whole influence area.) Some processes are in the model described at the spatial resolution of subregions – with each subregion consisting of a number of nodal influence areas. The manner in which the nodal influence areas have been aggregated into subregions is shown in Fig. 7.

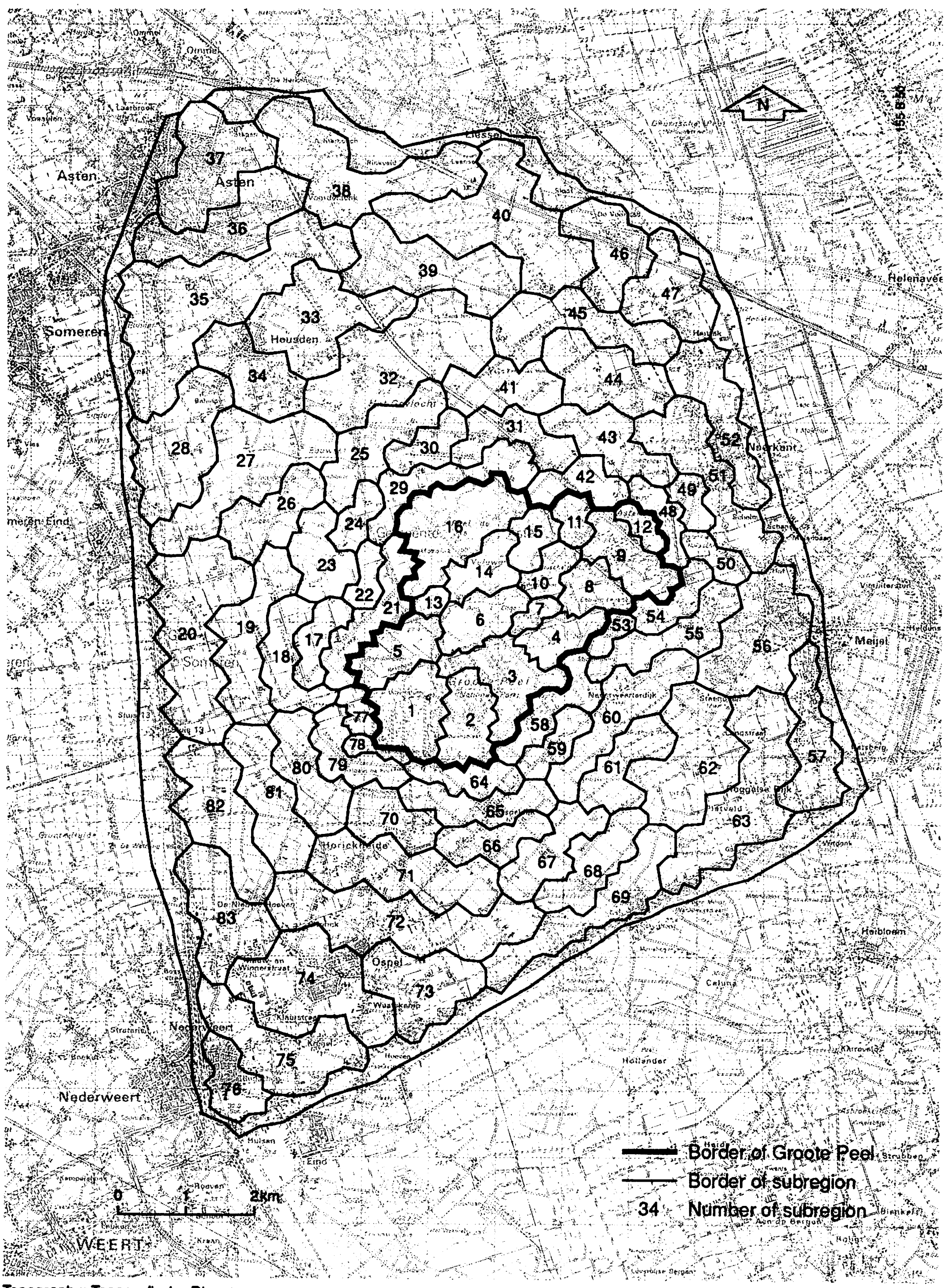


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Fig. 7 Division of the study region into subregions

In the area outside the *Groote Peel* the grouping of nodal points into subregions was not only based on soil physical properties and hydrological conditions, but also on the geometric orientation towards the nature area: longitudinality of subregions was only allowed in a direction parallel to the boundary of the nature area. This method was followed in order to achieve a homogeneous degree of interaction between water management measures in a certain subregion and the effect on the *Groote Peel.* If the longitudinality were to have been chosen in the direction of the nature area, water management measures in the nodal points nearest to the *Groote Peel* would have had a substantially larger effect than the ones at the other end of the subregion. Since scenarios are developed at the resolution level of subregions (see chapter 4), an inhomogeneous degree of interaction between the various nodal points within a subregion and the nature area would have lead to suboptimality.

Geohydrologic schematization

The geohydrologic schematization used by Poelman (1987) involved seven layers, consisting of four aquifers and three aquitards (Fig. 8). Since the transmissivity of the first two 'aquifers' (layer 1 and layer 3) is very low (respectively 2 and 25 $m^2.d^{-1}$), a schematization into four layers such as given by Wit (1986) can just as well be used. In the latter schematization the water-bearing properties of layer 1 and layer 3 are added to that of layer 5; this combined transmissivity is attributed to layer 2 of the four-layer schema-

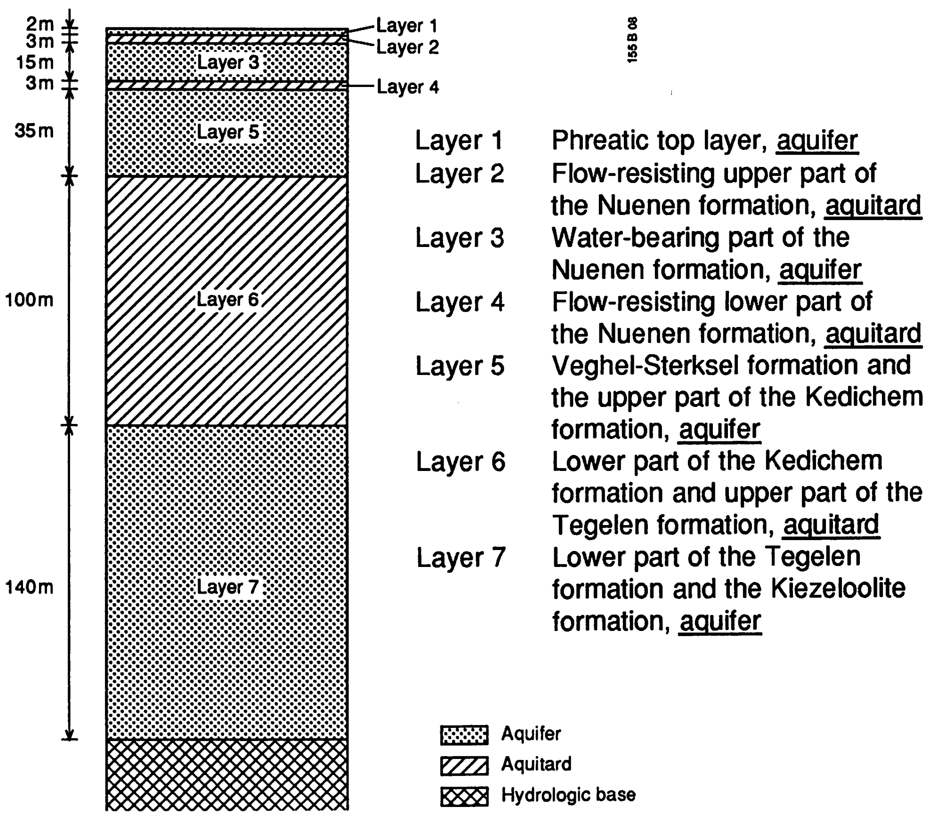

Fig. 8 Geohydrologic schematization involving seven layers (Poelman, 1987)

tization. The vertical resistance of layer 2 and layer 4 of the seven-layer schematization are added up and attributed to layer 1 of the four-layer schematization (Fig. 9).

Though the seven-layer schematization has been used for many of the simulations (especially for the evaluation of internal measures within the nature area), in the following only the four-layer schematization will be referred to because of the insignificance of the differences between the obtained results.

The values of geohydrological parameters (KD-values of aquifers, c-values of aquitards) were obtained from Wit (1986) and some additional field work reported by Poelman (1987). The vertical resistance of the top aquitard, however, was for the *Groote Peel* obtained through a calibration procedure, as is discussed below in Section 2.4.2. The reason for singling out the resistance within the *Groote Peel* for calibration was that this parameter is very determining for the ecological potential of the nature area and for the degree in which external influences penetrate to it. In Figs. 10 and 11 the values of KD- and c-values are shown in as far as they were obtained from direct interpretation of field investigations.

For the specific storage coefficient of the subsoil a value of $2 \cdot 10^{-5}$ was obtained from Te Beest (1985). This value has been used for all of the layers.

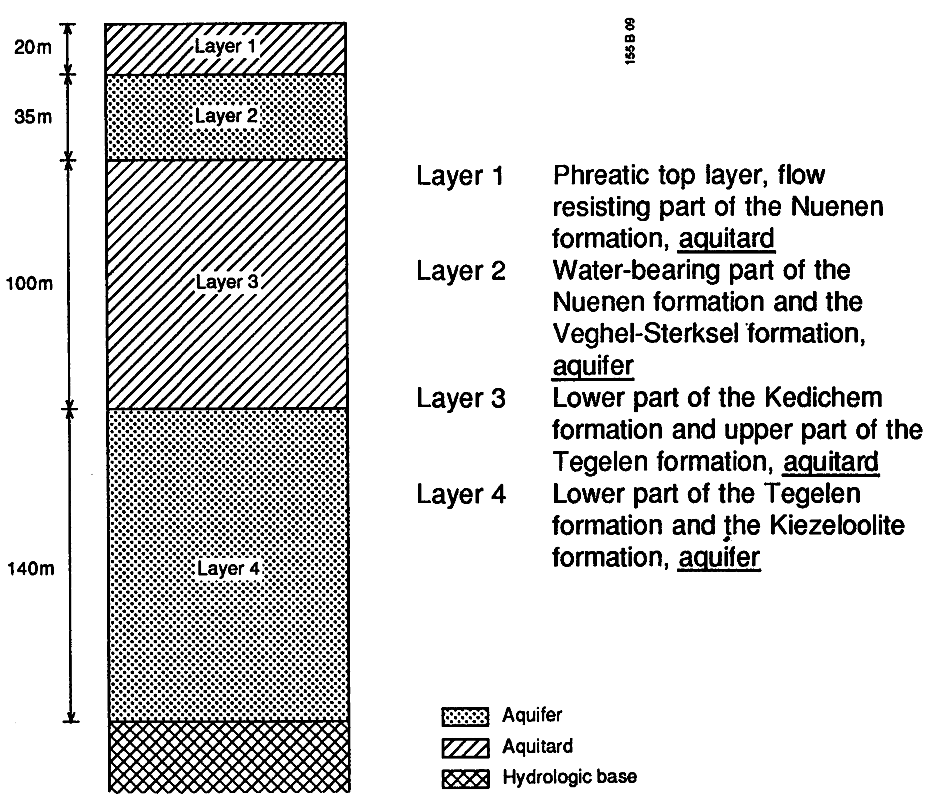

Fig. 9 Geohydrologic schematization involving four layers (Wit, 1986)

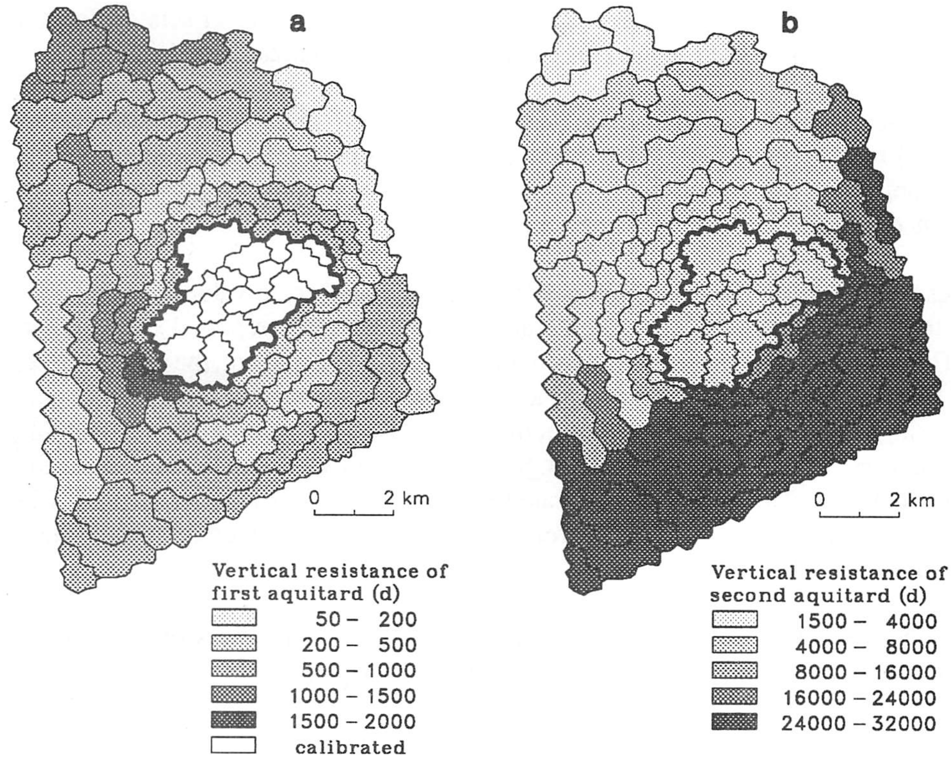

Fig. 10 *Subregional values of vertical resistance of first aquitard, excluding values for subregions in the Groote Peel (a), and second aquitard (b). (From Poelman, 1987)*

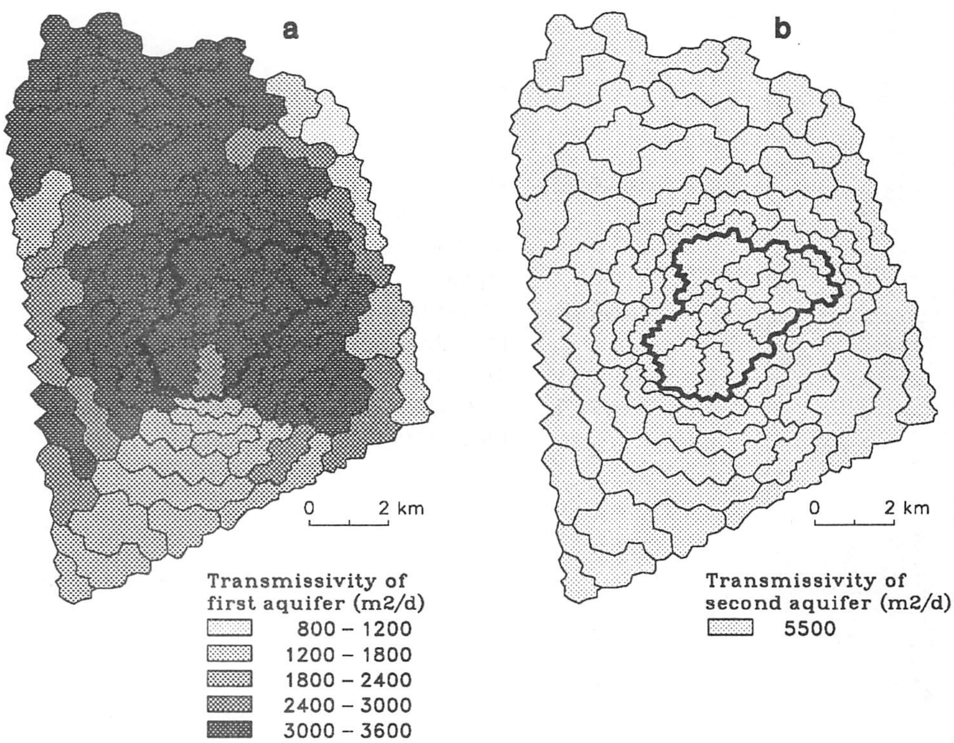

Fig. 11 *Subregional values of transmissivity of first aquifer (a) and second aquifer (b). (From Poelman, 1987)*

Boundary conditions of groundwater flow

The groundwater flow boundary conditions along the perimeter of a study region can in SIMGRO either be defined in terms of fixed hydraulic heads or fixed fluxes. Both have their specific drawbacks, especially if like in the present case the study region is relatively small in relation to the transmissivity of the regional aquifers. Since a redefinition of the study region used by Poelman (1987) was not possible within the project schedule, the boundary condition with the least drawbacks had to be resorted to.

The drawback of boundary conditions in terms of fixed hydraulic heads is that they lead to an underestimation of effects (of for instance groundwater extractions) in the agricultural area on the hydrology of the *Groote Peel* – the nearer a measure is situated to the boundary of the study region, the greater the underestimation is. The underestimation is due to the circumstance that the fixed hydraulic head along the boundary is maintained under all conditions, even if it means that a large amount of water ('out of nowhere') is needed for this.

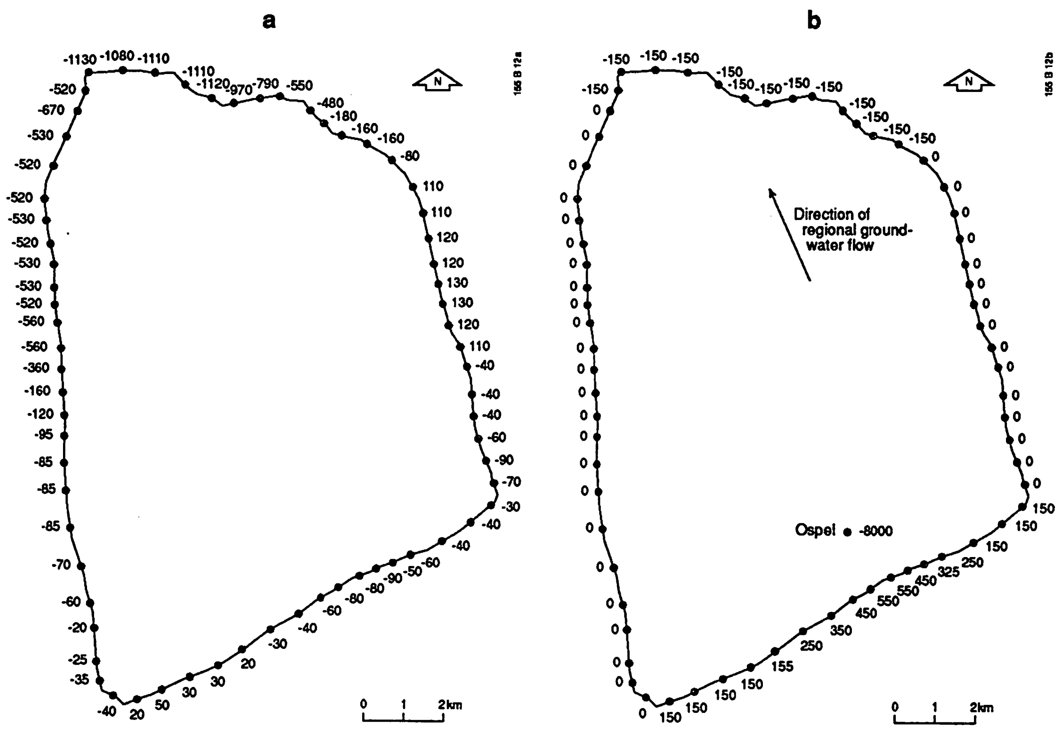

Fig. 12 ***Boundary fluxes of the first aquifer (a) and the second aquifer (b), including the public water supply extraction at Ospel. The dots indicate the locations of nodal points for which fluxes are specified. A positive value indicates an inflow, a negative one an outflow. Values in*** $m^3.d^{-1}$.

The drawback of fixed fluxes along the boundary is that they can lead to an overestimation of effects of measures on the hydrology of the *Groote Peel*. This is especially so for measures that are located just within the boundary of the study region. Nevertheless, flux boundary conditions were deemed preferable because the errors they cause are known to be less serious than those due to fixed heads. Data for the boundary fluxes were initially obtained through interpretation of the field investigations reported by Wit (1986). The values for the first aquifer were adjusted by Poelman (1987) through calibration with a steady-state model. The values for the second aquifer along the northern boundary were obtained from a model for a larger area (Querner & Van Bakel 1989). The values are shown in Fig. 12. Along the eastern boundary the flux in the second aquifer (Fig. 12b) is zero due to the presence of the *Peelrand* fault. This fault forces the regional flow to follow a north-westerly direction. This also explains the (approximate) assumption of a zero flux along the western boundary. In the first aquifer the *Peelrand* fault is only partially impermeable, as can be seen from the non-zero values of the fluxes in Fig. 12a.

Water demands for public water supply are satisfied by means of extractions from the main regional aquifer (layer 4 of the schematization given in Fig. 9). The locations of the nearest three well sites are shown in Fig. 13. The influence of these extractions on the hydrology of the study region is implicitly contained in the boundary fluxes. From the results of other studies (IWACO, 1987 and 1989) it has been concluded that the influence of the public water supply extractions manifests itself as an extra downward seepage of 20 mm/year, in terms of an average over the whole study region.

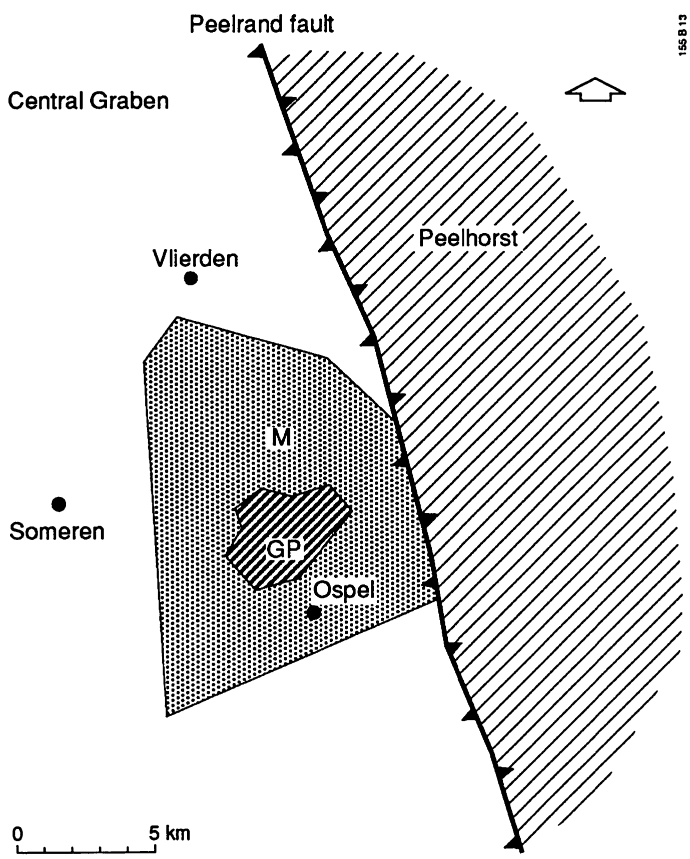

Fig. 13 ***The study region (M) (and the Groote Peel, GP), placed in the wider geohydrologic context. Locations of major groundwater extractions for public water supply (> 3 million $m^3.yr^{-1}$) from the second aquifer are indicated by dots. The Peelrand fault (teethed line) marks the transition between the Central Graben containing deep aquifers (to a depth of 300 m), and the Peelhorst containing only shallow aquifers (to a depth of 20 m)***

Surface water system and its interactions with groundwater
For characterizing the surface water system and its interactions with groundwater use has been made of the SIMGRO options for:
- trenches;
- tertiary water courses;
- secondary water courses.

Each of these classes of channels had to be attributed a drainage resistance and a drainage base, for each of the nodal points. The large canals along the perimeter of the study region hardly interact with the groundwater (Wit, 1986) and have therefore not been modelled.

The trenches have been given a very shallow drainage base at 0.05 m below soil surface and a very low drainage resistance of 5 d. The trenches thus effectively function as a means of avoiding the computation of groundwater levels that rise above the soil surface.

Except for the tertiary drainage resistances within the *Groote Peel*, the same characteristics of secondary and tertiary water courses have been used as obtained by Poelman (1987) with a calibration procedure. The nodal values of the drainage resistance are shown in Fig. 14a. The presented values pertain to the pre-1985 situation. Since 1985 (the year that the *Groote Peel* was designated to become a national park) the farmers

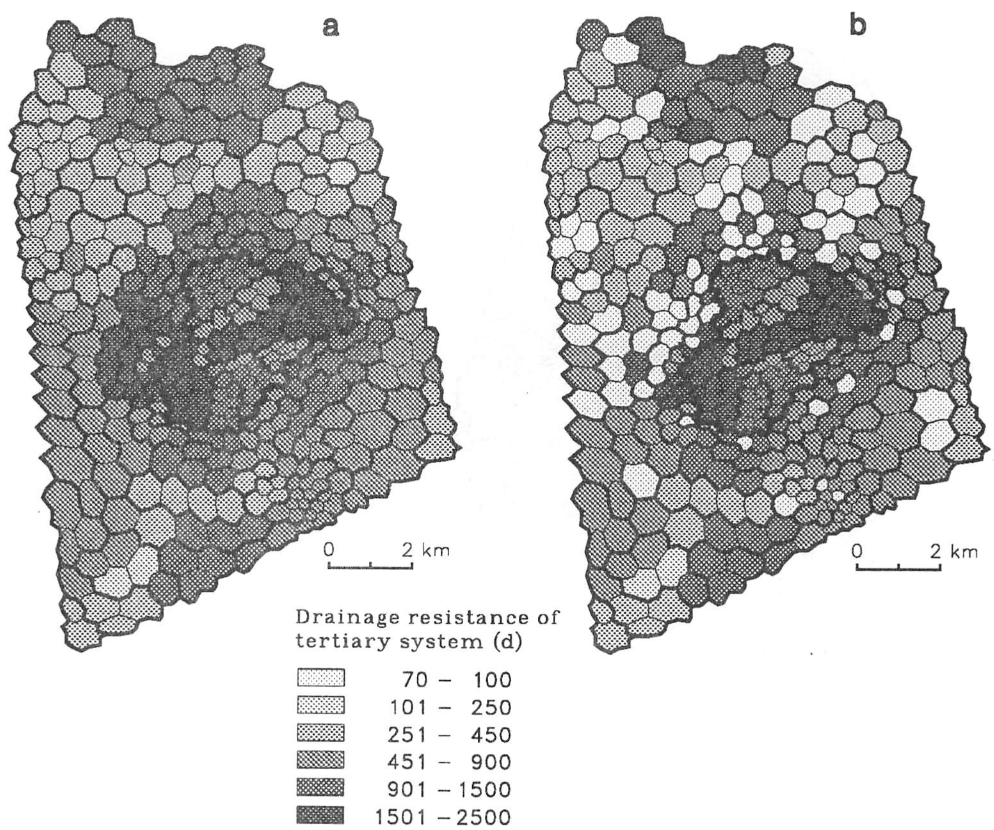

Fig. 14 ***Nodal drainage resistances attributed by Poelman (1987) to the tertiary water courses in the pre-1985 situation (a) and in the 1988 situation (b) in which subsurface drainage has been installed in a substantial part of the area (nodes with drainage resistance of 70 d)***

have invested in installing drainage systems, especially in the area to the north of the nature area. In the model the drained areas have been given a very low tertiary drainage resistance of 70 d. The 1988 situation is shown in Fig. 14b. The drainage resistances of secondary water courses are shown in Fig. 15. The drainage base of the tertiary water courses has been taken at 0.80 m below soil surface throughout the region, including the nodes where the tertiary system has a low resistance due to the presence of drains; the drainage base for the secondary water courses has been taken at 1.40 m below soil surface. For situations in which infiltration takes place, the flow resistance has been set at a value that is 10% higher than the drainage resistance.

For simulating the surface water management in the agricultural area the scheme given in Table 1 has been used. Inside the nature area, the 'target' surface water level is the same throughout the year, because the water management does not have to take into account the danger of crop damage due to water-logging. Whereas in the agricultural area the level has been defined relative to the ground level in a nodal point, in the *Groote Peel* the level has been defined relative to the average ground level in a subregion. The used levels are shown in Fig. 16.

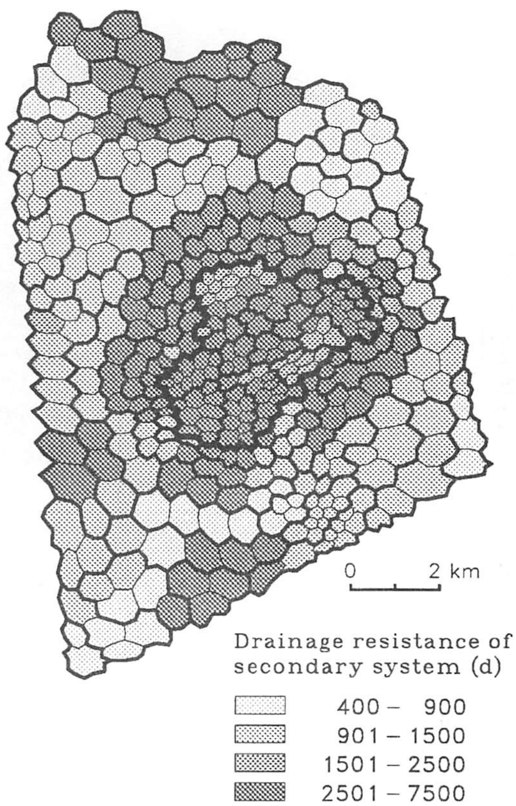

Fig. 15 Nodal drainage resistances attributed by Poelman (1987) to the secondary water courses

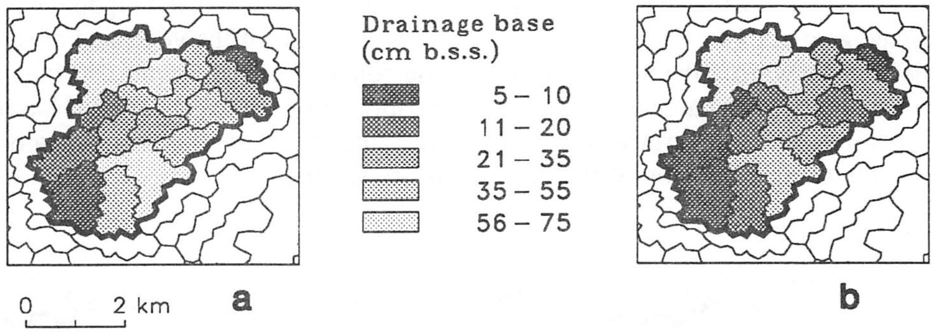

Fig. 16 Subregional levels of the drainage base within the Groote Peel in the 1985 situation (a) and after water conservation measures completed in 1987 (b)

Table 1 Surface water level management scheme in the area surrounding the Groote Peel

Surface water target level (m b.s.s.)	Range of groundwater levels (m b.s.s.)
1.30	< 0.90
1.20	0.90 - 1.00
1.15	1.00 - 1.10
1.10	> 1.10

For characterizing the surface water system SIMGRO requires:

- the relationship between the water level and the amount of water in storage;
- the relationship between the water level and the discharge in the secondary water courses, for the winter situation in which the weirs have been lowered as much as possible.

In the part of the study region outside the *Groote Peel* the water courses have a relatively small cross-section and the amount of water that can be kept in storage is small. The exact form of the relationship between the water level and the amount of water in storage was therefore considered to be of little consequence for the modelling. (They are described in Poelman (1987)). The relationship between the water level and the discharge was also considered to be of small importance in the present study. If the aim would have been to simulate the occurrence of high water levels during flash floods, then this would have been a different matter. As it was, the surface water level was only of interest in as far as it influenced groundwater conditions. For the interaction between surface water and groundwater only the long-duration levels count, not the short-duration peaks. From knowledge of the field conditions it was concluded that a level of 1.30 m below soil surface was a good estimate for the long-duration surface water level conditions during winter.

In contrast to the situation in the surrounding area, within the *Groote Peel* the water storage function of surface water plays a major role, as has been explained in Section 2.3. From field investigations (Joosten, pers. comm.) the percentage area covered by 'diffuse' surface water has been estimated as shown in Fig. 17a. This is defined as the area that is covered by surface water in the situation with water levels of 0.20 m below soil surface. The extra inundation that occurs in situations with even higher levels is not counted as part of the diffuse surface water, but as a part of the vegetated area (see the trajectory between a depth of 0.20 m and the soil surface in Fig. 5b.) In Fig. 17b the estimated percentage area is shown for the situation in which the water level has dropped to 0.50 m below soil surface. The ratio between the latter and the former area is a point along the storage function of the diffuse surface water.

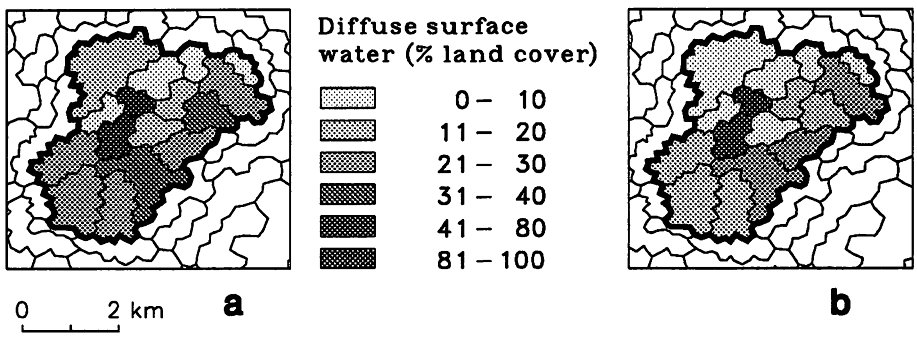

Fig. 17 ***Subregional percentages of 'diffuse' surface water in the Groote Peel, in the situation with a water-level of 0.20 m below soil surface (a) and 0.50 m below soil surface (b)***

Within the *Groote Peel* various water conservation measures have been taken. One of these being the channeling of surface water discharge from one subregion to the next. The structure of the surface water system within the *Groote Peel* is shown in the form of arrows in Fig. 18. The arrows have only been used for indicating flow from one subregion to another; flow that leaves the nature area is not indicated, except at the points where it is gauged. In some cases only part of the outflow passes to another subregion inside the *Groote Peel,* and the rest 'leaks' to the surrounding agricultural area (by for instance over-topping the levees along the circumference of the bog reserve). In such cases, the amount of the flow that actually passes to the neighbouring subregion is indicated by means of a percentage. In the agricultural area all of the drainage outflow from a subregion is assumed to leave the region without any further influence on the regional hydrology, through the secondary water courses. One such water course, the *Eeuwselsche Loop* (see Fig .1), actually cuts through the bog reserve. This explains the location of the gauging points S9 and S10 (see Fig. 18).

The large canals that run along the perimeter of the study region (Fig. 1) do not interact with the groundwater, but they do, however, provide a pathway for supplying water to the region during the summer season. In the current situation a supply of in total 500 $l.s^{-1}$ is possible to the northern half of the study region. On average this means a supply of 0.1 $l.s^{-1}.ha^{-1}$. Nearly all of the externally supplied water is used for maintaining the summer target level in the secondary water courses. Only a very small amount is used for sprinkling from surface water.

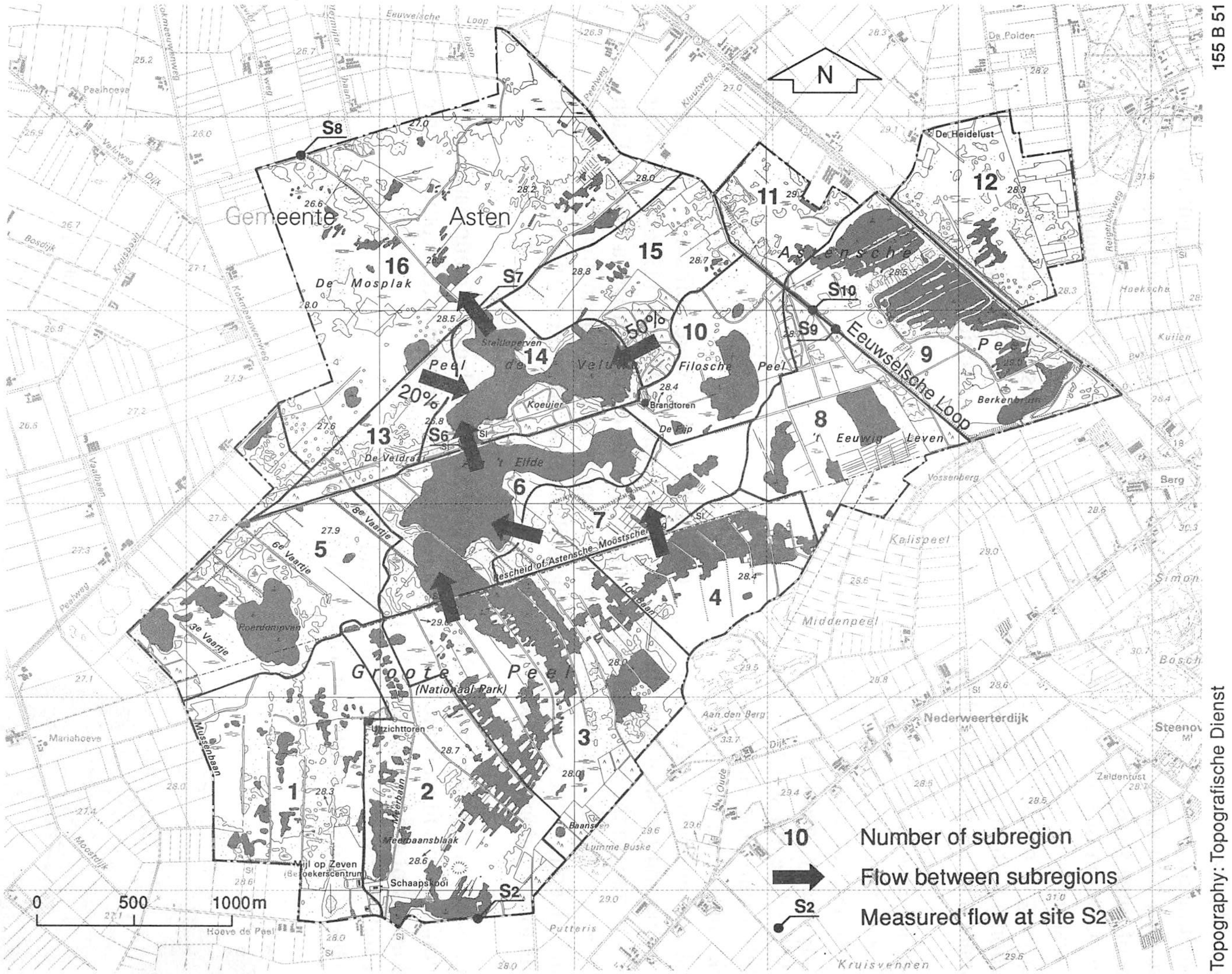

Fig. 18 ***Topographic map of the Groote Peel, showing the major surface water drainage units (modelled as subregions), the flows between the major units, and the flow gauging points***

Unsaturated zone
For modelling the processes in the unsaturated zone SIMGRO requires soil physical and land-use data on a subregional basis. The procedure for providing the soil physical data consists of three steps:
- schematization of the diversity of soils in the region into a limited number of soil physical units;
- processing of raw soil physical data (water retention curves, unsaturated conductivity functions) with the steady state model CAPSEV (Wesseling, 1991);
- attribution of a single soil physical unit to each of the subregions.

The used schematization involves six units:
1. Thin peat on a sandy subsoil
2. Thickish peat on a sandy subsoil
3. Slightly loamy sand ('HN21');
4. Black 'beek' earth soil ('Zg');
5. Slightly loamy fine sand ('HN23')
6. Black 'dikke eerd' soil ('EZ').

The first two units only occur within the *Groote Peel*; they were defined by Poelman (1987), using soil physical data obtained by Stokkermans & Wösten (1986). The other four units pertain to the surrounding agricultural area, as defined in Drent (1989). Each unit has been defined in terms of a sequence of layers and accompanying thicknesses. These are given in Annex 1, along with the soil physical properties. The attribution of soil units to subregions is shown in Fig. 19.

The processing of raw soil physical data with CAPSEV involves the computation of:
- the equilibrium soil moisture content as a function of the groundwater depth, for three thicknesses of the root zone (0.25, 0.50 and 0.75 m);
- the capillary rise as function of the groundwater depth;
- the phreatic storage coefficient as a function of the groundwater depth.

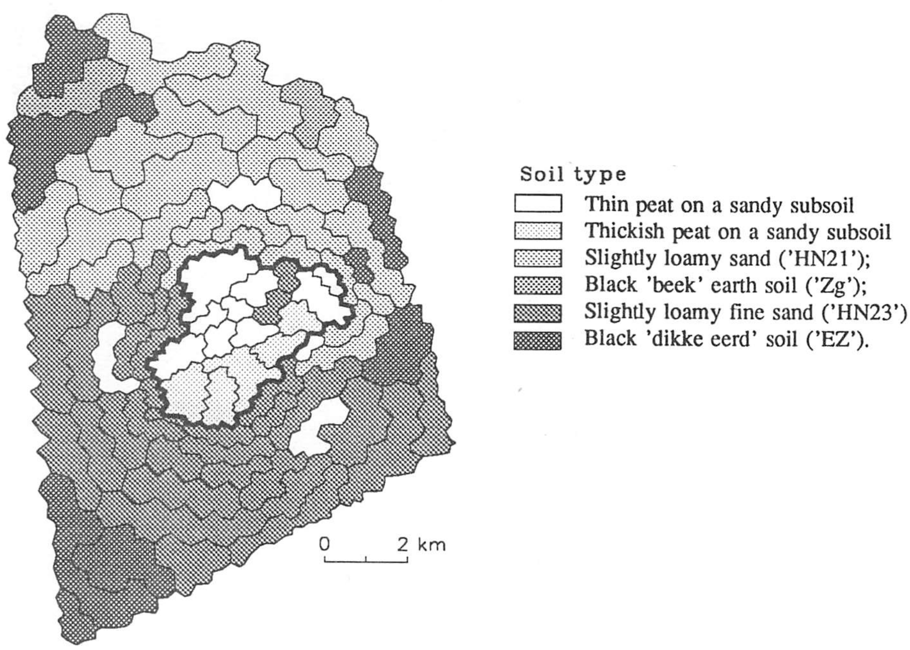

Fig. 19 Attribution of soil units to subregions

For doing the capillary rise and storage coefficient calculations CAPSEV requires a representative value for the pressure head in the root zone. From computational experience and comparison with results from more sophisticated models for soil moisture in the presence of a water table (Querner & Van Bakel, 1989) a pressure head of -500 cm has been found to be appropriate for soils that are under agricultural production; this corresponds with a pF-value of 2.7. For the peaty soils in the *Groote Peel* such a pF-value was, however, considered to be too high, in view of computational experience obtained from applying a sophisticated soil moisture model to similar soils (Schouwenaars, 1990). A pressure head of -300 cm (pF = 2.5) has therefore been used instead. Another specific characteristic of peaty soils that has been taken into account is that due to the presence of large pores left behind by decayed roots, the storage coefficient will never become lower than roughly 15% (Schouwenaars, 1990). The value of the storage coefficient has been set to this limiting value in the case that a lower value was computed with CAPSEV. Another specific characteristic of peaty soils is the expansion and contraction ('Mooratmung') that occurs during wetting and drying out. This effect can add to the storage coefficient as shown by Schouwenaars (1990). Since, however, the computed storage coefficients are thought to already have been rather high, no further adjustments were made. The processed data are given in Annex 1.

The types of land use are in SIMGRO termed 'technologies'. A certain degree of schematization is usually inevitable; for this reason a technology usually represents a category of land use. The following technologies have been discerned in the present study:

1. Arable land, non-sprinkled
2. Maize land, non-sprinkled
3. Grassland, non-sprinkled
4. Arable land, sprinkled
5. Maize, sprinkled
6. Grassland, sprinkled
7. Deciduous forest
8. Pine forest
9. 'Nature' vegetation (non-forest)
10. Urban area
11. 'Diffuse' surface water

In Table 8 of Annex 1 the assumed rooting depths (if relevant) are given, for the various soil physical units; these rooting depths are assumed to be constant under all conditions. An overview of the distribution of the area over the various technologies is given in the pie charts of Fig. 20.

As can be seen from the pie charts nearly all of the sprinkled area concerns grassland. In the model sprinkling is assumed to have a peak capacity of 25 mm per 7 days. Sprinkling is assumed to start when the soil moisture content drops below a certain critical level (Querner & Van Bakel, 1989), in the period between May 1 and September 1.

The evapotranspiration of a technology is calculated in two steps (Feddes, 1987):

- multiplication of the reference-crop evapotranspiration according to Makkink by the crop factor, yielding the potential evapotranspiration;
- multiplication of the potential evapotranspiration by a soil moisture reduction factor ('relative evapotranspiration'), yielding the actual evapotranspiration.

Fig. 20 Overview of 'land use' in the Groote Peel (a) and in the surrounding area (b)

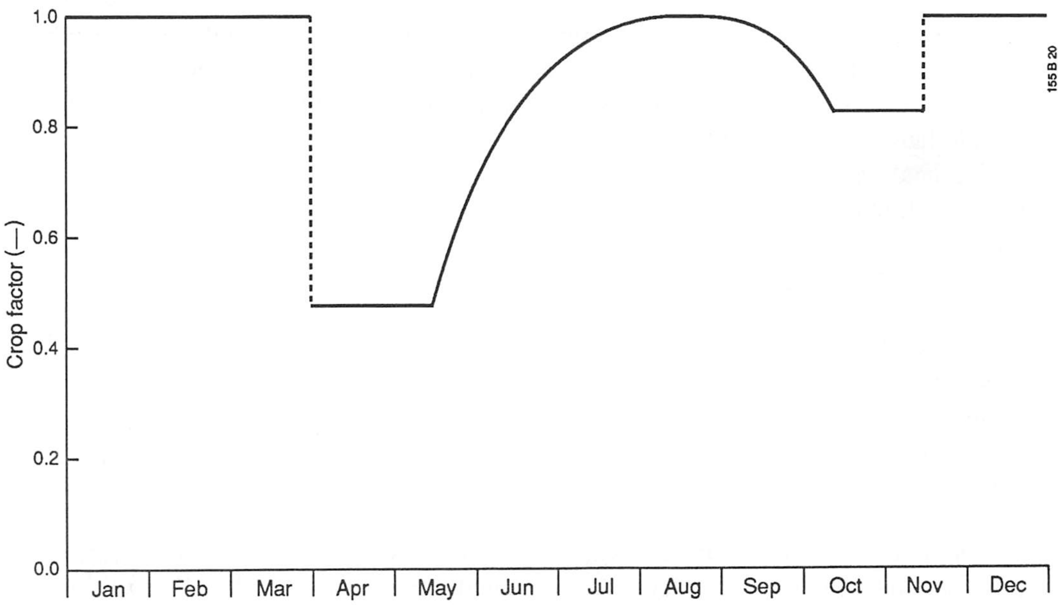

Fig. 21 Crop factor of Molinea caerulea, the dominant 'nature' vegetation in the Groote Peel (adapted from Schouwenaars, 1990; the crop factor relates the potential evapotranspiration to the reference-crop evapotranspiration according to Makkink – see also Feddes, 1987)

For the crop factors the values given by Feddes (1987) have been used, except for the non-forest vegetation in the bog reserve. Since the vegetation of the bog reserve is dominated by *Molinea caerulea*, the function derived by Schouwenaars (1990) was deemed appropriate, as shown in Fig. 21. The low values at the beginning of the growing season are due to the circumstance that the leaves of *Molinea* have to develop anew at the beginning of each growing season. For the winter season a factor of 1.0 has been used, even though the leaves of the *Molinea* vegetation wither at the end of the growing season. The justification for nevertheless using a factor of 1.0 is that during the winter

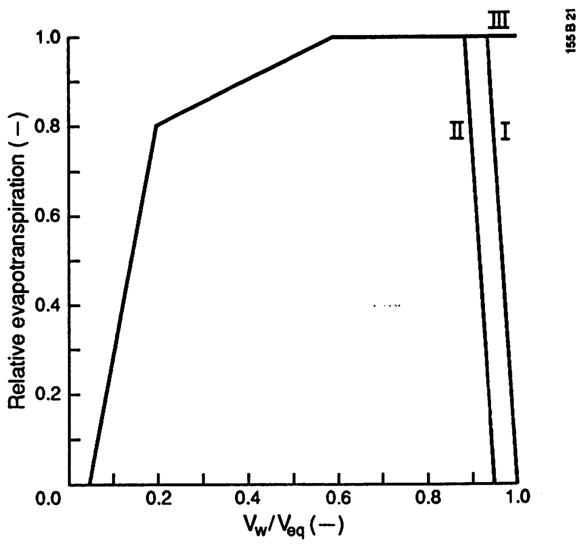

***Fig. 22** Relationships for calculation of the relative evapotranspiration from the soil moisture condition (I = standard curve, II = curve for plants sensitive to water-logging; III = curve for plants in nature areas) (from Querner & Van Bakel, 1989). The relative evapotranspiration is defined as the ratio between the actual and the potential evapotranspiration. The soil moisture condition is defined as the ratio between the simulated moisture contents of the rootzone and the moisture contents under fully saturated conditions (i.e. with the groundwater level at the soil surface). In this study relationship III has been used throughout, also for the agricultural lands.*

and early spring the bog reserve is wet and marshy and has therefore a high evaporation, which compensates for the nearly zero transpiration.

For computing the reduction of the evapotranspiration as a consequence of soil moisture depletion, the relationships given in Querner & Van Bakel (1989) have been used (Fig. 22), except for the 'wet' ends of the curves. Standard procedure is to use curve I or II of Fig. 22 for the agricultural technologies. The assumption is that under very wet conditions a lack of oxygen in the root zone disrupts the water uptake process. In a nature area the vegetation is assumed to be adapted to wet conditions. For this reason curve III is commonly used for nature areas, with no reduction at the wet end. In the present study, however, curve III has been used for all of the technologies. The reason for this being that the standard procedure overlooks the fact that under very wet conditions small pools will be formed that compensate for the reduction of the transpiration by the crops. By neglecting this effect and using curve I or II, as has been done by Poelman (1987), the following feedback loop was introduced in the model:
- very wet conditions lead to a reduction of the evapotranspiration;
- a reduction of the evapotranspiration leads to even wetter conditions;
- this leads to an even greater reduction of the evapotranspiration;
- and so on.

By introducing this form of 'positive' feedback the model can get trapped into simulating very wet conditions. Since under these conditions the evapotranspiration has been reduced to zero, the only way of restoring a normal situation is through the draining away of groundwater to surface water, because at the places where such situations tend to develop the presence of upward seepage is more likely than that of downward seepage. So dewatering by means of downward seepage is not possible. If the drainage resistance is very high, e.g. 1000 d, the return to a normal situation can take months, which is clearly a non-accurate simulation of the real situation.

2.4.2 Calibration and validation

Since the conclusion of the study reported by Poelman (1987) various new data from field investigations have become available:

- discharge measurements at various sites within the *Groote Peel* for the winter seasons of 1985/86, 1986/87 and 1988/89;
- groundwater and surface water levels for the period 1/4/1985-15/9/1989.

The data have been collected and made available by the National Forestry Service in collaboration with the Government Service for Land and Water Use. In the present study they have been used in a number of ways for calibration and validation purposes.

The first type of parameter that was investigated with the measured data was the drainage resistance of the 'tertiary' water courses within the *Groote Peel*. Poelman (1987) had used values in the range of 800-1800 d (see also Fig. 14). Such values imply a sluggish reaction to precipitation and lead to the simulation of tail-flows that continue throughout most of the summer period. Practical observations showed, however, that usually the outflow has become very low by the end of May, implying a not so sluggish type of system. For this reason the value of the drainage resistance was reduced to 250 d, for all the nodes within the *Groote Peel*. No further fine tuning of this resistance was deemed relevant because it was expected that such further calibration would of little consequence for the type of results that were to be obtained with the model.

The parameter that was considered to be of prime importance for the results was the vertical resistance of the top aquitard within the *Groote Peel*. Calibration of this resistance can be done through comparison of computed and measured discharges, because of the influence that the vertical resistance has on the outflow: the higher the resistance, the higher the outflow. That is because the higher the resistance, the lower the downward seepage; and since the precipitation excess has to leave the system somehow, a lower downward seepage leads to an increase of the discharge. (The evapotranspiration is hardly influenced due to the circumstance that the high moisture storage capacity of the peaty soil leads to near-potential values that are hardly influenced by changing groundwater conditions.) Thus if the computed discharge is higher than the measured one, the vertical resistance has apparently been set too high.

Crucial for the accuracy of the calibration is the quality of the used meteorological data, especially with respect to the precipitation – local variations can otherwise give rise to substantial errors. For the precipitation the data from the two weather stations *Someren* and *Heibloem* have been used, located respectively 5 km to the west of the *Groote Peel* and 5 km to the east. Based on an analysis with Thiessen-polygons, the weights for computing the weighted mean of the precipitation were respectively taken as 0.38 and 0.62. For the potential evapotranspiration the data of the stations at Eindhoven and Gemert have been used; both are within a 30 km range from the *Groote Peel*.

Table 2 Totals of meteorological data and measured discharges for the calibration and validation periods. The length of a period is given in the column L, the total of the precipitation in the column P, the total of the potential evapotranspiration of grass in the column E_{pot}, and the measured discharge in the column Q. The listed values of the measured discharge include the estimates of the 'diffuse' outflow that escaped actual measurement.

Period	L (d)	P (mm)	E_{pot} (mm)	Q (mm)	Q (1000 m^3)
05/7/1985 - 20/5/1986	319	663	388	180	2250
20/5/1986 - 28/4/1987	342	668	468	120	1500
1/11/1988 - 16/5/1989	197	348	184	96	1200

In Table 2 aggregated values of the available discharge measurement data are given, along with summated meteorological data for the relevant periods. For applying the calibration procedure the discharges measured for the winter season of 1988/89 were used, because these were considered to be the most reliable. As can be seen from Table 3, the simulated discharges for the sites 6, 7, and 8 (see Fig. 18 for their location) are on the high side. That is because in reality the weirs at these sites have been blocked towards the end of the measurement period (at a time different from the other weirs), which has not been simulated in the model. Thus the simulated discharge continues for these sites a month longer than actually was the case. At site 9 the simulated discharge is less than the measured one due to the fact that subregion 8 of the model is smaller than the corresponding drainage unit in the *Groote Peel.* Considering that the measured data have an estimated standard error of 20%, further fine tuning of simulated discharges was deemed irrelevant. The calibrated values of the vertical resistance of the top aquitard are shown in Fig. 23.

Table 3 Comparison between measured and simulated discharges (after adjustment of input parameters for the period 1988/89 (November 1 - May 16) for various measurement sites (see Fig. 18). Measured values obtained from Van Amerongen (1989).

Measurement site	Measured discharge (1000 m^3)	Simulated (1000 m^3)	Difference (%)
2	110.0	113.8	3
6	272.0	331.4	22
7	392.6	405.1	3
8	715.8	758.0	6
9	82.0	58.0	-29
10	55.8	50.0	-10
Total(*)	963.6	979.8	2

* The total discharge is smaller than the sum of the separate discharges due to the fact that some of the measurement sites are situated along the same outflow path

Apart from the measured discharges, a certain amount of outflow escaped measurement by flowing into the surrounding agricultural area at various points along the perimeter of the *Groote Peel.* This explains the discrepancy between the 'total' given in Table 3 and the value given for 1988/89 in Table 2: the 'diffuse' outflow was estimated at 200 000 m^3 for 1988/89, bringing the total discharge up to 1.2 million m^3.

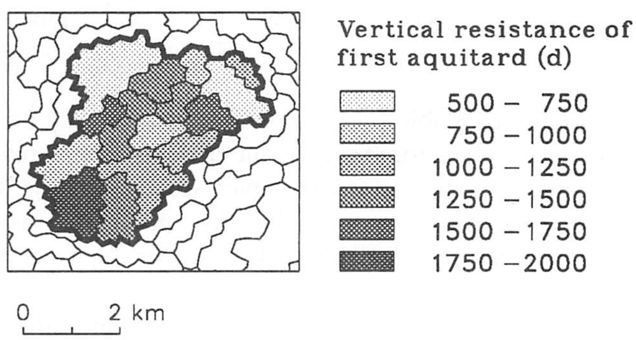

Fig. 23 Calibrated values of the vertical resistance of the top aquitard in the Groote Peel

The danger of calibrating the vertical flow resistance in the above described manner is that it perhaps is not the vertical resistance but rather the calculated evapotranspiration that is causing the water balance deviations. This makes independent validation of the model an absolute necessity. Such a validation was made possible by the availability of discharge data for the winter seasons of 1985/86 and 1986/87, though the data for these periods have a much lower reliability than the ones for the calibration period. (The lower reliability is due to the fact that prolonged periods of heavy frost occurred in both winters, and that not a proper record has been kept of iced up conditions with no throughflow.) In view of the lower reliability of the data only the totals of the measured outflows have been compared. For 1985/86 the measured total was 2.25 million m^3 and for 1986/87 1.50 million m^3; the simulated discharges are respectively 2.03 and 1.11 million m^3. The differences between measured and simulated discharges are acceptable if one considers that the estimated standard error of the discharges is more than 20% and that the discharge is a 'left-over term' of a water balance with an average annual precipitation of 9 million m^3 on the 'incoming' side. An error of for instance 5% in the measurement of the precipitation gives already an error of 0.45 million m^3 in the water balance. Since the measurement of precipitation did not take place in the bog reserve itself, but at two stations in the near vicinity, an error of 5% is very easily made. This observation puts the differences between simulated and measured discharges into the right perspective.

Further validation of the model using water level data was deemed problematical, especially for the measurement sites within the *Groote Peel.* Within the *Groote Peel* the problem is that at a close range of only a few meters very different conditions can prevail. This is reflected in the differences between the measured water-level trajectories shown in Fig. 24. The variability of conditions was found to be far greater than the difference between simulated water level trajectories for two different parameter values

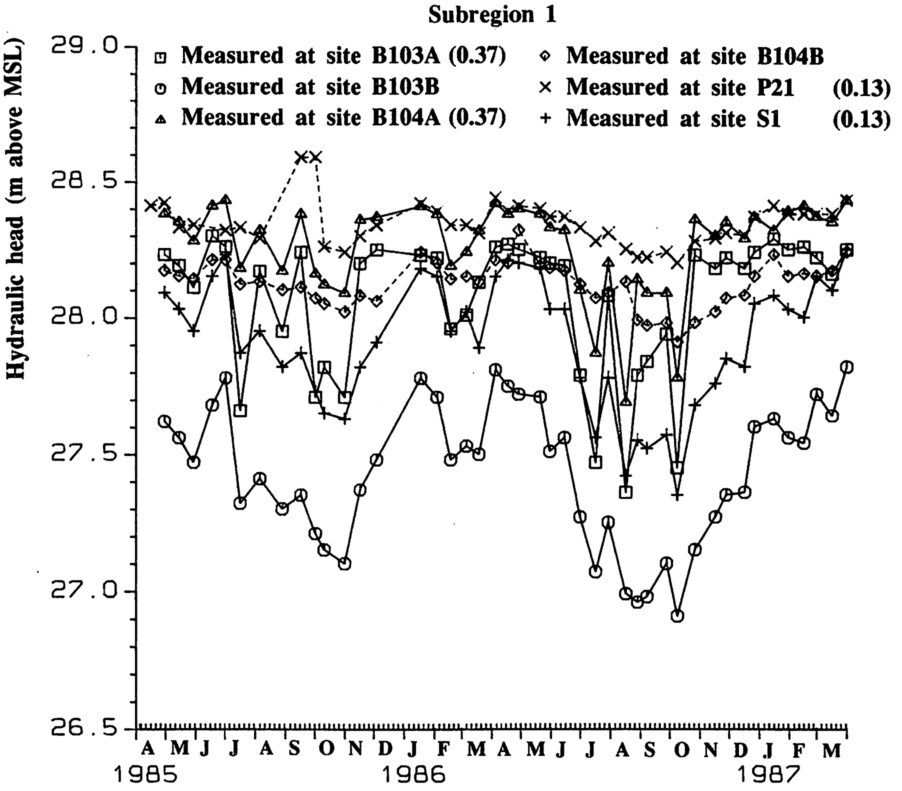

Fig. 24 Measured water level trajectories in subregion 1 of the Groote Peel. The locations of measurement sites are given in Joosten & Bakker (1987). The trajectories for e.g. site 104A and 104B pertain to measurements at the same site, but with the filter of the measurement tube at a different depth (A above B). The values given between brackets are factors used in computing the weighted mean water level shown in Fig. 25.

of for instance the vertical flow resistance. In order to use the measured trajectories for actual validation of the simulated ones, a great many measurement sites would be needed – the spatial variability of the actual conditions requires a great many sites in order to reduce the standard error in the estimate of the 'average' trajectory. Even though there may seem to be a large number of sites for which data are available – roughly one hundred – for the mentioned purpose it is not enough. Nevertheless, an impression of the match between model and reality can be obtained from the available data by computing average water level trajectories for the various subregions. An example of such a comparison is given in Fig. 25, showing the trajectory of the weighted mean of the measurements and the trajectory of the hybrid water level.

In computing the weighted mean of the measurements, care has been taken to ensure that the sum of the weights (given between brackets in Fig. 24) of the measurements of surface water levels is equal to the fraction of the area occupied by diffuse surface water as shown in Fig. 17. As can be seen from Fig. 25, the hybrid water level follows the long-term fluctuations of the weighted mean fairly well, but does not follow the short-term fluctuations. The erratic behavior of the measured trajectory can have various possible causes. One possibility is that part of the rainfall is not properly absorbed by the topsoil and reaches the groundwater through large pores. The complete set of available data for sites within the *Groote Peel* are given in Annex 2.

The use of measured water level trajectories in the area surrounding the *Groote Peel* was limited to getting an overall impression of the validity of the model. For each of the available sites the nearest node of the model was identified. Per node the measured and computed trajectories are given in Annex 2. An example of such a set of curves is given in Fig. 26. Apart from a vertical shift, the simulation of the water levels is reasonable, as can also be seen from the other sets of curves given in Annex 2. The vertical shift can be due to a variety of reasons, especially local variations of the ground level and the distance from surface water channels. As can be seen from careful examination of the location map given in Joosten en Bakker (1987), many of the measurement sites are located along roads or near farmhouses. This reduces the representativeness of the measured data and makes it hard to use them for validation of the simulated groundwater levels, because the latter represent average conditions within the 'influence area' of a node.

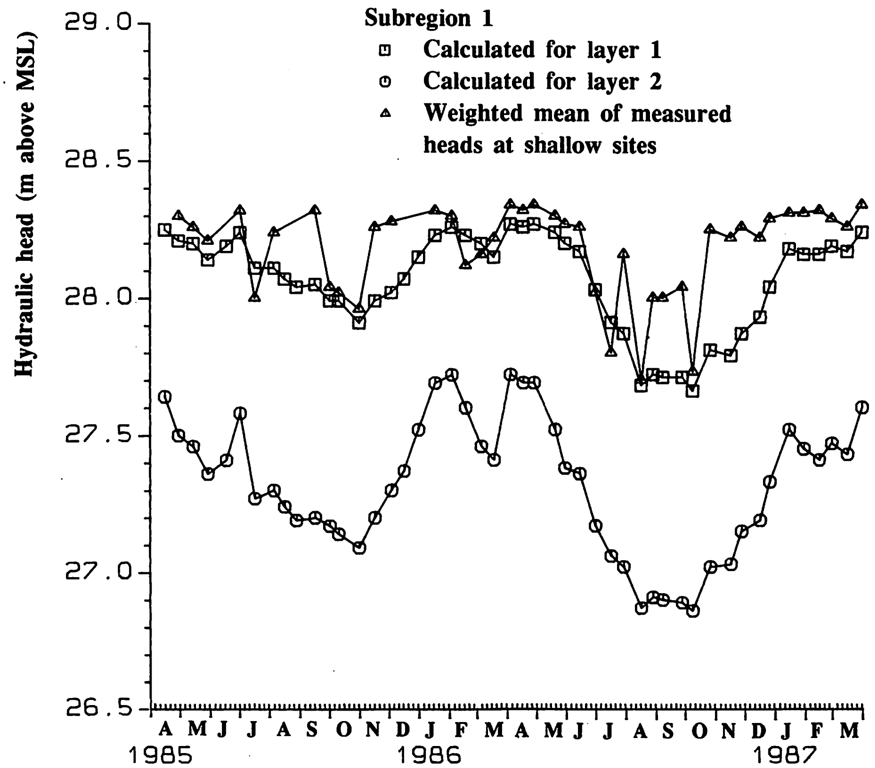

***Fig. 25** Comparison between the weighted mean of measured water level trajectories and the hybrid water-level, for subregion 1 of the Groote Peel. The weights used for computing the mean trajectory are given in Fig. 24.*

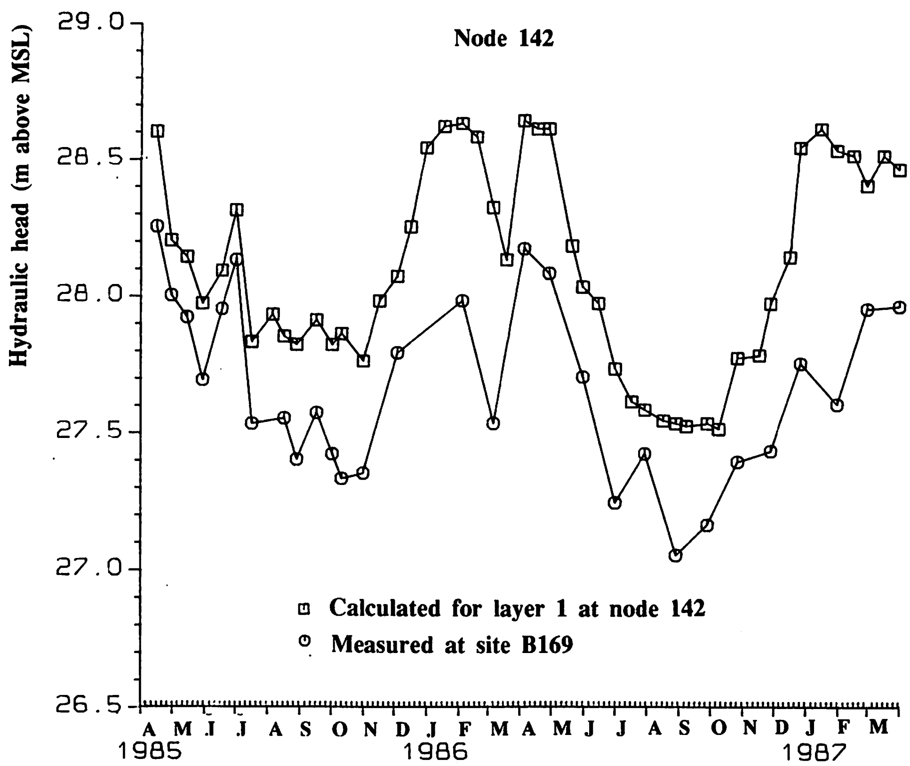

Fig. 26 Comparison between measured and simulated groundwater level trajectories at a location in the surrounding area

2.4.3 Results for the ten-year simulation period

The simulations performed with the model for diverse purposes have been done with meteorological data of the period 1971-1981. For the precipitation data have been used of the measurement station at *Someren*, which lies roughly 5 kilometers to the west of the *Groote Peel*. For the simulation period it was not necessary to use the average of the stations to the east and west of the nature area like with the calibration, because for the simulation it is only important that the used data are accurate in a statistical sense. (For this reason the data used by Poelman (1987) were in error – instead of using the local data, values were used of *De Bilt*, for which the annual precipitation excess during the used simulation period of 1974-76 was roughly 40 mm higher than in the study region.) The half-yearly totals for the simulation period are summarized in Table 4. The over-the-years average of the data is slightly drier than the climatological value; this is due to the extremely dry year of 1976. (The climatological mean of the precipitation at *Someren* is 730 mm).

Table 4 Half-yearly totals of the meteorological data for the simulation period 1971-81, obtained from the weather stations Someren (precipitation) and Eindhoven/Gemert (potential evapotranspiration of grass). The precipitation deficit has been calculated as [potential evapotranspiration - precipitation]. The aridity of the summer seasons is given in terms of the exceedance probability of the precipitation deficit (Werkgroep Herziening Cultuuurtechnisch Vademecum, 1988.)

Period ending on	Precipitation (mm)	Potential evapotranspiration (mm)	Precipitation deficit (mm)	Aridity of summer (%)
1-10-1971	348	462	114	35
1-04-1972	210	117	-93	-
1-10-1972	445	402	-43	90
1-04-1973	230	105	-125	-
1-10-1973	324	468	144	20
1-04-1974	406	104	-302	-
1-10-1974	382	450	68	60
1-04-1975	525	100	-425	-
1-10-1975	295	473	178	15
1-04-1976	254	104	-150	-
1-10-1976	210	533	323	<3
1-04-1977	360	107	-253	-
1-10-1977	424	402	-22	90
1-04-1978	428	102	-326-	
1-10-1978	330	404	74	60
1-04-1979	386	99	-287	-
1-10-1979	298	406	108	40
1-04-1980	379	100	-279	-
1-10-1980	422	442	20	80
1-04-1981	412	100	-312	-
mean value	707	548	-159	

In Fig. 27a/b an example is given of the simulated downward/upward seepage for the current water management situation in the *Groote Peel* and in the surrounding area. For comparison, the spatial pattern of hydraulic head differences as indicated by Wit (1986) is given in Fig. 28. In the *Groote Peel* there is only downward seepage; no upward seepage occurs, at least not on the scale that is considered here – in small patches of relatively low-lying land some upward seepage may occur. In the surrounding area the zones of upward seepage are to be found in the 'valleys' of the original riverlets that have now been normalized and have become part of the system of secondary water courses: to the north of the *Groote Peel* the *Voordeldonkse Broekloop* and to the west the *Aa*. There are two reasons for the high downward seepage along the northeastern perimeter of the study region. First, the presence of the *Peelrand* fault (cf. Fig. 13) virtually shuts out the inflow of groundwater from the east, which leads to relatively low pressure heads in the subsoil, which in turn induces high values of downward seepage. Second, the import of 0.1 l.s^{-1}.ha^{-1} of surface water from an external source (a canal running parallel to the border of the study region) makes possible a downward seepage that far exceeds the precipitation excess.

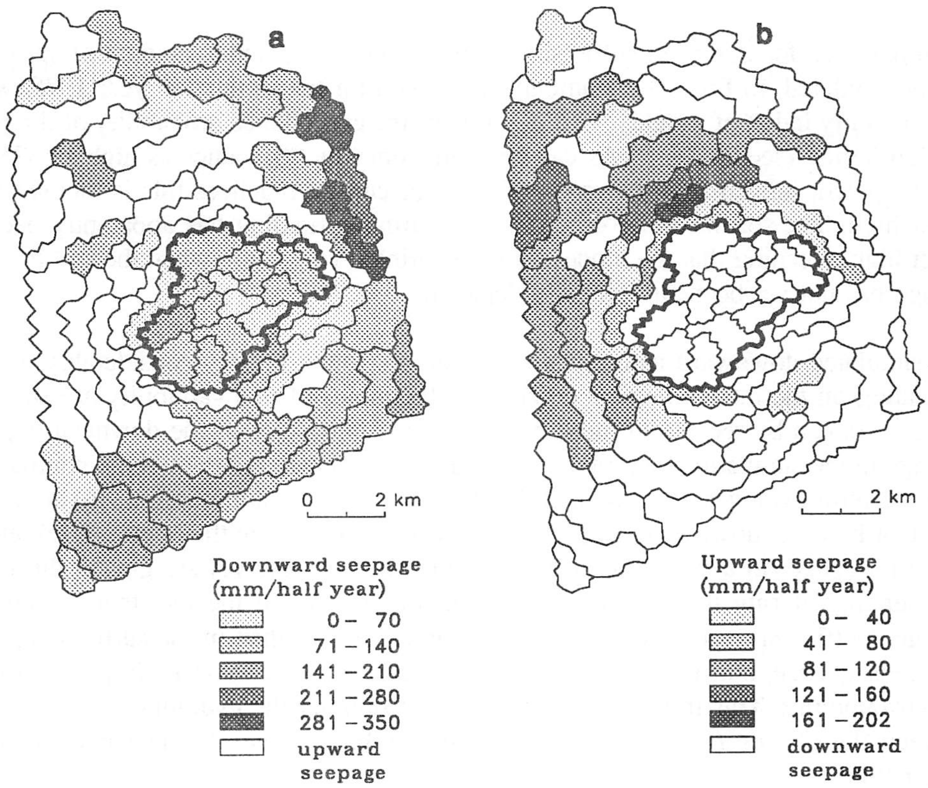

Fig. 27 Subregional values of the downward seepage (a) and the upward seepage (b), as computed for the summer of the simulation year 1971

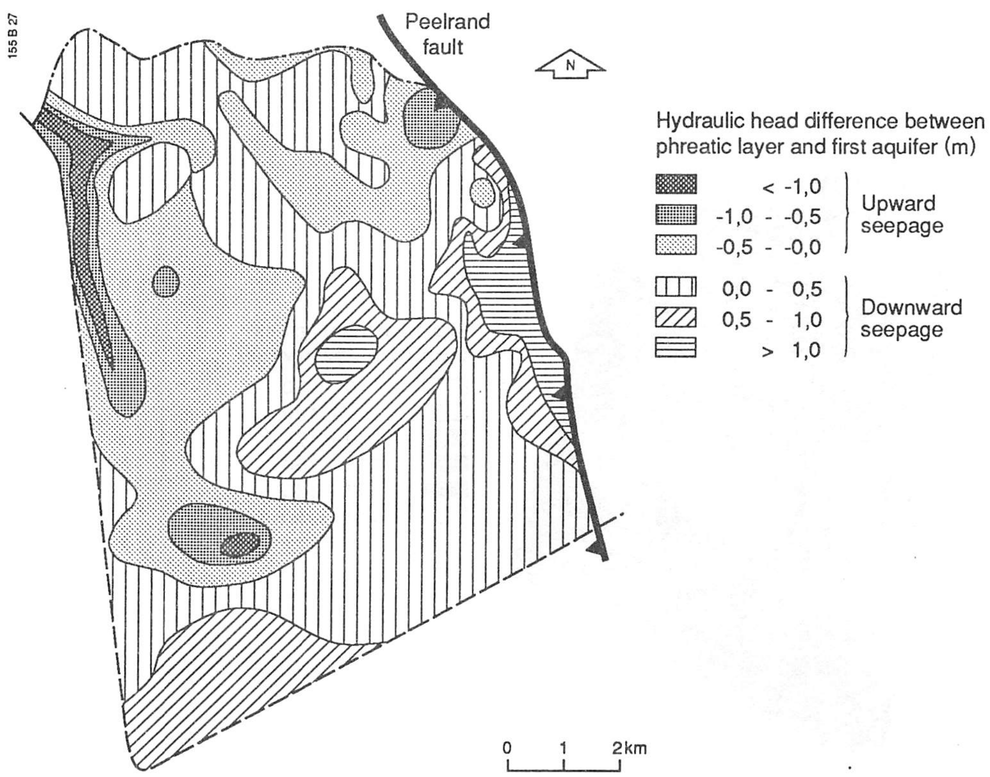

Fig. 28 Spatial pattern of the hydraulic head difference between the phreatic layer and the first aquifer, in August 1982 (Wit, 1986)

Of importance for interpreting the simulation results is the actual amount of sprinkling that is simulated. In Fig. 29 the amounts are given for the simulation year 1975, which has an aridity index of roughly 15% in terms of the exceedance probability of the precipitation deficit (see Table 4). As can be seen from Fig. 29, values as high as 325 mm are computed; judged from the point of view of current practices this is thought to be rather high. The soil moisture criterion for starting sprinkling has apparently been set rather high, meaning that the model starts to sprinkle very soon, when the soil moisture storage has not yet been substantially depleted.

The simulated downward and upward seepage are found to vary considerably in time, depending on the meteorological conditions. Examples of this variability are shown in Fig. 30. As can be seen from these bar charts, the intensities of the downward/upward seepage in the simulation year of 1971 (used in Fig. 27) are relatively high compared to the long-term averages as computed for the ten-year simulation period. It can also be seen that both the downward seepage (from a subregion inside the bog reserve) and the upward seepage (in a subregion to the north of the bog reserve) are greater during the summer than during the winter. The reason for this lies in the fact that the phreatic storage coefficient inside the *Groote Peel* is much higher than in the surrounding area; as a consequence, during summer the water level in the *Groote Peel* drops less than in the surroundings. This in turn means that during summer the hydraulic head difference between the *Groote Peel* and its surroundings is bigger than during winter, meaning higher fluxes.

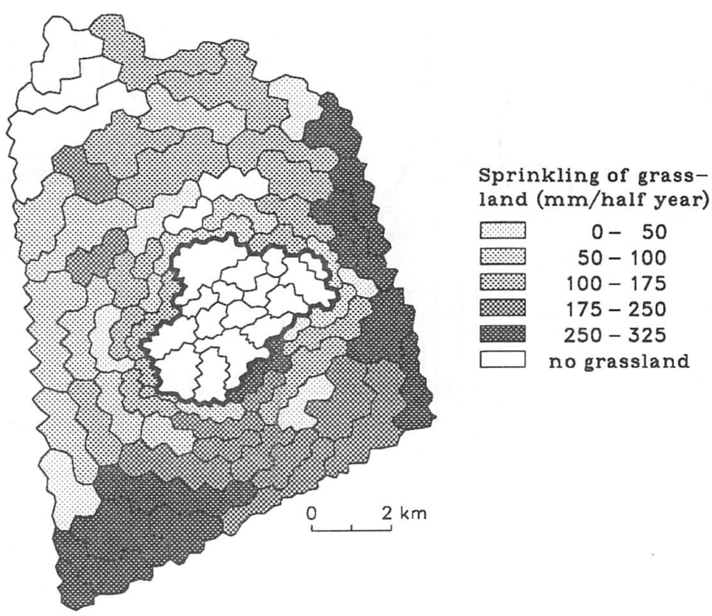

Fig. 29 Subregional amounts of sprinkling computed for the simulation year of 1975

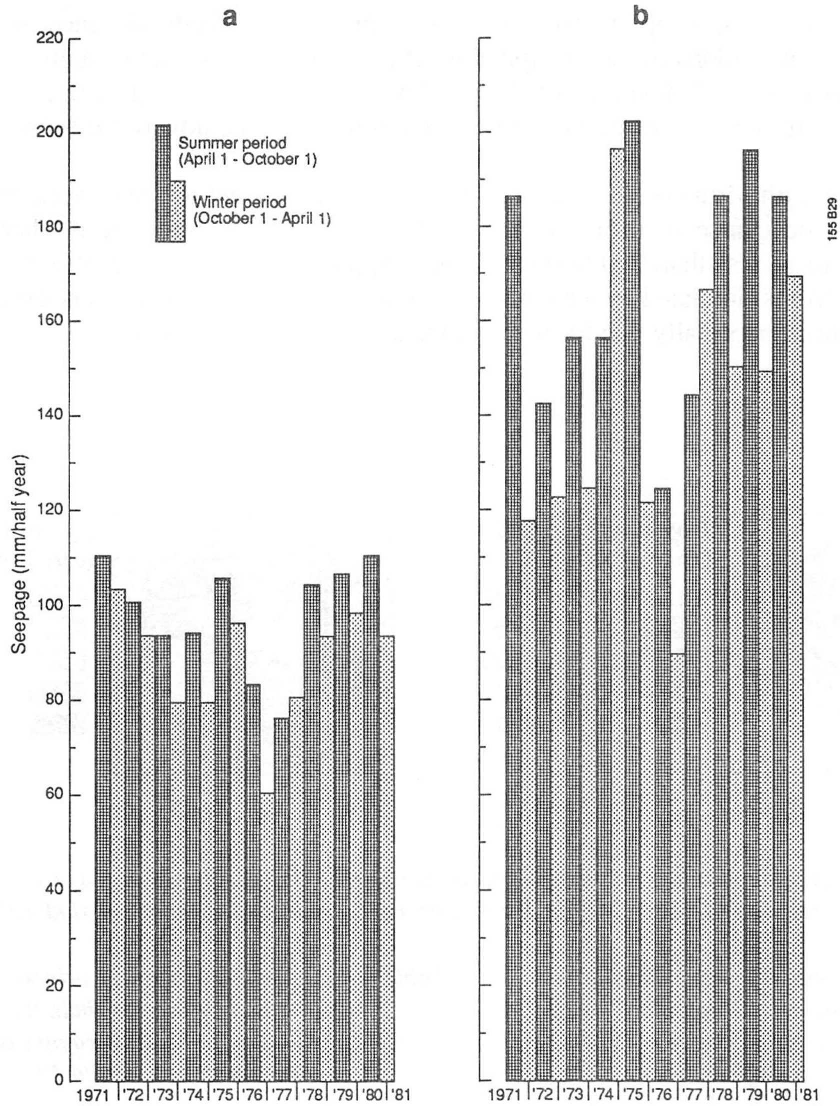

***Fig. 30** Temporal variation of simulated half-yearly downward seepage in subregion 1 (a) and upward seepage in subregion 30 (b). (For the location of the subregions see Fig. 7)*

In the following, some more results will be given for the *Groote Peel* itself. In Fig. 31 this concerns the long-term averages of the downward seepage and the hybrid water-levels, as computed using the 10 year simulation period 1971-81. In Table 5 the computed discharges are given and in Table 6 the long-term averages of the main terms of the water balance. As can be seen from Table 5 the occurrence of a year for which the model computes a zero discharge is by no means exceptional. This can easily be explained from the long-term averages given in Table 6. The discharge is hydrologically speaking a left-over term: it is the amount of the precipitation that remains after the evapotranspiration and the downward seepage have been subtracted. (Also the storage depletion in the preceding period has first to be replenished for outflow to occur.) A higher precipitation is in general coupled to a lower value of the potential evapotranspiration (see also Table 4). For the actual evapotranspiration this is also the case, because in the *Groote Peel* the reduction of the evapotranspiration due to soil moisture stress is not very strong. (The peaty soil has an very large storage of available soil moisture.) Thus the evapotranspiration hardly provides a 'feedback' mechanism for dampening fluctuations of the precipitation. It certainly is not strong enough to prevent that a relatively small deviation of the precipitation from the average value leads to a large fluctuation of the discharge, either in the upward or the downward sense.

That years with virtually no discharge from the *Groote Peel* are not an exception is shown by the course of events in the year 1988/89; in that year the discharge was estimated to be less than 200 000 m³ (Jonkman, pers. comm.). A complete absence of discharge like is simulated by the model will in reality only occur under very exceptional circumstances, especially due to the heterogeneity of the nature area.

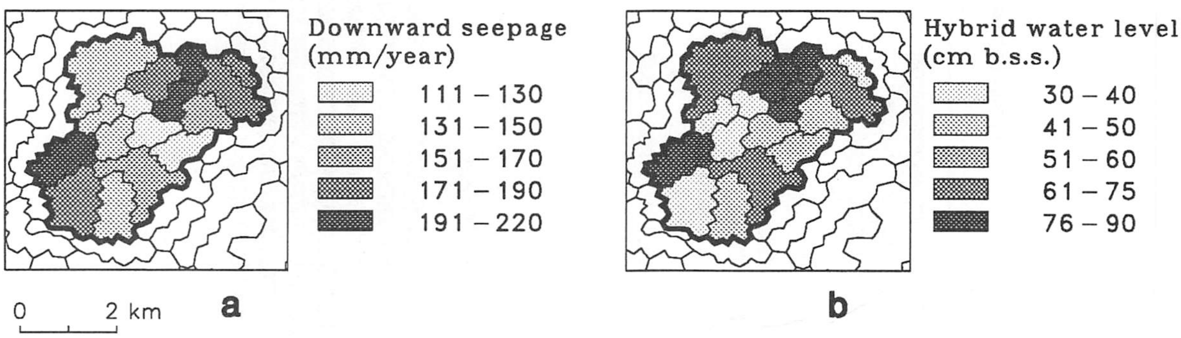

Fig. 31 Subregional values of the long-term average of the downward seepage (a) and the hybrid water-level (b) within the Groote Peel, as simulated for the period 1971-81

Table 5 Simulated total discharges from the Groote Peel for the simulation period 1971-81. (Hydrological year taken from April 1 - March 31)

Period	Discharge (mm.yr⁻¹)
1971-72	14
1972-73	4
1973-74	15
1974-75	148
1975-76	24
1976-77	0
1977-78	<1
1978-79	59
1980-80	67
1980-81	114
average	45

Table 6 Long-term averages of principal terms of the water balance of the Groote Peel, as computed for the simulation period 1971-1981

Term	Long-term average average (mm.yr⁻¹)
Precipitation	707
Evapotranspiration	501
Downward seepage	161
Discharge	45

2.5 Critical assessment of modelling

Like any modelling exercise the present study has its weaknesses that can be subject to criticism. Broadly speaking these deficiencies can be divided into those stemming from:
- discrepancies between the physical reality and the concepts that the model is based on;
- deficiencies in the implementation of the model.

As put forward in Section 2.3 the model SIMGRO was originally developed with agricultural areas in mind. Various adaptions had to be made in order to apply it to the type of situation in a bog reserve like the *Groote Peel.* A disadvantage of the introduced 'hybrid water level' concept is that it is a macroscopic approach. It therefore only allows an indirect prediction of effects on actual water levels in the *Groote Peel.* Such an indirect prediction could perhaps be attempted by means of the diagrams in Annex 2. Since such a translation would (at the utmost) only be possible for the gauged locations it remains very difficult to get an overall idea of the prevailing hydrological conditions and the predicted changes in the bog reserve. In Section 3.1 an approach will be put forward for evaluating the ecological consequences of hydrological changes in a manner that is conceptually compatible with the followed way of hydrological modelling.

Various points of criticism are possible with respect to the way in which SIMGRO has been implemented. As can be seen from Fig. 7 the distance between the western border of the *Groote Peel* and the western border of the study region is only 3 km. The same applies to the situation with respect to the southern border. A distance of 3 km is rather small, as can be concluded from the geohydrological parameters displayed in Fig. 10 and Fig. 11. For the top aquitard and the first aquifer the so-called leakage factor can roughly be calculated as (using rough averages of the geohydrological parameters):

$$\lambda = \sqrt{(KDc)} \approx \sqrt{(3000 \cdot 750)} = 1500\ m.$$

The leakage factor is a measure for the distance at which hydrological changes can be felt to a substantial degree. At roughly twice the distance of the leakage factor the influence will have become nearly zero. Seen in this way, the above mentioned distances of 3 km between the borders of the nature area and the study region seem to be just sufficient. However, since there are also interactions via the deeper aquifer, it would have been preferable to have located the borders 2 km further away from the nature area.

A further weak point of the modelling is the limited validation of the model in the surrounding agricultural area. Though there is a quite decent corroboration between simulated and measured water level trajectories (see Annex 2), further checks could have been made on the water balances. This is especially the case with respect to the supply of surface water to the northern half of the study region. No checks have been made with respect to amounts of infiltration that the model simulates and the amounts actually observed in practice. Such data could have been used as a check of the drainage/infiltration resistances of the secondary water courses. These resistances have been obtained from a calibration procedure using a steady state groundwater model (Poelman, 1987). The used procedure did not involve the use of advanced mathematical 'inverse modelling' algorithms. Furthermore, the assumption has been made that in the current situation the infiltration resistances are 10% higher than the calibrated drainage resistances. That is a very rough approach.

The variation in the quality of the available data and the complexity of a regional model make it usually impossible to obtain a quantified estimate of the reliability of model outputs. A thorough sensitivity analysis can, however, give a good impression of this aspect – if combined with knowledge about uncertainties in the parameters themselves – and should not be omitted like was the case in the present study. Nevertheless, a model is nearly always of value as a 'thinking partner' that contains accumulated 'state of the art' knowledge about environmental processes in a region.

3 EFFECTS ON NATURE AND AGRICULTURE

3.1 Effects on nature

The goals that have been formulated for the *Groote Peel* are directed towards conserving and if possible enhancing the natural values that are currently present. The central theme is the regeneration of the original bog-forming vegetation, dominated by the peat mosses of the *Sphagnum* genus, of which there is less than 1 ha left. The presence of living bog vegetation is one of the floristic values of the area. Furthermore, the *Groote Peel* is an important sanctuary for birds. Thus also avifaunistic values are relevant.

3.1.1 Floristic values

Apart from remnants of the living bog vegetation, the *Groote Peel* contains a number of other rare groundwater-depending vegetation types that cover 170 ha of the 1340 ha. The distribution of this 170 ha over the various species is given in Table 7. (This table could be expanded to include less valuable types.) Of the types in the *Groote Peel* the bog vegetation is the most demanding in terms of the hydrologic conditions, with respect to both water quantity and quality. This vegetation only thrives in an ombrotrophic environment, meaning that no water other than water of rainfall quality should reach it. This entails that no upward seepage should occur and that there must no direct contact with surface water of a 'foreign' quality. The water quantity condition is that the water level should roughly remain within 20 cm of the 'ground' level. Various measures can influence the fulfilment of this condition:

- recycling of surface water discharge that has been stored during the preceding winter(s), if the water has not become polluted;
- impediment of the dewatering that takes place through drainage to surface water;
- increase of the local storage capacity (porosity and the presence of open water);
- reduction of the downward seepage.

Through recycling of surface water discharge it is in principle possible to create a continuous area where the water-level condition of *Sphagnum* moss is fulfilled. From a hydrological viewpoint the only question is what the size of such an area can be.

Measures to impede drainage to surface water and measures to increase the local storage capacity have a positive effect on the fulfilment of the water level condition. However, if the downward seepage is not at the same time maintained within a certain critical limit, the hydrologic condition will not be fulfilled. Inversely, if the downward seepage has been reduced to nearly zero, this does not necessarily mean that the hydrologic condition will be fulfilled. Since the downward seepage is influenced by measures in the area surrounding the *Groote Peel* it is of special interest here. For quantifying the influence of external circumstances it has been used as the key intermediate variable.

With respect to the downward seepage it is known from practical observations in other bog reserves that for the climatological conditions in the *Groote Peel*, the long-term average of the downward seepage should not be more than roughly 30-50 $mm.yr^{-1}$ (Joosten,

***Table 7** Occurrence of rare vegetation types in the Groote Peel and their demands on the maximum winter water level and the minimum summer water level, in cm below soil surface (a negative value means a level above soil surface)*

Type of vegetation	Area (ha)	Minimum summer water level (cm b.s.s.)	Maximum winter water level (cm b.s.s.)
Living bog	< 1	20	0
Bog-related vegetations	13	40	0
Cotton grass swamps	7	80	-40
Oligotrophic willow shrublands	13	60	-20
Mesotrophic willow shrublands	10	60	-20
Moist birch forests	3	60	0
Species-rich moist heathlands	40	80	20
Other moist heathlands	30	80	20
Species-rich moist grasslands	35	80	20
Bog heathlands	3	100	20
Bog heath birch forests	15	100	40
Total	170	-	-

pers. comm.). As can be seen from Fig. 31 this is much less than the computed long-term average for the various subregions of the *Groote Peel,* which are shown to vary between 110 and 220 $mm.yr^{-1}$. This could lead one to believe that in the current situation the bog-forming vegetation does not stand any chance at all and that there is also no impact of external measures on the ecological value of the area. However, this way of reasoning overlooks two things:

- within the nature area there is a great spatial variability of the thickness of the humified peat; since this humified peat has a high flow resistance, the downward seepage is locally very low at the places where the peat is relatively thick;
- apart from some patches with living bog vegetation, the *Groote Peel* contains other species that are hydrologically less demanding, but nonetheless of ecological importance.

The spatial variability of the thickness of the humified peat is illustrated by the fact that though the average thickness is not more than 30 cm, the local thickness can vary between zero and a few meters (Joosten and Bakker, 1987). These two extremes correspond to two cases in which the potential success of the bog-forming vegetation is not influenced by external conditions:

- at the places where there is no humified peat at all the vertical flow resistance is so small and the downward seepage so high that re-establishing the bog-forming vegetation can hardly be considered possible;
- at the places where there is a very thick layer of humified peat the local hydrology is virtually isolated from the regional system, thus leading to a negligible influence of external measures.

It is argued that between these two extremes, there must a transition zone in which there is a sensitivity to external measures. In this zone the downward seepage is exactly equal to the critical value and the peat has a corresponding critical thickness. The critical thickness will vary as a consequence of changes in the hydraulic head in the underlying aquifer – a decrease of the hydraulic head will cause an increase of the average downward seepage; this in turn will lead to an increase of the critical thickness to compensate for the increased downward force on the water. The bigger the critical thickness, the smaller the percentage of the area where the downward seepage is equal to or less than the critical value.

The line of argument given above has been developed into a quantitative method for translating hydrological changes to ecological ones. Since, however, a series of assumptions had to be made, the method remains a qualitative one in many respects. To start with, the assumption was made that the vertical resistance of the top aquitard is only partly due to the presence of peat; the remainder was assumed to be caused by the presence of loamy material in the shallow subsoil. For a certain peat thickness class the resistance can then be calculated as:

$$C_p = C_b + C_s d_p \tag{3.1}$$

where

- C_p - total vertical flow resistance of a peat thickness class (d)
- C_b - basic vertical flow resistance (d)
- C_s - specific vertical flow resistance (d/m)
- d_p - average peat thickness of class p (m)

The second assumption is that within a subregion of the *Groote Peel* there is a uniform drop of the hydraulic head between the phreatic layer and the first aquifer, and that it can be computed in an approximate fashion with:

$$\Delta h = W_a C_a \tag{3.2}$$

where

- Δh - drop of hydraulic head between the phreatic layer and the first aquifer (m)
- W_a - long-term average of the downward seepage (m/d)
- C_a - average vertical flow resistance of a subregion (d)

For each peat thickness class the long-term average of the downward seepage, W_p, can be calculated as:

$$W_p = \Delta h / C_p = \Delta h / (C_b + C_s d_p) \tag{3.3}$$

The sum of the downward seepages (of the separate classes) multiplied by their respective areal fractions, f_p, must equal the long term subregional average:

$$W_a = \Sigma f_p W_p \tag{3.4}$$

If a value has been assumed for the basic resistance C_b, then the only unknown in the above equations is the specific resistance C_s. However, a solution can not be obtained under all circumstances. Take for instance the case of a C_b-value that is 0.5 of the average resistance C_a and a subregion where the peat thickness class with a zero peat thickness has an areal fraction that is bigger than 0.5. In such a case the calculated

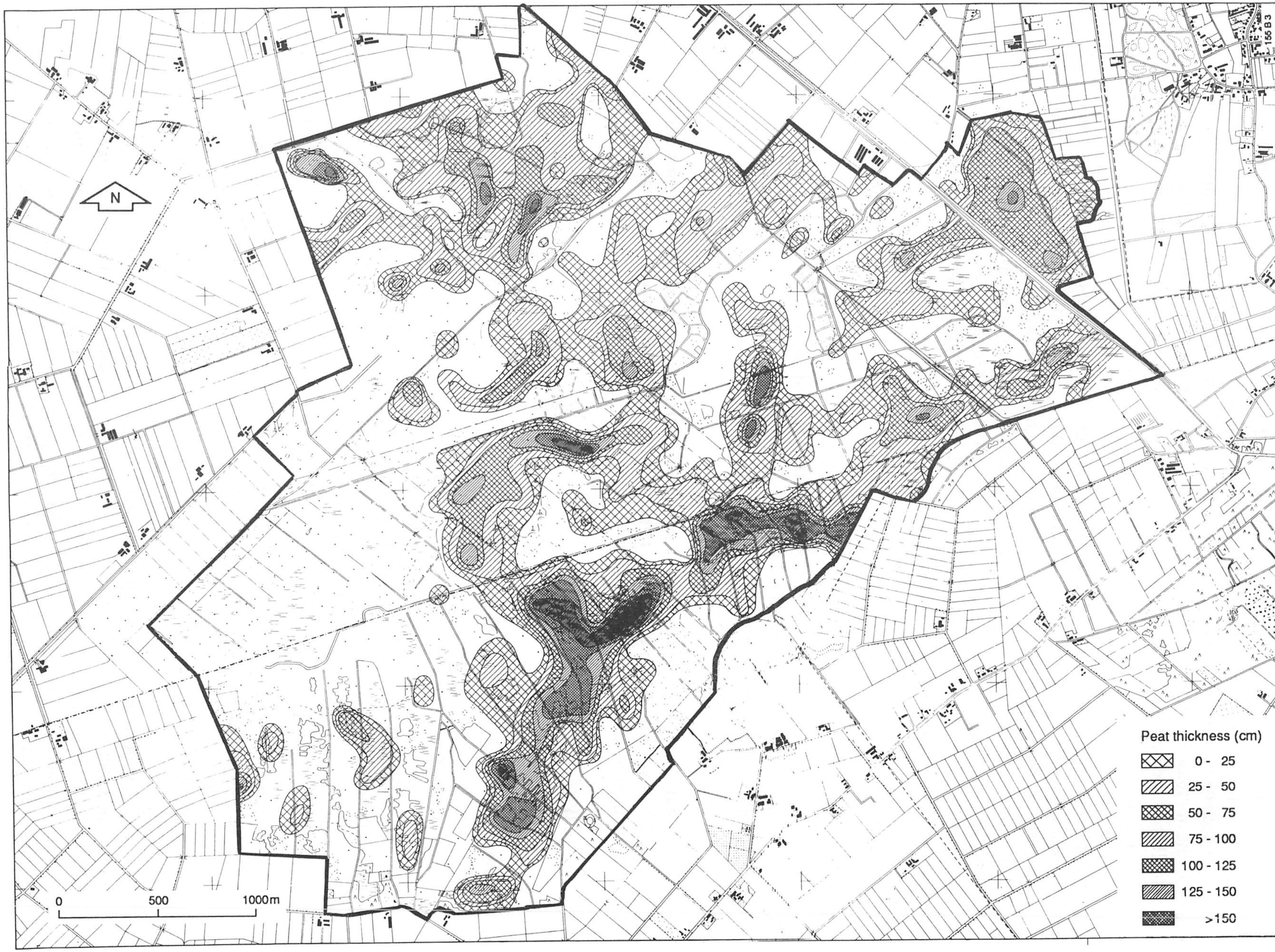

Fig. 32 Thickness map of remaining minerotrophic peat (from Joosten and Bakker, 1987)

downward seepage from this fraction accounts for more than the total of the average seepage W_a (see Eq. 3.4), irrespective of the value assigned to C_s. Such a situation does not make sense, however. In the course of making some preliminary computational experiments with a C_b-value of 0.5, it turned out that the above kind of failure of the method occurred rather frequently; so instead a value of 0.67 was chosen for practical reasons. It should be realized, however, that this value is probably rather high, thus under-estimating the role of the peat in determining the local value of the vertical flow resistance.

Before actually applying the approach, some further reasoning was followed. This concerns in the first place the fact that two different types of peat-thickness maps were available, one for the so-called minerotrophic peat and one for the strongly humified *Sphagnum* peat. In addition to these maps information is available on the presence of loam lenses in the shallow subsoil (Joosten and Bakker, 1987). By way of example the thickness map for minerotrophic peat is given in Fig. 32. Since the method is anyhow a very rough one, it was decided to make no attempt to combine the two maps in the form of an overlay. From knowledge of the field situation it was concluded that in subregions 1, 2, 3, 4, 8 and 12 (Fig. 7) the map for strongly humified *Sphagnum* peat gives the best indication for the vertical flow resistance of the peat and for the remaining subregions the map for minerotrophic peat. Furthermore, it was concluded from the map giving the presence of loam lenses that there was a quite strong correlation between the presence of loam and the presence of minerotrophic peat. For this reason the value of the

***Table 8** Fractional areas of the peat thickness classes in the 16 subregions of the Groote Peel and the calculated values of the specific resistance C_s. These values should be seen as results of the followed procedure. In terms of the physical characteristics only the order of magnitude has any meaning. The column for the average vertical flow resistance C_a contains the values that have been calibrated according to the procedure given in Section 2.4.2.*

Sub-region	Peat thickness class (in cm) 0	0-25	25-50	50-75	75-100	100-125	125-150	C_s (d/cm)	C_a (d)
1	17.0	41.1	19.9	17.0	3.5	0.8	0.7	31.6	1892
2	10.4	41.2	27.8	13.4	7.2	0.0	0.0	19.2	1352
3	36.2	34.9	12.8	15.4	0.7	0.0	0.0	35.6	1121
4	10.7	37.3	42.7	9.3	0.0	0.0	0.0	16.2	1070
5	100.0	0.0	0.0	0.0	0.0	0.0	0.0	-	943
6	32.5	24.9	21.0	13.4	5.4	1.5	1.3	23.0	1356
7	30.5	38.2	22.9	3.8	2.3	2.3	0.0	25.0	964
8	38.7	43.8	6.4	6.4	3.9	0.8	0.0	72.2	1667
9	50.2	23.3	19.7	5.4	1.4	0.0	0.0	40.0	700
10	61.8	18.2	12.7	1.9	1.8	3.6	0.0	-	1367
11	53.7	26.8	17.1	2.4	0.0	0.0	0.0	83.7	934
12	11.1	16.7	66.7	5.5	0.0	0.0	0.0	14.6	1189
13	75.0	10.0	10.0	5.0	0.0	0.0	0.0	-	1720
14	44.4	23.4	21.0	9.3	1.9	0.0	0.0	54.0	1497
15	38.5	32.1	28.8	0.0	0.6	0.0	0.0	49.0	1320
16	42.4	20.7	20.7	10.3	4.1	1.5	0.3	18.2	670

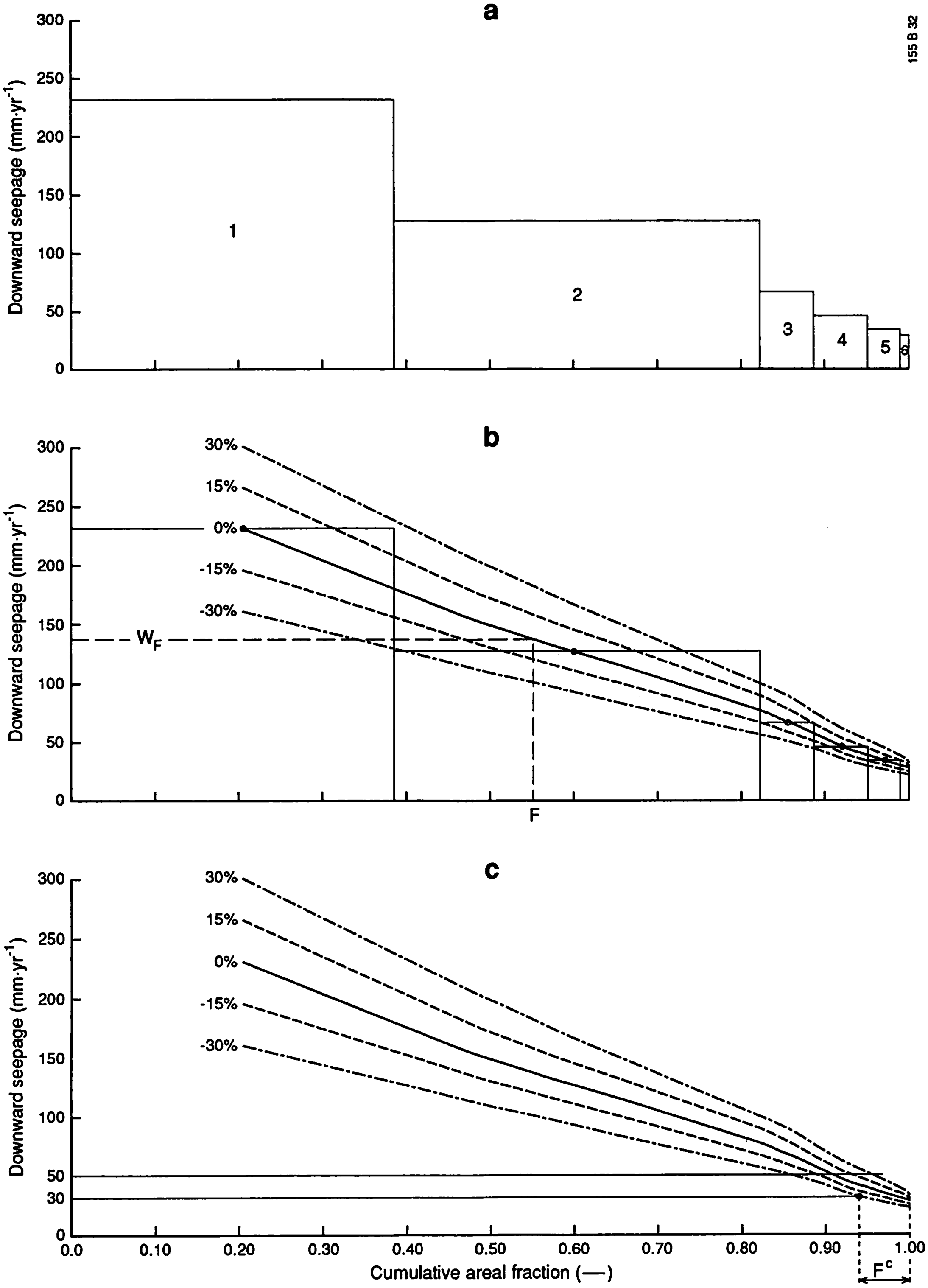

Fig. 33 ***Stages in the procedure for determining the change of area where the downward seepage is less than a certain critical value.***

a. ***Representation of the downward seepage per peat thickness class (1-6) in the form of block diagram with on the horizontal axis the cumulative areal fraction.***

b. ***Approximation of the continuous curve for the seepage as a function of the cumulative fraction and the curves for the situations with increased (+15% and +30%) and decreased seepage (-15% and -30%). For a given fraction F the downward seepage is equal to or greater than W_F.***

c. ***Reading off the complementary fraction F^c for two different assumed levels of the critical downward seepage (30 and 50 mm.yr^{-1}).***

peat thickness used in Eqs. 3.1 and 3.3 was doubled for the minerotrophic peat thickness classes involving a thickness of more than 50 cm.

In Table 8 a list is given of the fractions that the various peat thickness classes occupy in the 16 subregions of the Groote Peel along with the values of the average vertical flow resistance C_a and the calculated specific resistance C_s. As can be seen from Table 8, the percentages of the thicker classes are so small that it would require a very fine grid in order te represent them accurately by means of finite elements, thus justifying the here followed procedure which does not make use of the exact location of the thick peat occurrences. The downward seepage (calculated with Eq. 3.3) of each areal fraction given in Table 8 can be graphically represented in the form of a block diagram, with on the horizontal axis the cumulative fraction of the peat classes. In Fig. 33a this has been done for subregion 8. The total area of the blocks is equal to the average downward seepage (cf. Eq. 3.4). The next step in the procedure is to draw a curved line through the centers of the blocks, thus approximating the continuous form of the relation between the cumulative areal fraction and the downward seepage (Fig. 33b). Each point on the curve indicates that within a fraction F of the subregion the downward seepage is equal to or greater than W_f. Apart the curve for the current situation, also the curves for various changes of the average seepage are drawn in (+15%, +30%, -15%, -30%). It is then possible to determine the intersections with an assumed critical level of the downward seepage. In Fig. 33c this has been done for levels of 30 and 50 mm.yr^{-1}. By reading off the complementary fraction (F^c) with respect to the cumulative fraction of 1.0, it is then possible to determine which fraction of the area has a downward seepage that is *less* than the assumed critical value.

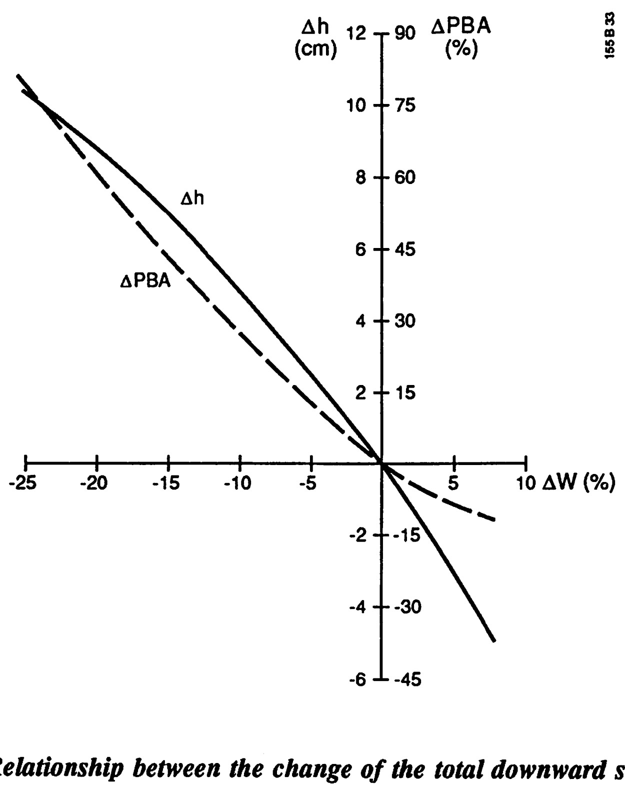

Fig. 34 Relationship between the change of the total downward seepage ΔW and:
- the change of the 'potential bog area' (ΔPBA)
- the change of the average water level (Δh)

The above described procedure has been applied to all of the 16 subregions. If the results for the separate subregions are added up it turns out that if a critical downward seepage of 30 $mm.yr^{-1}$ is assumed, the calculated area with less than critical seepage is about 38 ha (3% of the *Groote Peel*); for a critical downward seepage of 50 $mm.yr^{-1}$ this area is about 88 ha (7% of the *Groote Peel*). However, these areas only give an indication of the area that complies with a certain seepage criterion. Apart from downward seepage there is also the influence of the situation with respect to drainage to surface water and also the influence of the local storage capacity. Therefore a certain reduction of the mentioned areas should be applied. This problem is circumvented by presenting all results as percentage changes with respect to the current situation. It then appears that the relative change is roughly the same for both the assumed values of the critical downward seepage (30 and 50 $mm.yr^{-1}$).

In the following, the term 'potential bog area' will be used to indicate the area where, given the prevailing climatological conditions, the seepage criterion for the growth of bog-forming vegetation is fulfilled. For a number of scenarios (Van Walsum, 1990) the computed change of the 'potential bog area' has been plotted against the change of the total downward seepage. Through the points a regression curve has been drawn that is shown in Fig. 34. (The actual data are given in Table 10 of Van Walsum (1990)).

Less downward seepage, resulting in more stable water levels is also favorable for the types of vegetation that are less demanding than the bog-forming vegetation (see Table 7). So a reduction of downward seepage will lead to a general upgrading of the ecological value of the area. For this reason the 'potential bog area' is used as an overall ecological indicator for the *Groote Peel.*

3.1.2 Avifaunistic values

A great many bird species are permanently based in the *Groote Peel* or use it as a stepping stone on their migration route. The bog reserve itself, however, functions mainly as a sanctuary – it can only supply part of the required forage. This is especially so during the breeding season, which is the time when the demand is high. For this reason the surrounding agricultural area plays an important role as a foraging ground during the spring. In this respect the wet grasslands are the most important – the higher the groundwater levels the softer the soil and the easier it is for the birds to extract soil fauna from it. Another aspect of the high groundwater levels is that in order to have enough oxygen the soil fauna is forced to abide just below the soil surface, thus forming an easy prey for the birds. Based on recent information the most important foraging grounds have been mapped as shown in Fig. 35 (obtained from P. van Tilburg, Asten). Comparison with Fig. 27b shows that there is a good correlation with the presence of upward seepage, as could be expected.

As a consequence of meteorological variations, the groundwater levels vary from year to year; thus also the conditions in the foraging grounds are variable. The question is which type of year is most important for the (local) survival of a certain species. The consulted ecologists tend to attach more importance to the wet years than to the dry ones; the given reason being that conditions in the dry years are anyhow so adverse that breeding is doomed to fail. Since the (local) survival of many bird species does not

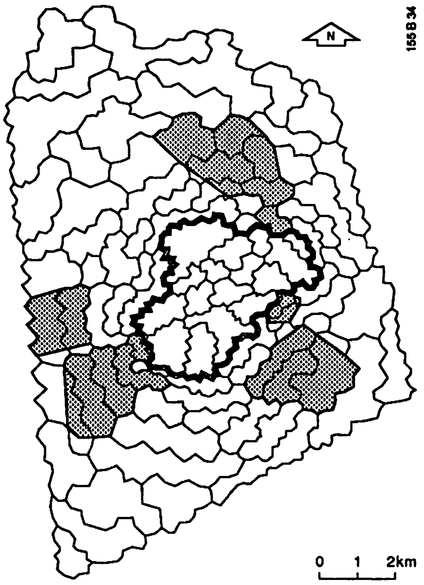

Fig. 35 ***Bird foraging grounds in the area surrounding the Groote Peel***

depend on year-to-year success of breeding, it is thought to be essential that once every few years the conditions should be favorable. For this reason the formulated indicator for the avifaunistic values was made a function of the spring groundwater levels in the three wettest years of the simulation period 1971-81 (1975, 1978 and 1981). A weighted mean was computed of the groundwater levels in 5 areas shown in Fig. 35, averaged over the three selected years.

3.2 Effects on agriculture

The productivity of agricultural lands can be negatively influenced by both too wet and too dry conditions. These conditions are determined by a number of factors. Of interest here is the influence of the groundwater level, because the focus of the present study is on the regional conflict of interests as a consequence of effects transmitted by the regional aquifers. A too high groundwater level inevitably causes crop damage due to water-logging. On the other hand a too low groundwater level causes a loss of crop production owing to a reduction of the capillary rise from the watertable to the root zone – under the circumstances prevailing in the region capillary rise can supply up to 20% of the soil moisture requirement.

3.2.1 Waterlogging

A too high groundwater level has a negative effect on the productivity through various mechanisms. Arable land loses productivity mainly because of the delayal in the sprout-

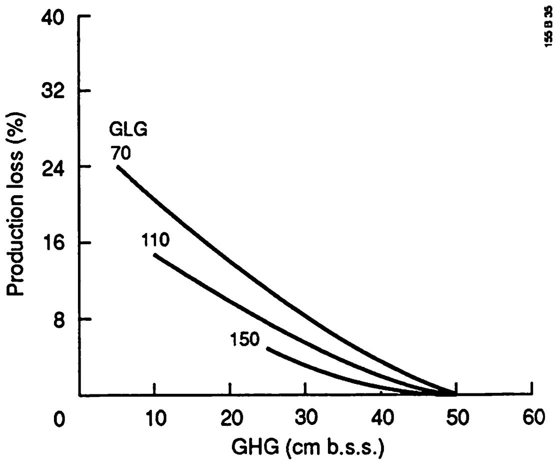

Fig. 36 Example of a set of HELP-curves (Landinrichtingsdienst, 1987) for calculating the production loss casued by too high groundwater levels

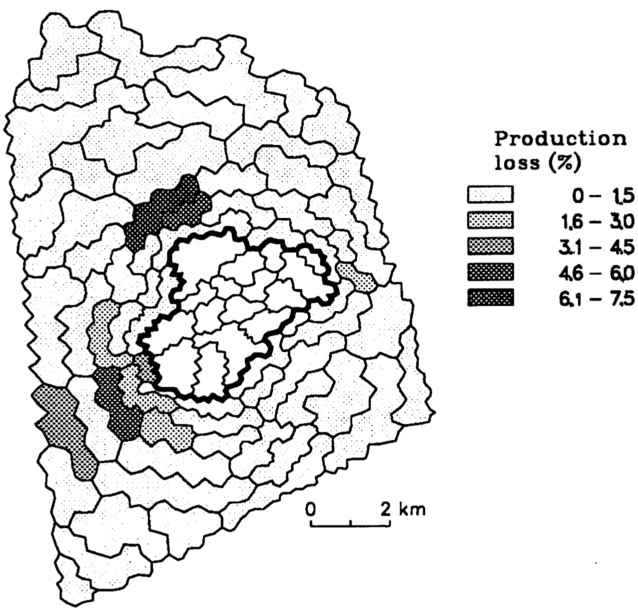

Fig. 37 Calculated loss of productivity caused by too wet conditions in the current situation. GHG := 'average highest groundwater level'; GLG:= 'average lowest groundwater level'[1]

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[1] The 'average highest groundwater level' is obtained from a time series of groundwater levels in the following manner: Per hydrological year (April 1 - April 1) the level on the 14th and 28th day of each month are examined, and the highest three are selected. This is done for each of the years for which a complete set of data is available (there should at least be 8 years of data). The levels are then simply averaged. For obtaining the 'average lowest groundwater level' an identical procedure is followed, with the difference that per year not the three highest levels are selected, but the three lowest ones.

ing of seedlings. Another factor of importance is that a too high groundwater level makes the soil too soft for doing the preparatory work needed for sowing and also doing actual sowing itself. Grassland loses productivity through for instance the damage that is done by the cows when treading on soil that is too soft for bearing their weight. For calculating the damage caused by too wet conditions use has been made of a so-called HELP-curve (*Landinrichtingsdienst*, 1987). Such a curve gives the approximate relationship between the loss of productivity and the 'average highest groundwater level'. There are separate curves for different values of the 'average lowest groundwater level'. The curves used in this study are shown in Fig. 36. The same set of curves has been used for all the soil units and for both arable land and grassland; thus the method has here only been applied in a rough manner. The result of the followed procedure is shown in Fig. 37, giving the calculated loss of productivity in the current state.

When calculating the effect of installing drainage pipes, the assumption is made that the loss of productivity shown in Fig. 37 is removed. This, however, somewhat underestimates the effect of installing drainage – it is known that in the region the occurrence of loam lenses in the shallow subsoil is quite common, causing the local presence of perched watertables. The associated loss of productivity caused by these perched watertables is not included in followed damage assessment procedure. Thus the actual damage caused by too wet conditions is underestimated by the values depicted in Fig. 37.

3.2.2 Soil moisture deficits

Lack of moisture supply results in reduction of the actual transpiration. A good measure for the loss of productivity is the difference between the actual transpiration and the potential transpiration. This loss of productivity can be reduced either by sprinkling or by raising the groundwater levels and thereby increasing the capillary rise.

Sprinkling leads to near-optimal crop production in as far as water is a limiting factor for growth. The economic viability of sprinkling is, however, a controversial matter. That is because if one only looks at the long-term average of the rise in productivity and compares it to the average cost of possessing and operating the required sprinkler apparatus, the net benefits turn out to be negative. However, farmers do not take their investment decisions based only on crop productivity – a smooth risk-free operation of the farm also has its value, although it is hard to quantify it monetarily. Since the economic valuation of sprinkling is so problematic, no attempt has been made to quantify the effects of sprinkling in the present study.

The influence on crop productivity through changes in the groundwater levels has been quantified in a straightforward manner:

- for the simulation period 1971-1981 the average effect on the transpiration is computed for arable land, maize land, and grassland;
- in order to take account the effect of small scale variations of the field topography a reduction of 25% has been applied to the results;
- calculation of the monetary effects is by multiplication of the transpiration effects by fixed conversion factors.

Since the simulation period of 10 years in length includes the relatively very dry year of 1976, with an 'aridity index' of less than 3% (meaning that statistically speaking only one in every 30 years is drier than the considered one), the effects for 1976 were only counted with a weight of 0.01 in the averaging procedure (instead of the normal 0.10 for the effects in the other years.)

3.2.3 Monetary valuation of effects on agriculture

About the conversion from effects in terms of crop production to monetary units there is a great deal of controversy, mainly stemming from the variability of the efficiency with which farms are operated. Expressed in [Dutch guilders/ha/% of production] the used conversion factors are:
- 50 for arable land;
- 38 for maize land;
- 45 for grassland.

The crop production was assumed to be directly proportional to the evapotranspiration; the used conversion factor was 4.1 mm evapotranspiration per % of crop production.

4 EVALUATION OF INTERNAL MEASURES

As stated in the introductory chapter a number of internal measures have been evaluated with the model:

- alterations of the drainage base within the *Groote Peel*;
- the construction of reservoirs for storing the winter outflow and re-using the stored water during the ensuing summer.

The results of the performed simulations have been fully reported in *Projectgroep de Groote Peel* (1990). In the following only brief descriptions are given of the followed computational procedures. Results are only included by way of illustration.

4.1 Alterations of the drainage base

The evaluated alterations of the drainage base concerned in the first place an assessment of the water conservation measures completed in 1987 (see Fig. 16). These measures have raised the average water level in a subregion, which in the model has been simulated by raising the drainage base. As a consequence of the raised water levels within the *Groote Peel* the downward seepage has increased; this in turn has led to an increase of the upward seepage in parts of the surrounding agricultural area, accompanied by a rise of phreatic groundwater levels.

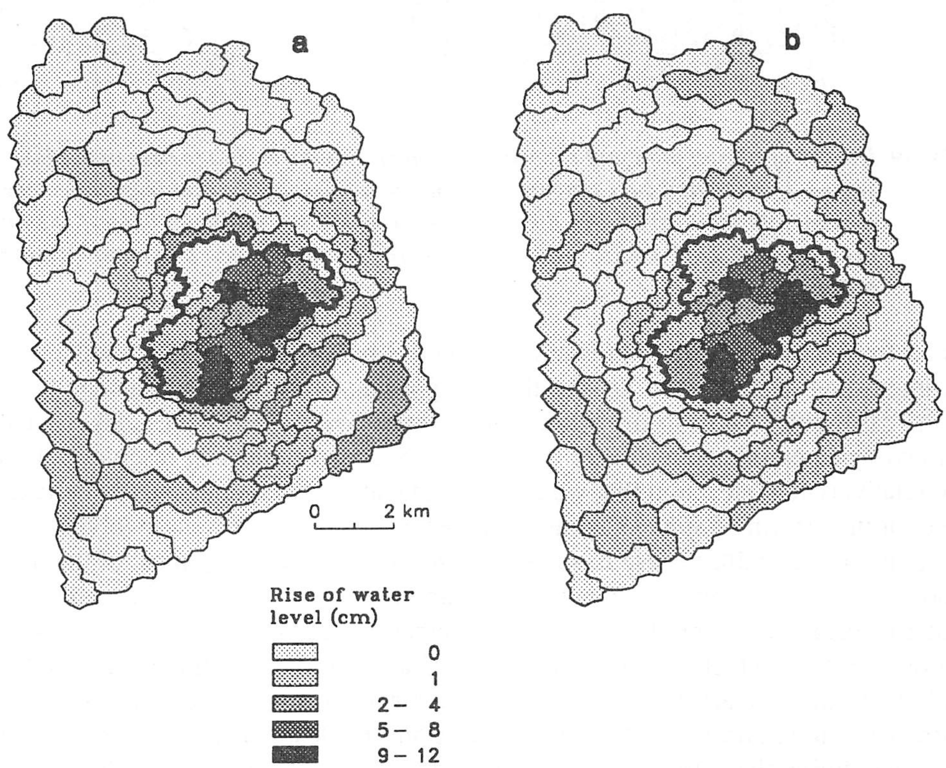

***Fig. 38** Effects of water conservation measures (cf. Fig. 16) on the 'Average highest groundwater level' (a) and on the 'Average lowest groundwater level' (b)*

The mentioned assessment was needed in order to get an idea of the resulting loss of agricultural production associated with water-logging. As can be seen from Fig. 38 the simulated rise of the 'average highest groundwater level' is very small, thus hardly causing any extra loss of agricultural production. Furthermore, also the 'average lowest groundwater level' is raised, thus causing a slight increase of the agricultural production through an increase of the capillary rise. This reduces even further the net damage caused by the water conservation measures within the *Groote Peel.*

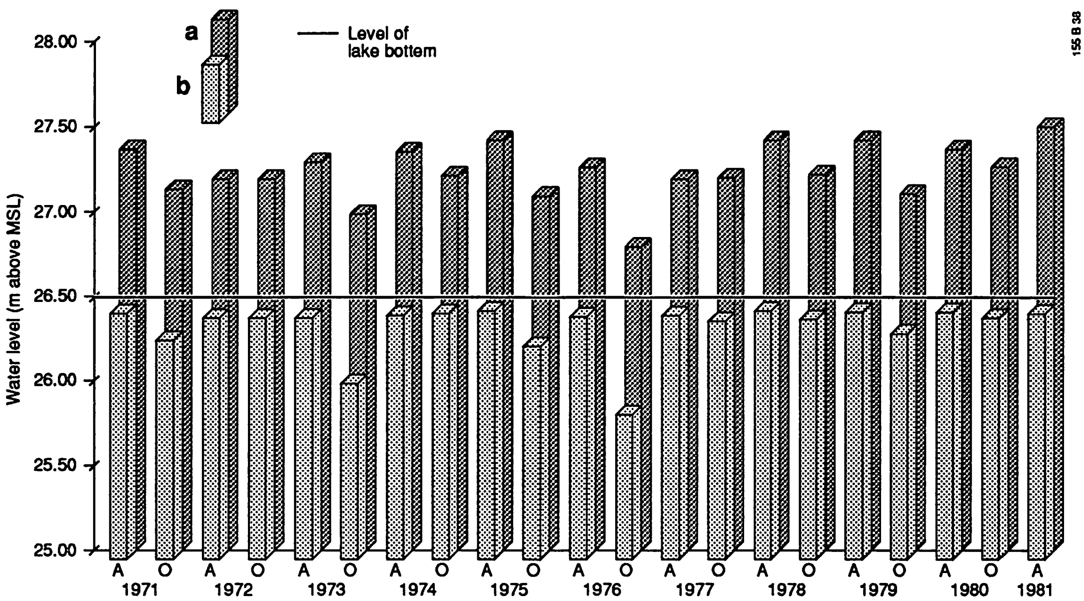

***Fig. 39** Results of a computational experiment concerning the drainage base of the lake represented by subregion 14. Comparison between the simulated water level trajectory in the current situation (a) and in the situation in which the drainage base of the lake has been lowered by 85 cm (b). Only the levels for the dates April 1 (A) and October 1 (O) are given.*

Apart from measures directed towards raising the drainage base, it is for some situations an interesting alternative to do exactly the opposite – to lower the drainage base. This is the case with respect to the central lakes of the *Groote Peel.* These lakes have been formed by damming the relatively low-lying central part of the bog reserve. But it is just the relatively low elevation that would make the land that is now covered by lakes suitable for the growth of *Sphagnum* moss. A computational experiment involving an 85 cm lowering of the drainage base in subregion 14 showed that during most of the time very stable water levels could be obtained over an area of some 33 ha. The stability of the water levels is caused by the fact that the downward seepage (cf. Fig. 31) is changed to upward seepage, which in turn is caused by a drastic drop of the phreatic hydraulic head. In Fig. 39 the comparison is given between the simulated water level trajectories in the current situation and in the hypothetic situation of a lowered drainage base. It can be seen that during the extremely dry summer of 1976 the lowering of the drainage base is counterproductive – instead of stabilizing the level as is usually the case, the fluctuation is actually increased. That is because in such an extremely dry year the upward seepage is not strong enough for maintaining a high groundwater level. And since there is hardly any surface water (due to the draining of the lake), there is also relatively little water in storage. This means that once the level starts to drop, it drops faster than in the original situation.

4.2 Construction of storage reservoirs

By constructing storage reservoirs it is in principle possible to store part of the winter outflow and to re-use it during the summer months for infiltration in a network of shallow trenches. Apart from the technical and hydrological aspects, there is of course the question of whether the stored water has a suitable quality for regenerating the bog-forming vegetation: if the quality is poor, there is the danger that other less valuable species are given an even better chance – in the latter case the bog-forming vegetation would be overgrown. This and other aspects have been dealt with extensively in *Projectgroep de Groote Peel* (1990). In the following only a short description is given of the hydrological modelling.

Various alternatives have been formulated involving one or more storage reservoirs. An example of an alternative involving three reservoirs is shown in Fig. 40. For being able to simulate such a hypothetical situation the model had to be adapted to accommodate for:
- the manner in which the discharged surface water is collected during the winter months;
- the manner in which the stored water is used during the summer months, i.e. the operational strategy.

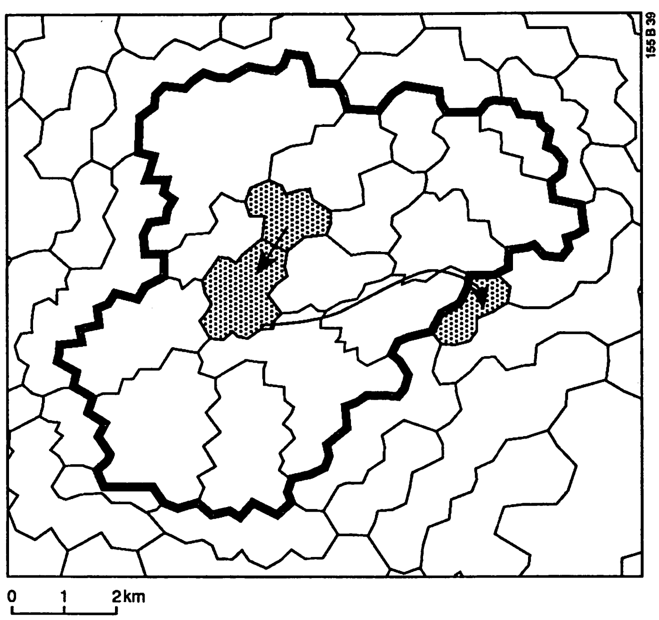

***Fig. 40** Example of an investigated alternative for creating storage reservoirs (Alternative V given in Projectgroep de Groote Peel, 1990). The arrows indicate the modifications of the surface water outflow structure as given in Fig. 18.*

Adapting the model to the new situation during the winter months consisted simply of modifying the surface water outflow structure according to the arrows given in Fig. 40. Furthermore, the outflow that otherwise would have 'disappeared' to the larger channels in the surrounding agricultural area was redirected towards the central lake that is represented by subregion 6. The simulated operational strategy during the summer months depended on the type of question that was put to the model; two types of question had to be answered:

- what is the maximum size of the area that, through use of water from the reservoirs, can be supplied with enough water to under all climatological conditions fulfill the water level requirements of the bog-forming vegetation ?
- what can be achieved if the water available in the reservoirs is spread over a large part of the *Groote Peel*, soon after the beginning of the summer season ?

The first type of question relates to what has been called the concentration strategy, because it involved supplying water to a relatively small part of the *Groote Peel*; the second type of question concerns what has been called the spreading strategy, because it involved spreading the available water over a relatively large part of the bog reserve. In the latter case it is of course not possible to maintain hydrological conditions that are everywhere optimal for the growth of the bog-forming vegetation; the idea of supplying water was in this case to provide a general upgrading of hydrological conditions.

For being able to answer the area question with respect to the concentration strategy, it was first necessary to make a list giving – in descending order of priority – the nodal points that potentially come under consideration for being supplied with water. Use was made of the map giving the location of current ecological values (*Projectgroep de Groote Peel*, 1990). The result is graphically shown in Fig. 41 (only for the first 18 nodes). Each nodal point has been attributed a target level, based on knowledge of the field conditions.

In the model a nodal point that has been selected for being supplied with water is given an 'injection' of 5 mm from one of the reservoirs if the simulated water level drops below the target value. The number of nodal points that can be supplied is determined through an iterative procedure, involving repeated runs with the simulation model. For each subsequent run the number of nodal points on the 'supply list' is made larger, thus making it possible to determine the number of nodal points that can just be supplied from the reservoirs. The adding on of nodal points is done according to the priority list. But once the area that is to be supplied has been determined, the priority order does not play a role anymore – the size of the area is such that there is exactly enough water to supply all the chosen nodes.

For the example given in Fig. 40 the area that could be supplied with water was determined to be 99 ha out of a total 1340 ha, i.e. only 8.5 of the nodal points shown in Fig. 41. Fig. 42 illustrates the manner in which the water management of the central lakes has been simulated, in this case the lake represented by subregion 6. As can be seen from the comparison between the water level trajectory for the current situation and the one for the situation with reservoirs, the reservoir is never depleted to a level that is lower than in the current situation. The main reason for the relatively small size of the area that can be supplied is the high loss of water through evaporation from the reservoirs and the increased downward seepage through the bottoms of the reservoirs caused by the raised water levels. The loss of water is exacerbated by the fact that there are winters that do not yield any discharge at all for supplementing the amount of stored water (see Table 5). This means that in order to have enough water for supplying the selected area at all times, it is necessary to use water that has been collected the winter before last – the prolonged period of storage is the cause of high water losses.

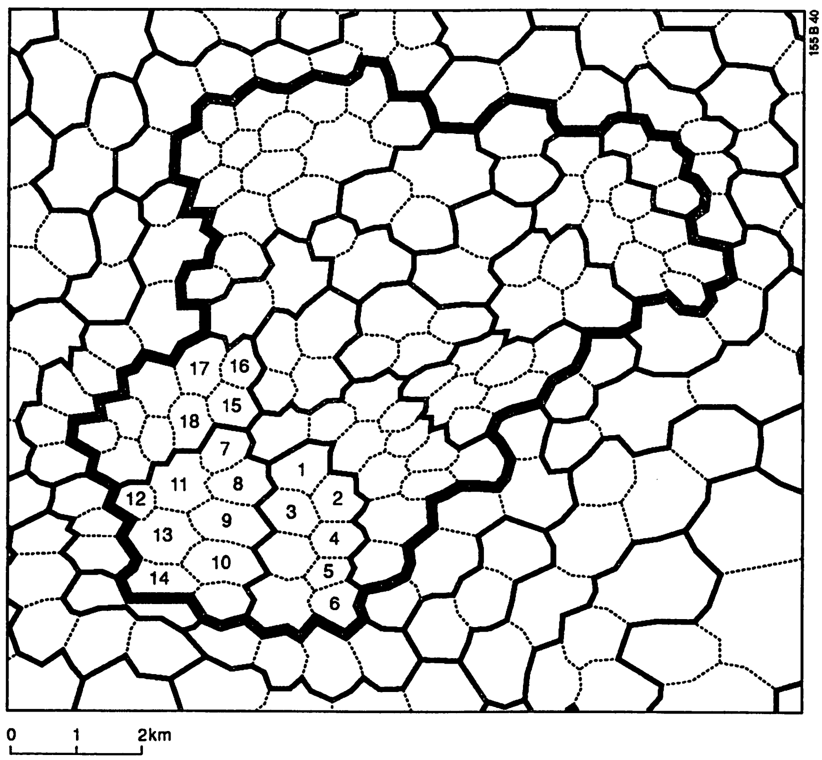

Fig. 41 Nodal influence areas (bounded by dotted lines) that come under consideration for being supplied with water under the concentration strategy. The numbers give the priority order in which the nodal points should be supplied with water. (Only the first 18 nodal influence areas on the priority list are shown.)

As mentioned above, the alternative for the concentration strategy is the spreading strategy, in which the stored water is spread over a large part of the nature area. The idea of this strategy is to avoid the high water losses from the reservoirs by making use of the available water as soon as possible. Evaluation of this strategy consisted simply of running the model with a fixed number of nodal points that are to be supplied with water – no iterative running was required in this case. As soon as the water level of a nodal point drops below the target level, an injection of water from the reservoirs is made – at least, as long as there is still enough water available. Results of simulation runs made for the spreading strategy are fully reported in *Projectgroep de Groote Peel* (1990). The results show that the achieved raising of water levels is not very substantial. The main reasons for this are that:

- in the current situation the mean yearly outflow that can be stored is only around 550 000 m^3 (see Table 5), though this outflow will be become slightly larger due to the re-cycling;
- re-use of winter outflow induces extra downward seepage (owing to raised water levels) and also some extra evapotranspiration.

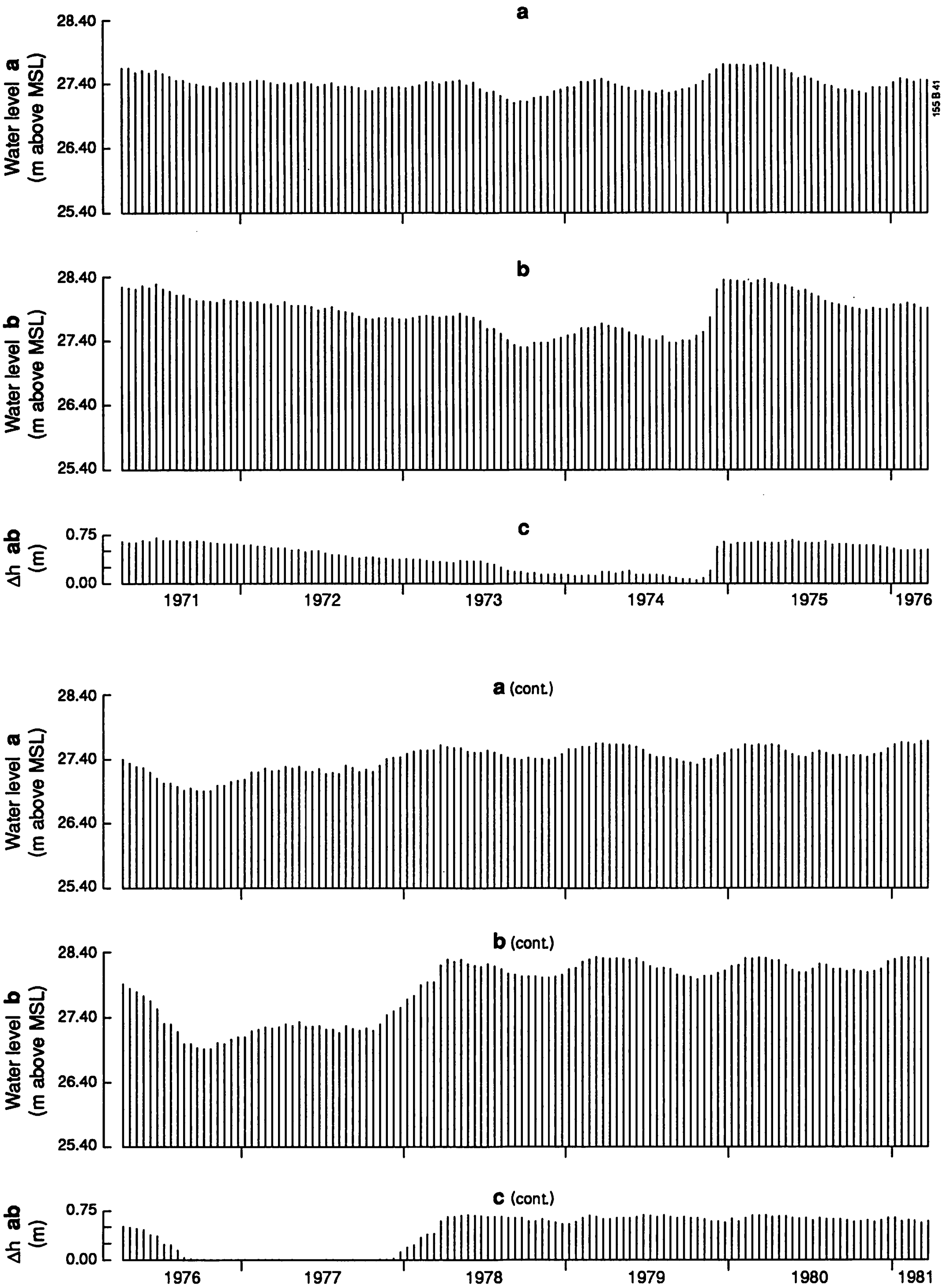

Fig. 42 Comparison between water level trajectories simulated for one of the central lakes (subregion 6) in the current situation and in the situation that the lake is used as a reservoir for supplying water to certain parts of the Groote Peel

5 DECISION SUPPORT SYSTEM FOR EXTERNAL MEASURES

5.1 Introduction

Concerning the water management in the area surrounding the *Groote Peel* the following potential measures were considered to require decision support:
- regulating the subsurface drainage of agricultural lands;
- regulating the sprinkling of agricultural lands from groundwater and/or surface water;
- modifying the surface water management, with or without supply of water from external sources.

Extraction of groundwater for public water supply (which takes place from the second aquifer of the schematization given in Fig. 9) is not included in this list because it requires modelling on a much larger scale than the regional one of this study. Nevertheless, the current model has been used for estimating the total effect of the existing extractions. This was done through making runs with modified boundary fluxes; results have been reported in Van Walsum (1990).

In the following, attention will be focussed on the developed decision support system for measures with respect to the above listed activities. After giving an overview of the used methodology in the next section, a description is given of the potential developments associated with the list given above, including combinations of them (e.g. expansion of drainage in combination with increased surface water supply during the summer.) Next, a description is given of the simplified model that has been developed for use in combination with Linear Programming. Finally some results are included by way of example.

5.2 Methodology

For reasons of simplicity, it is assumed that the regional water management is in the hands of one (imaginary) regional authority. The design of a future state of a region has been conceived to consist of two separate stages with corresponding elements of the decision support system (Fig. 43; Orlovski et al., 1986):
- identification of the future possibilities for a region using the scenario generating system (SGS);
- analysis of potential water management measures using the policy analysis system (PAS).

With the scenario generating system the regional authority can generate scenarios that meet certain requirements with respect to the well-being of the different water users. This well-being is quantified in terms of indicator values, being the ecological value of the *Groote Peel* on the one hand and the economic performance of the surrounding area on the other. The SGS generates, in a sense, a reference state of future regional development that could be reached if all the water users would behave in the way the authority wants.

The need for having a policy analysis system (PAS) stems from the desire to predict the effects of certain policy measures without having to actually try them out. If it turns out that the reference state (identified by the SGS) is not reached, the authority can either

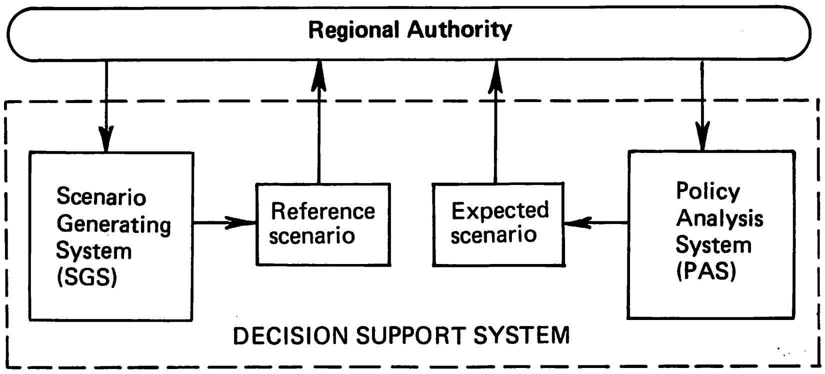

Fig. 43 Overview of the decision support system for external measures. With the SGS future possibilities for a region can be identified. With the PAS the regional authority can analyze the effects of potential water management measures.

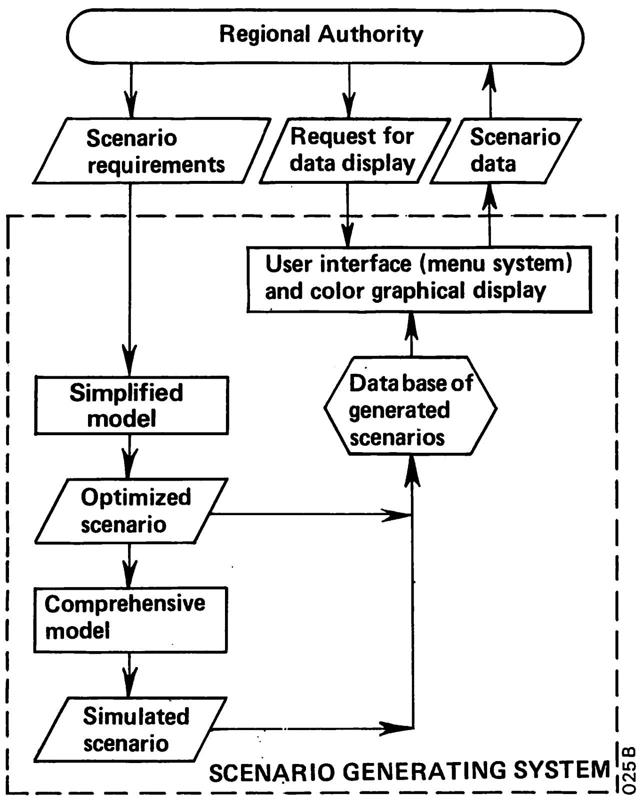

Fig. 44 Overview of the separate components of the scenario generating system

try another policy or else lower his ambitions. The behavioral responses of farmers (and other water users) are, however, hard to predict using mathematical models. That leaves common sense for predicting the reactions of water users to various measures. This can lead to additional constraints in the SGS in order to ensure that the obtained scenarios have an increased practical value. Since the PAS does not involve the use of models, attention will here be focused on the scenario generating system.

The model SIMGRO provides a relatively detailed description of the relevant processes and is therefore here called a comprehensive model. The disadvantage of such a model is that, because of its complex mathematical form it is not possible to couple it to an algorithm for the screening of scenarios in an automated way. Such a form of coupling is necessary for finding – within an acceptable period of time – scenarios that are 'efficient'. By the latter is meant that a generated scenario can not be improved upon with respect to one of the conflicting interests without damaging the other. For achieving this simplified models are more suitable. Because such simplified models are a relatively crude approximation to reality, comprehensive models will always be needed for verification and more accurate estimation of scenarios that seem promising.

An overview of the scenario generating system and its components is given in the flowchart of Fig. 44. As can be seen from this chart a 'User interface and color graphical display' (Van Walsum, 1991) is included. Such a system is needed for analyzing and interpreting the large numbers of input and output data of the models.

5.3 Potential developments of activities that influence the regional hydrology

5.3.1 Subsurface drainage of agricultural lands

An inventory has been made of the lands that to any degree suffer from loss of production caused by too wet conditions (see also Section 3.2.1). These lands could potentially be drained; whether this would be economically viable is in many cases very hard

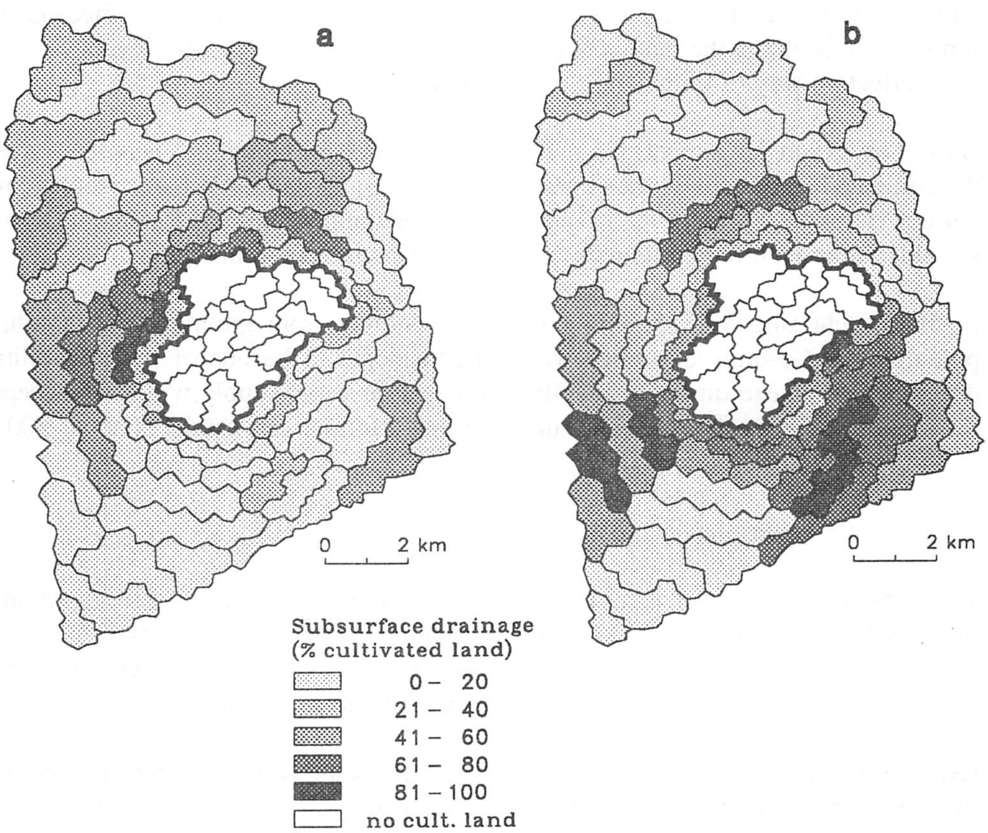

***Fig. 45** Subregional percentages of lands that already have been drained in the current situation (a) and the potential expansion (b)*

to assess, however. The spatial distribution of the lands that have already been drained in the current situation is shown in terms of subregional percentages in Fig. 45 (cf. Fig. 14b in which the drained nodes are those in the first legend class); also the potential expansion is shown (relative to the current situation).

In principle it would be possible to undo some of the drainage that has been installed. This was, however, not considered to be feasible from a political viewpoint. (Though even more drastic measures like swamping of the land could perhaps be implemented if the land is bought from the farmers – see Section 5.3.4). Such a limitation is an example of a limitation that stems from the 'PAS' described in Section 5.2.

5.3.2 Sprinkling from groundwater and/or surface water

With respect to the potential development of sprinkling, both expansion and contraction are considered to be possible, though perhaps only in the long run (in the case of contraction). Expansion of sprinkling to all cultivated land is, however, not considered realistic. That is because the economic viability of grassland sprinkling is doubtful if considered in terms of the net long-term average yield. (Sprinkling of land used for horticulture is of course a quite different matter, as is sprinkling of arable land.) One of the reasons for nevertheless sprinkling grassland is that it provides a form of insurance for very dry years: If a farmer does not have any sprinkled grassland, in dry years he will have to buy large amounts of feedstuff on the commercial markets. Because other farmers will be doing the same, prices will tend to rise to unpredictable levels. Sprinkling is an effective way of eliminating this economic uncertainty.

Basing on expert judgement, the maximum expansion of sprinkling was set at 25% of the cultivated land, with all the expansion involving grassland. (Or the percentage in the current situation – whichever is higher. The maximum subregional percentage of the sprinkled area is in the current situation up to 32% in a few subregions.)

In the current situation, sprinkling is almost entirely from groundwater. In future, a partial or total switch to surface water is considered to be one of the possibilities – depending of course on the availability of a surface water supply within an acceptable distance. In practice the maximum distance that a farmer can handle is about 300 m.

5.3.3 Surface water management

The current surface water level management is thought to be fairly well approximated by the scheme given in Table 1, involving a summer target level of 1.10 m b.s.s. In the northern half of the study region there is also a supply of surface water from external sources; on average the peak supply capacity is about 0.1 $l.s^{-1}.ha^{-1}$.

Exploratory calculations with SIMGRO showed that water conservation by means of raising the summer target level to 0.90 m b.s.s. does not substantially affect the conditions in the *Groote Peel*, i.e. does not substantially lower the downward seepage. Because this study was directed towards finding efficient ways of protecting and – if possible – improving the wetland qualities of the *Groote Peel*, the options with a target level of

0.90 m b.s.s. were not given any further consideration. Continued exploratory calculations showed that a substantial effect could be expected from a supply of surface water with a peak capacity of 1/6 $l.s^{-1}.ha^{-1}$, in combination with a summer target level of 0.70 m b.s.s.. The main reason for the increased effectiveness of a 0.70 m b.s.s. target level is that the tertiary surface water system (including the drains, if present) has been given a drainage base of 0.80 m b.s.s., meaning that a surface water level of 0.70 m b.s.s. causes the tertiary system to become infiltrating. Another reason for the effectiveness of a 0.70 m b.s.s. level is, of course, the increased hydraulic pressure head. The used surface water management scheme for calculations involving a summer target level of 0.70 m b.s.s. is given in Table 9.

Table 9 Surface water level management scheme for calculations involving water supply in combination with a summer target level of 0.70 m b.s.s.

Surface water target level (m b.s.s.)	Range of groundwater levels (m b.s.s.)
1.30	< 0.65
1.10	0.65 - 0.75
0.90	0.75 - 0.80
0.80	0.85 - 0.90
0.70	> 0.90

Given the promising effects on the *Groote Peel*, tentative plans for expanding the surface water supply capacity to a minimum level of 1/6 $l.s^{-1}.ha^{-1}$ have been drawn up for the purpose of being able to more accurately simulate various supply scenarios. (In the northern half of the study region there is already a supply of 0.10 $l.s^{-1}.ha^{-1}$; thus in thispart the expansion is an enhancement of the existing capacity.) The areas that could be supplied with (extra) water are shown in Fig. 46. Extra surface water could be supplied from three inlet points (A, B and C); not shown in Fig. 46 is the actual network of channels that could be supplied with water. This network is given in *Landinrichtingsdienst* (in preparation).

The areas that potentially could be supplied from a certain inlet point have in some cases been subdivided into a number of subareas (e.g. A_1) and in one case even into sub-subareas (e.g. $A_{0,1}$). The idea being that full implementation of a scheme for supply from a certain inlet point is not mandatory. At the other extreme, implementation on a subregional basis is considered to be not possible owing to practical considerations. Partial implementation is only considered possible for whole sub(sub)areas at a time. Given the route that the supplied water has to follow, partial implementation is however subject to the following constraints:
- if $A_{0,2}$ then also $A_{0,1}$;
- if $A_{0,3}$ then also $A_{0,2}$;
- if A_1, then also $A_{0,1}$;
- if A_2, then also A_1;
- if C_3, then also C_2.

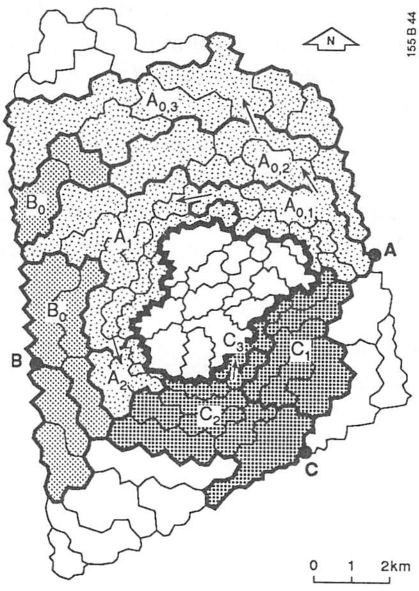

Fig. 46 Plans for expansion of surface water supply from external sources (Landinrichtingsdienst, in preparation). Extra supply of surface water is possible from the inlet points A ('Kanaal van Deurne'), B ('Zuid-Willemsvaart'), and C ('Noordervaart'). The actual network of channels is not shown, only the areas within the supply schemes. The area supplied from the same inlet point has been given the same hatching. Subareas are indicated with suffixes (e.g. A_1). The arrows indicate the pathway that the supplied water has to follow.

In SIMGRO the standard way of computing the infiltration of surface water is with an infiltration resistance that is 1.1 times the drainage resistance. However, especially if the surface water level is so much higher than in the winter situation, the infiltration resistance can actually be lower than the drainage resistance. This can be because the wetted perimeter of a channel increases with increasing water depth, thus reducing the entry and the radial flow resistance. This reduction of the entry resistance can be very substantial – the high summer water level causes strips of soil to become inundated that normally are not covered by water. The biological activity in this soil is very much greater than in the rest of the wetted perimeter, leading to a greater presence of macropores that lower the resistance to flow. In the case of drains being used for infiltration, however, the entry resistance is higher than in the drainage situation, as a consequence of partial clogging.

Apart from the situation in the channel itself, the groundwater level also determines the infiltration resistance – the lower it is, the higher the resistance. That is because a lower groundwater level also means a smaller vertical cross-section for the flow to pass through. In order to achieve a more realistic simulation of the infiltration process, SIMGRO has been adapted so that values of infiltration resistances can be specified independently from values of drainage resistances.

For the channels of the secondary system the infiltration resistance has been estimated simply on the basis of the effective distance between the secondary channels that become water bearing as a consequence of implementing a supply scheme. This has been done by making an inventory of the total lengths of water-bearing channels in each of the subregions within the supply schemes. The effective distances could then be obtained by calculating the quotients of these total lengths and the areas of the subregions. For most of the calculations a conversion factor of 1.25 $d.m^{-1}$ (obtained from 'expert judgement') has been used for converting the effective distances to infiltration resistances. Because the resistances were thus obtained on a subregional basis, the nodes within a subregion that fall within an (implemented) supply scheme are all given the same secondary resistance.

***Table 10** Annualized costs of water supply schemes (Province of North Brabant, 1990; see also Fig. 46). The listed costs apply to a supply level 1/6 $l.s^{-1}.ha^{-1}$. The costs of the combined implementation of B_0 and B_1 are f 14 900,--/yr lower than the total of the listed costs, as a consequence of technical considerations. Implementation of one or more of the C-schemes requires the construction of an inlet structure costing f 37 500,--/yr.*

Partial scheme	Area (cultivated land only) (ha)	Costs per unit of area for supply cap. of 1/6 l/s/ha ($f.ha^{-1}.yr^{-1}$)	Total costs ($f.yr^{-1}$)	Extra costs for extra supply cap. ($f.ha^{-1}.yr^{-1}$)
$A_{0,1}$	562	15	8 400	5
$A_{0,2}$	808	15	12 100	5
$A_{0,3}$	1191	15	17 900	5
A_1	1096	105	115 100	15
A_2	263	210	55 200	15
B_0	932	45	41 900	5
B_1	340	185	62 900	15
C_1	660	140	92 400	15
C_2	933	145	135 300	15
C_3	67	280	18 900	15

The situation with respect to the tertiary channels is more complicated. That is because the situation with drainage can be quite different from that with infiltration (apart from the obvious difference concerning the direction of the flow). For modelling a situation with drainage, the tertiary surface water system and its interactions with the groundwater can usually be described in terms of levels 'below soil surface'. For modelling the situation with infiltration, a complication occurs if the tertiary channels (or drains) do not have a zero bedslope, as is the case in the study region. A non-zero bedslope means that only part of the tertiary system becomes infiltrating when the level in the secondary system reaches a level of 0.80 m b.s.s. The part of the tertiary system that becomes infiltrating when the level in the secondary system rises to 0.70 m b.s.s., depends on the bedslope of the tertiary channels. The manner in which the infiltration resistance of the tertiary system has been calculated is described in Annex 3.

5.3.4 'Nature development'

An even more drastic measure than raising the surface water level to 0.70 m below soil surface is to virtually swamp a subregion, by for instance raising the level to 0.30 m b.s.s. (A level higher than 0.30 m b.s.s. is hardly considered possible, unless an extensive system of levees is constructed.) However, such a high level is not compatible with farming in the normal sense; thus this option is denominated as the 'nature development' option, involving the buying of land from farmers.

5.3.5 Combinatory developments

Summarizing, the possible potential developments are (with between brackets the number of possibilities):
- subsurface drainage can remain as it is in the current situation or be allowed to expand to 100% of the lands that to any degree suffer from too wet conditions (2);
- sprinkling can be forbidden altogether, or be allowed to take place from groundwater, or be allowed to take place from surface water. It is assumed that the maximum sprinkled area as defined in Section 5.3.1 can be reached by both sprinkling from groundwater and surface water, but intermediate situations are also possible (3 extremes plus intermediate situations);
- a surface water supply scheme can be implemented or not (2);
- land can be bought for nature development or not (2).

Table 11 ***List of theoretical combinations of partial developments with respect to subsurface drainage, sprinkling (0: forbidden, GW: from groundwater, SW: from surface water), implementation of a surface water supply scheme and buying land for 'nature development'. If there is reason to disregard a certain combination this is indicated by a non-zero digit in the last column, having the following meaning:***
1. The buying of land for nature development rules out the expansion of drainage and sprinkling from both groundwater or surface water
2. Sprinkling from surface water is only possible if at the same time a scheme for increased surface water supply is implemented.

Expansion of drainage (N/Y)	Sprinkling (0/GW/SW)	Surface water supply scheme (N/Y)	Buying of land (N/Y)	Reason for discarding (0/1/2)
N	0	N	N	0
N	0	N	Y	0
N	0	Y	N	0
N	0	Y	Y	0
N	GW	N	N	0
N	GW	N	Y	1
N	GW	Y	N	0
N	GW	Y	Y	1
N	SW	N	N	2
N	SW	N	Y	1/2
N	SW	Y	N	0
N	SW	Y	Y	1
Y	0	N	N	0
Y	0	N	Y	1
Y	0	Y	N	0
Y	0	Y	Y	1
Y	GW	N	N	0
Y	GW	N	Y	1
Y	GW	Y	N	0
Y	GW	Y	Y	1
Y	SW	N	N	2
Y	SW	N	Y	1/2
Y	SW	Y	N	0
Y	SW	Y	Y	1

In this list the surface water supply rate and the summer target level are not included, because they are seen as derived aspects that follow from the others. The listed potential developments of course do not have to take place in a mutually exclusive manner, thus they are partial potential developments. In theory there are 2*3*2*2 = 24 possible combinatory developments. Not all combinations are of practical meaning, however. The following considerations drastically reduce the number of relevant options:

1. The buying of land for nature development rules out the expansion of drainage and sprinkling from both groundwater or surface water;
2. Sprinkling from surface water is only possible if at the same time a scheme for increased surface water supply is implemented.

In Table 11 a list is given of the theoretically possible combinations and the reasons for discarding certain of them. In Table 12 this is followed by the reduced list containing only the combinations that are of practical interest. The combinations that do not involve implementation of a surface water supply scheme have been given two values for the supply rate: zero for the situation in the southern half of the study region, 0.10 $l.s^{-1}.ha^{-1}$ for the northern half of the study region. The exception to this is the second option on the list, involving the buying of land and no implementation of a surface water supply scheme: also in the northern half of the study region the supply rate has been set to zero. That is because raising the target level to 0.30 m b.s.s. in combination with the current supply rate requires nearly all of the extra infrastructure that is included in the costs listed in Table 10. Thus the combination of a target level of 0.30 m b.s.s. and a supply rate of 0.10 $l.s^{-1}.ha^{-1}$ is not included in the list.

***Table 12** Combinatory developments that are of practical interest (see heading of Table 11 for the explanation of the sprinkling options), with the most appropriate surface water supply rate and summer target level. By a surface water supply of '0.17+SW' is meant a supply of 0.17 plus the amount needed for sprinkling from surface water at a rate of 25 mm/week, of all the (grass)land as defined by the maximum scenario given in Section 5.3.2. If a differentiation has been made between the supply rate in the southern and northern half of the study region this has been indicated by for instance a supply rate of '0/0.10'.*

Expansion of drainage (N/Y)	Sprinkling (0/GW/SW)	Surface water supply scheme (N/Y)	Buying of land (N/Y)	Surface water supply ($l.s^{-1}.ha^{-1}$)	Summer target level (m b.s.s.)
N	0	N	N	0/0.10	1.10
N	0	N	Y	0/0	0.30
N	0	Y	N	0.17	0.70
N	0	Y	Y	0.33	0.30
N	GW	N	N	0/0.10	1.10
N	GW	Y	N	0.17	0.70
N	SW	Y	N	0.17+SW	0.70
Y	0	N	N	0/0.10	1.10
Y	0	Y	N	0.17	0.70
Y	GW	N	N	0/0.10	1.10
Y	GW	Y	N	0.17	0.70
Y	SW	Y	N	0.17+SW	0.70

5.4 Simplified model for scenario generation

5.4.1 Mathematical form

As stated earlier, a simplified model is the most suitable for scenario generation. Preferably it should consist of linear equations, because this allows the use of Linear Programming and its extensions. Since there is more than a single policy objective for the *Groote Peel* and its surroundings, the simplified model has to be formulated in such a manner that it can be used in conjunction with a procedure for multi-objective optimization. The following form satisfies this requirement:

$$f = Cx \,, \tag{5.1a}$$

$$l \leq x \leq u \,, \tag{5.1b}$$

$$Ax \leq b \,, \tag{5.1c}$$

where

f - vector of objective functions
C - objective function matrix
x - vector of decision variables
l - vector of lower bounds on decision variables
u - vector of upper bounds on decision variables
A - constraint matrix
b - 'resources' vector

The vector of decision variables here concerns the water management options in the subregions surrounding the *Groote Peel*. In addition to the above given type of constraints, some of the decision variables can be forced to take on certain discrete values. The model has been formulated in such a manner that the additional requirement is that only two values are possible: the lower and the upper bound. (Such decision variables are sometimes called binary variables.)

The vector of objective functions contains two components:
- the change of the 'potential bog area' within the *Groote Peel*;
- the change of the economic performance of the region, in terms of the net yearly income generated by agricultural activities in the area surrounding the *Groote Peel*.

Both components involve groundwater-related impacts of the water management options. This way of simplified modeling is commonly referred to as the response matrix approach. (For an excellent overview of types of simplified groundwater modeling in combination with mathematical programming the reader is referred to Gorelick (1983)). Apart from groundwater-related impacts the objective function matrix contains certain cost parameters and local economic benefits (e.g. the rise in production accomplished through sprinkling).

The constraint matrix contains – among other things – coefficients relating to the use of certain resources by the various water management options.

5.4.2 Decision variables

The potential developments listed in Table 12 are in the simplified model treated as options that are represented by decision variables. In Table 13 the options for the southern/northern part of the study area have been expanded to two separate ones. (And the order of the options has been made the same as in the computer implementation.) The options involving sprinkling are assumed to represent the extreme situation in which the maximum sprinkling scenario defined in Section 5.3.2 is reached.

All the options given in Table 13 are defined in terms of all the water management aspects. This means that they are mutually exclusive – it is not possible to implement two of the options at the same time, with both options applying to the whole area of a certain subregion. In the case of sprinkling, intermediate situations are possible, however; it is for instance possible to have a subregion with half the sprinkling from surface water and the other half from groundwater.

Table 13 ***Combinatory water management options for the area surrounding the Groote Peel. The sprinkling options have the following meaning: '0' - no sprinkling, 'GW' sprinkling from groundwater, 'SW' - sprinkling of from surface water. By a surface water supply of '0.17+SW' is meant a supply of 0.17 $l.s^{-1}.ha^{-1}$ plus the amount needed for sprinkling from surface water at a rate of 25 mm per week.***

Option	Expansion of drainage (N/Y)	Sprinkling (0/GW/SW)	Surface water supply scheme (N/Y)	Buying of land (N/Y)	Surface water supply ($l.s^{-1}.ha^{-1}$)	Summer target level (m b.s.s.)
1	N	0	N	N	0	1.10
2	N	0	N	Y	0	0.30
3	N	GW	N	N	0	1.10
4	N	0	N	N	0.10	1.10
5	N	0	Y	N	0.17	0.70
6	N	0	Y	Y	0.33	0.30
7	N	SW	Y	N	0.17+SW	0.70
8	N	GW	N	N	0.10	1.10
9	N	GW	Y	N	0.17	0.70
10	Y	0	N	N	0	1.10
11	Y	GW	N	N	0	1.10
12	Y	0	N	N	0.10	1.10
13	Y	0	Y	N	0.17	0.70
14	Y	SW	Y	N	0.17+SW	0.70
15	Y	GW	N	N	0.10	1.10
16	Y	GW	Y	N	0.17	0.70

The aspects listed as N/Y in Table 13 have been treated as discrete decisions. This has been done for the following reasons:
- expansion of drainage is a sensitive poltical iussue; it is either allowed or not;
- increasing surface water supply requires an overall upgrading of local infrastructure that can not be done partially;
- buying of land for 'nature development' requires taking a clear cut decision.

The reason given for the discreteness of the drainage decision is an example of a constraint deriving from the policy analysis system (PAS), or whatever is used instead (Fig. 43). Even though some of the aspects of the 16 options involve discrete decisions, continuous variables have been used for representing all of the options in the simplified model. The decision vector x contains 16 components per subregion; the transposed form of it is:

$$x^T = (x_{1,1},x_{1,2},\ldots,x_{1,16},\ x_{2,1},\ldots,x_{2,16},\ \ldots\ ,\ x_{N,1},\ldots x_{N,16})$$

where N is the total number of subregions in the area surrounding the *Groote Peel.*

Each component is allowed to vary on the interval [0;1]:

$$0 \leq x_{i,j} \leq 1 \quad \text{, for all } i=1,\ldots,N \text{ and } j=1,\ldots,16 \tag{5.2}$$

The three discrete aspects of the decision variables are handled indirectly through the use of a separate set of 0/1 variables collected in the vector y; the transposed form is:

$$y^T = (y_{1,1},y_{1,2},y_{1,3},\ y_{2,1},y_{2,2},y_{2,3},\ \ldots,\ y_{N,1},y_{N,2},y_{N,3}),$$

in which the first index refers to the subregion and the second to the three discrete aspects.

A further set of discrete variables concerns the implementation of the partial schemes for increasing the import of water from an external source (Fig. 46). These partial schemes (10 in total) are represented by 0/1 variables collected in the vector z, of which the transposed form is:

$$z^T = (z_1,z_2,\ldots,z_{10})$$

5.4.3 Objective function matrix

Whether the response matrix approach can be used for computing the objective functions depends on whether superimposition of effects is possible without making gross errors. In the case of a complex model like SIMGRO – which is non-linear and contains many forms of 'feedback' – it is not possible to justify the use of the response matrix approach through mathematical analysis. The only available method is verification of scenarios that have been generated through using the simplified model.

Basically, application of the response matrix approach is very simple. It requires making a 'spatial sensitivity analysis' in the following manner:

- a reference run is made with the comprehensive simulation model;
- a certain water management option is subsequently introduced in each of the subregions and for each of these 'traveling option' scenarios a simulation run is made;
- the results obtained for the reference run are subtracted from the results obtained for the separate 'traveling option' scenarios, thus yielding 'responses'.

Each run of the above described procedure yields a vector of impacts on the objective function values. The i-th vector is stored as the i-th column of the matrix C.

The response matrix approach has in the past mostly been used for optimizing the locations of groundwater wells, meaning that there was only one type of option to be investigated (i.e. groundwater pumping). Since in the present study there was more than one option under investigation, the use of multiple matrices had to be resorted to. Prior to applying the method, a choice had to be made between:

- first deriving response matrices for the 'basic' decisions (expansion of drainage, implementation of a surface water supply scheme, etc.), followed by a procedure for 'adding' effects of the basic decisions to obtain response matrices for combinatory options;
- deriving response matrices for all of the options listed in Table 13.

The first method has the advantage of being computationally less demanding; the disadvantage of it is, however, that a combinatory option often involves a completely new physical situation, making it hard to compute combinatory effects from the responses obtained for the basic options. For this reason the second method was chosen. As will be seen below, however, the first method was in the end used for some of the options.

The first option of Table 13 has been used for the reference scenario: option 1 is implemented in *all* the subregions of the study region (except for the subregions within the *Groote Peel*). This scenario is not the same as the 'current situation' – in the current situation there is a varying degree of sprinkling from groundwater, and in the northern half of the study region there is already a surface water supply of 0.10 $l.s^{-1}.ha^{-1}$. That option 1 is used for the reference scenario does not require it to be treated differently from the other options; the only aspect in which it stands out is that the response matrix for option 1 contains all zeros.

The choice of the option for the reference scenario is in a certain sense arbitrary, based to a large part on what is the most convenient from a practical point of view. The reference run should, however, not be too far removed from the current situation; otherwise it is hard to handle and interpret the response matrices when using them in the simplified model. With respect to the current situation it is only essential that it can easily be constructed through interpolation between options for which responses have been computed, superimposed on the reference scenario. For the southern half of the study area, the current situation is obtained from interpolation between options 1 and 3 (superimposed on the reference scenario); for the northern half it is obtained from interpolation between options 4 and 8 (both involving a water supply of 0.10 $l.s^{-1}.ha^{-1}$).

Several difficulties were encountered in deriving the coefficients of the response matrices. For each of the 15 water management options (the first option is the reference situation) and each of the 67 subregions in the area surrounding the *Groote Peel* a simulation run had to be made; this meant making a total of 1005 runs. Since the indicator for the ecological impact on the *Groote Peel* is related to the long-term average of the downward seepage, straightforward implementation of the procedure would have meant making runs of at least ten simulation years at a stretch. On the available computer, a VAXstation3100, each such a run requires roughly 3 hours of CPU-time; 1005 runs would have therefore required at least 4 months of continuous running. Since practical considerations ruled out this possibility, a less rigorous procedure had to be followed.

This procedure involved making the runs for the 'traveling options' with one-year periods, and then applying correction factors for translating the impacts to the long-term averages. Such an approach is only of practical value if the calculated factors are not wildly different from the unit. As will be elaborated on below, straightforward application of this method was not possible.

Selection of the one-year period for making the spatial sensitivity analysis was based on the notions that:

- the winter should be relatively wet, in order to ensure that effects relating to the subsurface drainage manifest themselves in the results;
- the summer should be relatively dry, in order to ensure that substantial effects relating to sprinkling and surface water infiltration are computed.

If the one-year period would have been chosen such that it is a 'representative' of 'average' meteorological year, the computed effects would have been small, thus making it numerically hazardous to relate them to long-term averages obtained with a ten-year simulation period.

For obtaining the correction factors, ten-year runs were made for scenarios with one of the 15 water management options implemented in all of the subregions of the surrounding area. The computed effects on the downward seepage from the *Groote Peel* are shown in Table 14 for a selected number of the subregions. Only these selected subregions of the *Groote Peel* were used because it was found that the followed procedure did not work well with subregions that have a very high downward seepage or that have a very small area.

Comparison of Tables 14 and 15 shows that for many of the options the effects computed with the ten-year runs (with a certain option implemented in the whole region) are very different from the summated effects of the one-year runs. The options considered to be really problematic are 9, 12, 13, 15, and 16. (Option 4 could perhaps have also been included in this list.) In some cases the sign is even opposite (9, 12 and 16). There are various reasons for these anomalies. To start with the one-year runs underestimate the effect of surface water supply, usually by at least 100%. The reason for this is that in the one-year runs, which are from October 1 to October 1, the surface water supply only comes into effect half way through the simulation year, i.e. at the beginning of the summer season (April 1). In the ten-year runs, however, the effect of surface water supply continues throughout the winter in the form of structurally higher groundwater levels. This is especially so in the subregions with a high downward seepage in the southern half of the study region. So the surface water supply has an effect on the regional hydrology the whole year round, even though the supply only actually takes place during the summer season.

A large deviation can also be caused by the circumstance that an option combines characteristics that have counteracting effects on the downward seepage from the *Groote Peel*. In the case of option 13, for example, expansion of drainage (leading to more downward seepage from the *Groote Peel*) is combined with implementation of a surface water supply scheme (leading to less downward seepage from the *Groote Peel*). That the sum of the seepage reductions computed from the one-year runs is so much smaller than the long-term average computed from the ten-year run is because in the chosen one-year simulation period the effect of drainage during the wet winter unduly dominates the effect of surface water infiltration during the summer. Apparently the chosen one-year simulation period has a relatively too wet winter. Instead of repeating the sensitivity analyses with a different one-year period, a more pragmatic approach was followed: the undue dominance was reduced by including only 50% of the winter effect in the summation of the one-year runs. The results of these summations are given in Table 16. As can be seen from the table, the summation of one-year effects is for option 13 now more

Table 14 Long-term averages of the downward seepage (from selected subregions of the Groote Peel) in the reference situation (option 1 of Table 13) and the relative changes computed for scenarios in which a certain option is implemented in all the subregions of the surrounding area. Values in 1000 $m^3.yr^{-1}$

Option	Subregion of the Groote Peel						
	1	2	3	4	8	9	16
1	233.2	149.3	222.4	81.8	104.9	196.5	272.1
2	-50.3	-50.5	-61.3	-41.0	-28.3	-67.6	-230.8
3	24.0	25.9	32.0	22.8	15.7	19.9	56.4
4	-7.8	-10.1	-13.3	-9.9	-7.0	-15.1	-19.8
5	-29.3	-36.6	-45.0	-30.8	-21.2	-47.2	-76.6
6	-106.8	-119.6	-148.8	-101.4	-65.6	-177.5	-394.3
7	-35.9	-45.4	-55.9	-39.3	-28.0	-67.3	-98.9
8	12.2	11.7	14.1	9.3	6.2	6.9	28.8
9	-20.3	-26.1	-32.3	-22.8	-14.7	-33.2	-51.9
10	8.3	7.9	9.2	6.4	4.3	6.3	29.7
11	32.3	33.5	40.8	29.0	20.1	23.9	84.0
12	0.9	-2.0	-3.6	-3.0	-2.5	-7.0	11.8
13	-20.3	-27.8	-34.4	-23.1	-16.4	-37.2	-42.0
14	-26.8	-37.0	-45.7	-31.4	-23.2	-56.7	-62.9
15	21.8	20.4	23.8	16.2	10.8	12.9	59.6
16	-13.2	-17.1	-22.0	-15.9	-10.3	-24.8	-36.2

Table 15 Summated effects (on the downward seepage from the Groote Peel) of one-year 'spatial sensitivity' runs for the 16 options of Table 13. (The effect of the reference option is per definition zero.) Each summation is over the 67 subregions for which one-year runs have been made. Values in 1000 $m^3.yr^{-1}$

Option	Subregion of the Groote Peel						
	1	2	3	4	8	9	16
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	-63.1	-49.9	-69.6	-35.4	-21.6	-63.2	-226.0
3	31.1	32.5	48.4	20.3	12.2	49.8	85.7
4	-1.2	-1.7	-4.2	-2.8	-1.6	-7.4	-4.2
5	-12.7	-14.6	-28.0	-13.3	-8.3	-28.0	-34.8
6	-88.7	-79.1	-119.9	-57.3	-34.3	-112.0	-296.8
7	-15.8	-18.5	-34.6	-16.9	-10.5	-38.8	-43.1
8	28.9	29.3	43.1	17.9	10.5	42.3	80.8
9	2.3	2.4	0.6	-0.4	0.8	8.3	13.2
10	12.5	14.6	20.3	11.5	6.8	22.4	40.7
11	45.3	47.4	71.0	33.6	20.2	75.0	132.6
12	11.3	12.9	16.1	8.7	5.2	15.0	36.5
13	-3.2	-3.4	-11.6	-3.1	-1.9	-8.3	0.4
14	-8.2	-9.8	-23.4	-8.7	-5.4	-22.4	-11.0
15	44.1	45.7	66.8	30.8	18.6	67.6	128.4
16	11.2	12.9	15.5	9.8	6.6	26.8	46.8

***Table 16** Summated effects (on the downward seepage from the Groote Peel) of one-year 'spatial sensitivity' runs for the 15 options: as in Table 15, but with the effects computed for the <u>winter period</u> counted for only <u>50%</u>. Values in 1000 $m^3.yr^{-1}$.*

Option	Subregion of the Groote Peel						
	1	2	3	4	8	9	16
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	-49.1	-34.9	-50.5	-26.0	-16.2	-47.3	-180.3
3	31.1	32.5	48.4	20.3	12.2	49.8	85.7
4	-1.2	-1.7	-4.2	-2.8	-1.6	-7.4	-4.2
5	-12.7	-14.6	-28.0	-13.3	-8.3	-28.0	-34.8
6	-74.8	-64.1	-100.8	-47.9	-28.9	-96.1	-251.1
7	-15.8	-18.5	-34.6	-16.9	-10.5	-38.8	-43.1
8	28.9	29.3	43.1	17.9	10.5	42.3	80.8
9	2.3	2.4	0.6	-0.4	0.8	8.3	13.2
10	7.1	10.7	12.4	7.8	4.7	14.2	15.2
11	39.9	43.5	63.2	29.9	18.1	66.9	107.1
12	5.9	9.0	8.3	5.0	3.1	6.9	11.0
13	-8.6	-7.3	-19.5	-6.9	-4.0	-16.5	-25.1
14	-13.7	-13.8	-31.3	-12.5	-7.5	-30.6	-36.5
15	38.7	41.8	59.0	27.1	16.5	59.4	102.9
16	5.8	9.0	7.7	6.0	4.5	18.6	21.3

in the order of magnitude of the long-term average given in Table 14. For options 9,12,15 and 16 the problems remain, however.

The problems with options 9, 12, 15 and 16 could of course have been solved by repeating the sensitivity analyses for a longer period. Since this was not possible from a practical point of view, recourse had to be taken to the method of 'constructing' an option from its basic characteristics. The characteristics of option 9, for instance, is also contained in options 3 and 5:

- option 3 involves sprinkling from groundwater;
- option 5 involves implementation of a surface water supply scheme and a supply rate of 0.17 $l.s^{-1}.ha^{-1}$.

The sum of the effects of options 3 and 5 is according to the ten-year results (Table 14) for subregion 1, for instance, 24000 - 29300 = -5300 $m^3.yr^{-1}$. This is very much different from the ten-year result for option 9, being -20300 $m^3.yr^{-1}$. That option 9 indicates a much greater reduction of downward seepage from subregion 1 than the sum of the two options can easily be explained from the influence that groundwater sprinkling has on the effect of surface water supply: extraction of groundwater for sprinkling causes a lowering of the groundwater levels, which in turn induces a higher infiltration rate of the supplied surface water. This observation led to an interpretation of the above given figures in the following manner:

$$e_9 = e_3 + c_f \cdot e_5, \quad \text{or} \quad -20300 = 24000 + 1.51 * (-29300)$$

Thus the extraction of sprinkling from groundwater induces a 51% increase of the effect of surface water supply. A similar approach has been followed for options 12, 15 and 16. In Table 17 the calculated correction factors are summarized. That these factors are

***Table 17** Correction factors for translating effects computed with one-year runs to the long-term averages computed with 10-year runs. The values relate the one-year values (with the winter effect counted for 50%, Table 16) obtained with the 'spatial sensitivity analyses' to the long-term averages obtained from the ten-year runs (Table 14). In the case of the options earmarked with a '*', a different procedure had to be followed. For these options the listed factors have the following meaning (applied to data of Table 14):*

$e_9 = e_3 + c_f \cdot e_5$; $e_{12} = e_{10} + c_f \cdot e_4$; $e_{15} = e_{11} + c_f \cdot e_4$; $e_{16} = e_{11} + c_f \cdot e_5$.

Option	Subregion of the Groote Peel						
	1	2	3	4	8	9	16
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	1.02	1.45	1.21	1.58	1.75	1.43	1.28
3	0.77	0.80	0.66	1.12	1.29	0.40	0.66
4	6.48	5.94	3.17	3.54	4.39	2.04	4.72
5	2.31	2.51	1.61	2.32	2.55	1.69	2.20
6	1.43	1.87	1.48	2.12	2.27	1.85	1.57
7	2.27	2.46	1.62	2.32	2.66	1.73	2.29
8	0.42	0.40	0.33	0.52	0.59	0.16	0.36
*9	1.51	1.42	1.43	1.48	1.44	1.12	1.41
10	1.17	0.74	0.74	0.81	0.90	0.45	1.95
11	0.81	0.77	0.65	0.97	1.11	0.36	0.78
*12	0.96	0.98	0.96	0.94	0.96	0.88	0.90
13	2.36	3.81	1.76	3.35	4.11	2.25	1.67
14	1.96	2.68	1.46	2.51	3.10	1.85	1.72
*15	1.35	1.30	1.28	1.28	1.33	0.73	1.23
*16	1.83	1.54	1.57	1.67	1.58	1.20	2.20

different for the different subregions of the *Groote Peel* is due to the fact that each subregion is dominated by a different part of the surrounding area. And each part of the surrounding area differs from the next. This variation of characteristics is also illustrated by Fig. 47, in which the the influence of surface water supply (option 5) on the downward seepage from subregion 1 of the *Groote Peel* is shown. One would expect that the subregions directly next to subregion 1 would have the greatest effect (the effects have been normalized to eliminate the influence of the size of a subregion), but this is found to be not the case. The reason being that in the area directly next to subregion 1 there is upward seepage, meaning that the groundwater levels are already rather high. This means that not much of the supplied surface water can infiltrate, leading to a relatively small effect on the *Groote Peel.*

Though the described procedure for obtaining the response matrices has a make-shift appearance, in practice it was found that verification of scenarios generated with the simplified model indicated that the obtained results corroborated quite well with the results of the ten-year simulations, as will be substantiated below. Furthermore, it is important to realize that the function of the simplified model is that it should serve the purpose of producing scenarios that are more effective than scenarios obtained simply through straightforward specification. This means that mathematical formalism – though as such desirable – is a secondary aspect, and not a prerequisite for achieving a certain degree of success.

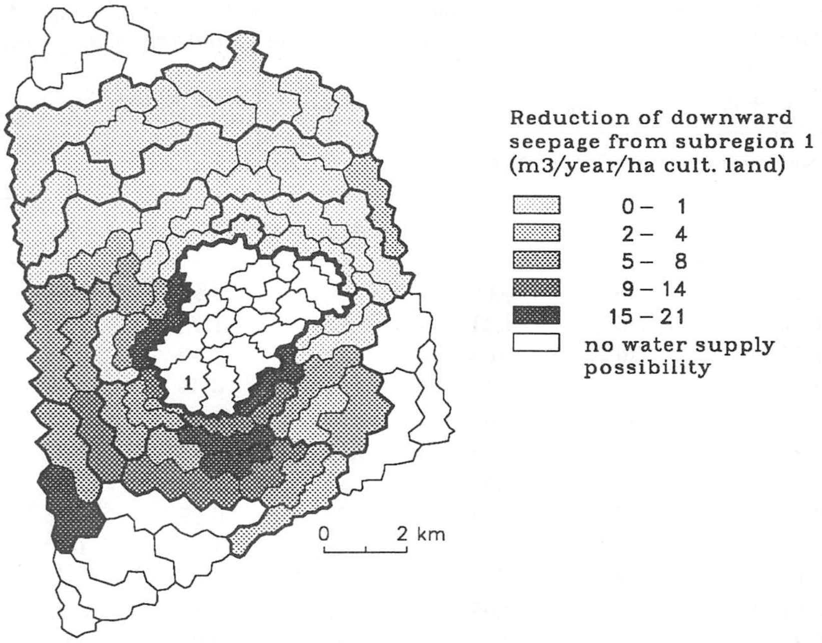

Fig. 47 ***Influence of surface water supply to the surrounding area on the downward seepage from subregion 1 of the Groote Peel, obtained by making a 'spatial sensitivity analysis' with SIMGRO. (Followed by applying the appropriate correction factor for making the translation to effects on long-term averages.) The influence has been normalized with respect to the area of a subregion, to avoid distortion.***

Apart from effects on the downward seepage from the *Groote Peel*, the water management options have of course also an influence on the economic performance of the surrounding area. Partly these effects are 'local', for instance the increased crop production as a consequence of sprinkling, partly they are regional, being a consequence of effects transmitted by the regional hydrologic system. The latter effects are similar to the effects on the downward seepage from the *Groote Peel*. For translating results obtained with the one-year simulations to long-term averages, correction factors were used in a fashion similar to what has been described above.

Apart from coefficients pertaining to the 16 water management options, the objective function matrix (economic performance part) also contains the cost coefficients of the surface water supply schemes given in Table 10.

Buying of land (options involving water levels of 30 cm below soil surface) is a relatively very expensive measure. It is therefore pointless to subtract the cost of buying the land from the indicator for the economic performance of the region, because it would totally dominate it. Another reason for treating it separately is that the financial means for such a type of measure would be forthcoming from a different source (money for 'nature development') and then only in the long run, coupled to a complete restructuring of agriculture on a larger scale than that of the study region.

5.4.4 Constraint matrix

Because each of the water management options given in Table 13 is completely defined in terms of the 'basic' decisions (expansion of drainage etc.), the options are mutually exclusive, meaning that it is not possible to simultaneously implement more than one option at a time in a certain subregion. However, in many cases intermediate situations are possible. The mutual exclusivity of the options requires that the following constraint should be complied with:

$$\sum_{j=1}^{16} x_{i,j} = 1 \quad , \text{for all } i=1,\ldots,N \tag{5.3}$$

The relation between the x-vector and the y-vector (representing the discrete aspects) is defined in terms of the following mapping:

$$y = Dx \; , \tag{5.4}$$

where D is a matrix consisting of elements $d_{k,l}$ that have either the value '0' or '1'. An element $d_{k,l}$ has the value '1' if the l-th component of the decision vector x involves the k-th discrete decision. Through treating the y-vector as consisting of discrete variables in combination with Eq. 5.4, the discrete aspects of the x-vector are taken into account.

From a practical point of view it is not possible to within a partial scheme for increasing water supply (cf. Fig. 46) differentiate between subregions where extra supply is made possible and where it is not. This is enforced by including constraints of the type (the second index of y refers to the second discrete type decision, of the threesome drainage, surface water supply, and buying of land):

$$\begin{aligned} y_{i,2} &= z_1 \quad , \text{for all } i \text{ within partial scheme } A_{0,1} \\ y_{i,2} &= z_2 \quad , \text{for all } i \text{ within partial scheme } A_{0,2} \\ &\ldots\ldots \\ y_{i,2} &= z_{10} \; , \text{for all } i \text{ within partial scheme } C_3 \end{aligned} \tag{5.5}$$

The path that the extra surface water supply has to follow (see the arrows in Fig. 46) dictates which of the upstream schemes have to be implemented before implementation of a certain downstream scheme becomes possible. This is reflected in the model by constraints of the type

$$z_2 \geq z_1 \tag{5.6}$$

The total amount of surface water supply that is made available to the study region has consequences for the amount that is available for other regions in the wider surroundings, because the total amount of water (that is tapped from the river Meuse) is limited in supply. This makes it important to include a constraint on the total amount that can be used:

$$\sum_{i=1}^{N} \sum_{j=1}^{16} q_{i,j} x_{i,j} \leq Q_t \tag{5.7}$$

where

$q_{i,j}$ - supply of surface water required for implementing the option represented by the variable $x_{i,j}$

Q_t - total amount of surface water supply that is available

In order to investigate the impact of withdrawing land from agricultural production, the following constraint has been included:

$$\sum_{i=1}^{N} \sum_{j=1}^{16} a_{i,j} x_{i,j} \leq A_t \tag{5.8}$$

where

$a_{i,j}$ - area of land required for implementing the option represented by the variable $x_{i,j}$

A_t - total amount of land that can be purchased for 'nature development'

There are a number of additional constraints that are not described here in a formalized manner. One of these constraints is that the total sprinkled area should remain the same as in the current situation, and that only *substitution* of sprinkling from groundwater by sprinkling from surface water is possible. (This constraint has been made optional in the computer code.)

5.4.5 Computational implementation

The computational implementation of the model has been done as a Linear Programming problem, using GEMINI (Lebedev, 1984) for the pre-processing and MINOS (Murtagh and Saunders, 1985) for the optimization. The LP-formulation was extended with procedures for dealing with:
- the discreteness of certain variables;
- the multi-objectivity.

Concerning the discreteness of certain variables, it is important to realize in what way they are discrete, especially whether non-discrete values have any meaning at all. If the latter is the case, then the only way of adequately dealing with them is by using a formally 'correct' mathematical algorithm, e.g. the branch and bound method. In the present study, however, the discreteness of certain variables derived mainly from the fact that scenarios involving intermediate values were not of interest from a policy point of view. Also, some of the derived relations in the simplified model are only good approximations if the decision variables take on discrete values. These relations are, however, not totally invalid for intermediate values. For instance, partial implementation of an option involving extra supply of surface water does not lead to wildly inaccurate prediction of the impact on the *Groote Peel*, though the used cost estimate will be too low. Such variables are sometimes referred to as being pseudo-discrete (see for instance

Gill et al., 1981). Because the discrete aspect is less strict, mathematically less 'correct' procedures can be applied without the danger of yielding scenarios that are substantially suboptimal.

For taking into account the discreteness of certain variables, the following cyclic procedure was followed:
- a scenario was obtained using LP, with the discrete variables allowed to have intermediate values on the interval [0;1]
- each of the discrete variables that had not been set to either 0 or 1 by the LP-algorithm was forced to either of these values depending on which was the nearest.

This procedure was repeated until the optimized scenario had become completely discrete in the desired respect. The procedure was repeated as a whole for the three subsets of discrete variables, in the order: surface water supply schemes, buying of land, expansion of drainage.

For dealing with the multi-objectivity the so-called constraint method has been used. This method consists of the following two steps:
- the setting of a lower (or upper) bound on one of the two objective functions;
- optimization of the remaining objective function.

In order to ensure that a scenario is obtained that makes maximum use of the possibilities of a region (i.e. that it is 'Pareto-optimal'), the *shadow price* of the constrained objective function has to be examined. This can be done by looking at its sign, in relation to whether the constraint is an upper bound or a lower bound. If the shadow price indicates that the constraint was not active, the bound should be 'tightened' and the optimization repeated. Another method that guarantees Pareto optimality consists of performing a second optimization, using the obtained value of the optimized function as a bound and optimization of the objective function that was constrained in the first optimization.

5.5 Examples of generated scenarios

The model was not run in the 'on-line' mode that perhaps is suggested by the scheme given in Fig. 44. Instead, a Working Group of representatives from various government agencies and representatives from the agricultural community requested a series of runs to be made that could then be discussed with senior officials that actually have decision-making powers. Runs were made for four combinations of the amount of surface water made available (Q_t) and the area of land available for 'nature development' (A_t). For each combination the following procedure was followed:
- maximization of the positive effect on the *Groote Peel*, through maximizing the reduction of downward seepage ΔW, thus yielding ΔW_{opt};
- maximization of the economic performance ΔS of the region for three levels of ΔW, i.e. $0.99\Delta W_{opt}$, $0.90\Delta W_{opt}$, and $0.80\Delta W_{opt}$.

This made it possible to for each combination of Q_t and A_t make a trade-off curve between ΔW and ΔS, as shown in Fig. 48 (after translating effects on the downward seepage to the 'potential bog rea', using the relationship given in Fig. 34). An example

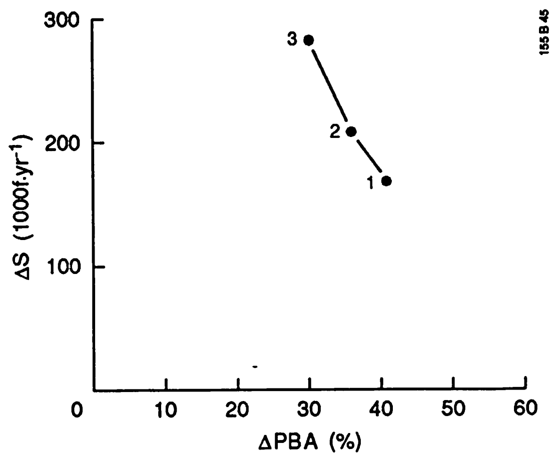

Fig. 48 ***Example of a trade-off curve between the increase of the 'potential bog area' (ΔPBA) and the change of economic performance of the surrounding area (ΔS) for a certain amount of surface water supply from an external source (the amount of land that can be bought for 'nature development' has been set to zero)***

Table 18 ***Comparison between the optimized reduction of the downward seepage from the Groote Peel, using the simplified model, and the verified value using the simulation model. The numbering of the scenarios corresponds to that in Fig. 48. The given given values are totals for subregions 1, 2, 3, 4, 8, 9, and 16.***

Scenario	**Optimized value (10^3 $m^3.yr^{-1}$)**	**Verified value (10^3 $m^3.yr^{-1}$)**	**Ratio (-)**
1	280	216	0.77
2	255	195	0.76
3	227	175	0.77

of a scenario for surface water supply is shown in Fig. 49a, and a scenario for the expansion of drainage in Fig. 49b.

The optimized scenarios were each verified with the simulation model, to get an idea of the accuracy of the simplified model. As can be seen from Table 18, the results obtained with the simulation model differ substantially from the ones obtained with the simplified model. (That the ratio between the optimized and verified value is nearly the same for all three of the scenarios is because, hydrologically speaking, the scenarios are not so very different from each other.) As has been argued before, however, the function of the simplified model is to be of use in the search for scenarios. A comparison between the efficacy of specified and optimized scenarios was made possible by the circumstance that the Working Group had formulated some scenarios that they considered to be worthwhile of investigation. Comparison with the scenarios obtained through optimization showed that for example the optimization made roughly 20% better use of the available surface water supply, as reported in Van Walsum (1990). Furthermore it was shown that – if combined with surface water supply – a substantial expansion of drainage could be allowed, without seeming to harm the bog reserve to a significant degree (see also Fig. 49b).

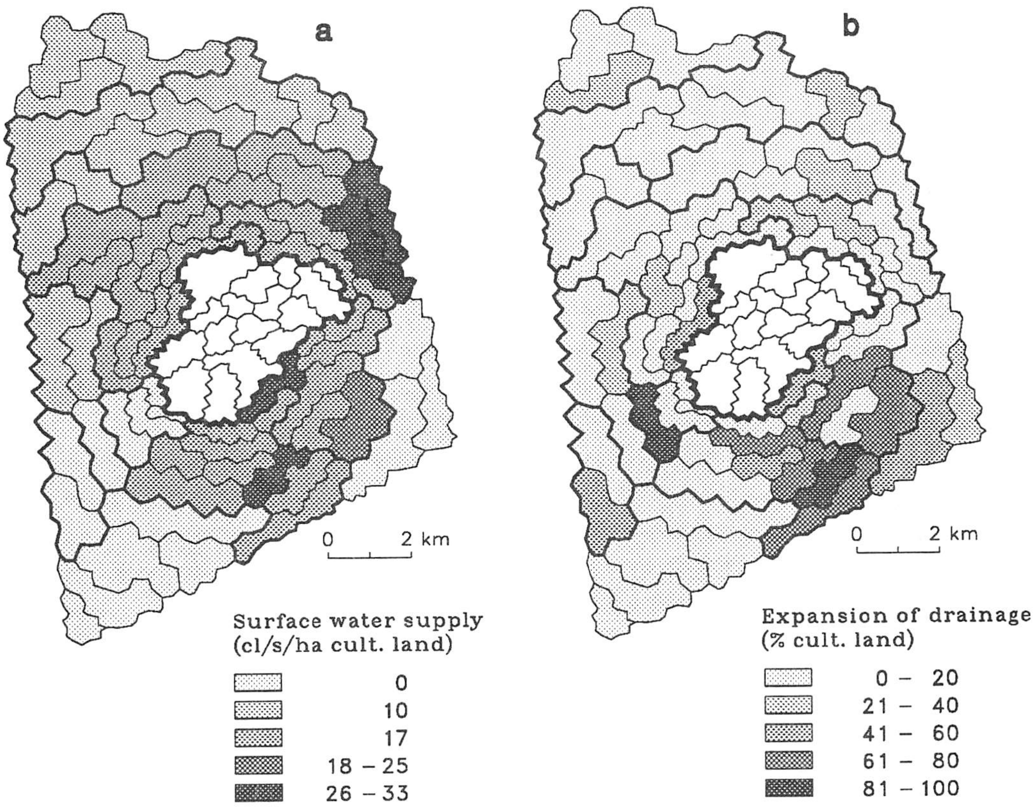

Fig. 49 Example of an optimized scenario for surface water supply (a) and expansion of drainage (b)

5 CONCLUDING REMARKS

A survey has been given of the modeling undertaken for providing decision support with respect to water management in the area surrounding the *Groote Peel*. The results having been reported elsewhere (*Projectgroep de Groote Peel*, 1990; Van Walsum, 1990) attention could be focused on the used algorithms, including results only by way of illustration.

The model SIMGRO as described in Querner & Van Bakel (1989), although essentially ripe for application to a wide range of situations in both agricultural areas and nature areas, required several adaptations to make it suitable for application to the *Groote Peel* and its surroundings. When using the model for the type of region considered and the kinds of questions that were to be answered, it became apparent on many occasions how vital it is to take the temporal variability of the regional hydrology into account. Furthermore, it was found that there simply is no substitute for making multi-year runs covering at least a ten year simulation period. Modelling approaches involving a 'representative year' (or 'representative summer' and 'representative winter') are thus doomed to misrepresent reality unless backed up by multi-year simulation runs.

The way in which the simulation model SIMGRO was implemented has various shortcomings. Partly this was due to the non-availability of GIS-procedures for setting the model up, and partly to the limited validation of the model. A thorough sensitivity analysis was also lacking. Lack of data (detailed water balances of the surrounding area) was a problem, but also the difficulty of bridging the gap between the model – which computes water levels that are representative for the whole 'influence' areas of nodes – and the point gaugings of the water levels. These point gaugings are rarely representative for larger areas. An accurate interpretation of water level data would therefore require being able to 'zoom in' with the model, using an explicit representation of the surface water system. By the latter is meant that the tertiary and secondary water courses should not simply be represented by 'drainage resistances' that apply to a whole nodal influence area of several hectares, but only by the entry resistance of the water courses themselves. The part of the resistance that is due to radial and horizontal flow in the vicinity of the water courses has then to be modeled through a very fine network of finite-elements (and extra layers, for a better approximation of the third dimension).

The availability of a zoom-in facility would not only be of great help in validating the model, but would also be of use in helping to bridge the gap between the regional modelling on the one hand and the very local scale of ecological impacts on the other. In this study the latter problem has been circumvented by using a macroscopic approach for translating the spatial variability of the peat thickness to the 'potential bog area'. This method is certainly open for improvement, though it will probably continue to be necessary to have a special proecdure for bridging the gap between regional hydrologic modelling and local ecological effects.

The developed simplified model served the purpose of finding scenarios that are more efficient than scenarios specified without the help of mathematical programming. The found scenarios make efficient use of available resources – for instance the surface water supply from external sources. Furthermore, the simplified model showed that a substantial area of agricultural land can be drained in the vicinity of the bog reserve without appearing to do much harm (except perhaps to the bird-foraging function of undrained lands). Such scenarios provide opportunities for reaching a compromise between nature conservation and agriculture.

Shortcomings of the simplified modeling were partly due to as yet unsolved methodological problems and partly to the lack of available CPU-power for deriving the coefficients of the response matrices. At the root of the methodological problems is the fact that the regional hydrologic system is non-linear, involving many types of feedback mechanisms. A shortcoming of the computational implementation of the simplified model is the use of a heuristic (adhoc) method for treating discrete variables. Whether this led to a lower efficacy in the search for scenarios remains yet to be investigated.

Finally it should be stated that the developed simplified model is still a working prototype; so much of this software still lacks the flexibility of easy application to other regions.

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ANNEX 1 Properties of soil physical units and pre-processed data for SIMGRO

The following soil physical units have been distinguished (between brackets the numbers are given of the corresponding units given in Drent (1989)):

The used schematization involves six units:
1 (-). Thin peat on a sandy subsoil
2.(-). Thickish peat on a sandy subsoil
3.(5). Slightly loamy sand ('HN21');
4.(7). Black 'beek' earth soil ('Zg');
5.(8). Slightly loamy fine sand ('HN23')
6.(9). Black 'dikke eerd' soil ('EZ').

The soil physical data used for the computations with CAPSEV are given in abbreviated form in Tables 1 and 2. Tables 3, 4 and 5 contain the data obtained with CAPSEV.

CAPSEV has been run with groundwater steps of 0.20 m at a time, i.e. with the same length of step as is used in the input file of SIMGRO. It is important that these two steps correspond; otherwise the numerical integration of the groundwater level changes in SIMGRO yields incorrect results for the storage fluctuations. For soil units 1 and 2 a pressure head of -300 cm has been used, and for the others a head of -500 cm (see Section 2.4.1). For soil physical units 1 and 2 the storage coefficient has been set to 0.15 in the cases that a lower value was calculated. Calculated capillary rise of more than 5 mm/d have been topped off and set equal to that value.

Table 1 Soil moisture contents (dimensionless fractions) as a function of the pressure head in the different layers of the soil physical units

Soil physical unit	Layer depth (cm b.s.s)	Pressure head (cm)									
		0	-10	-30	-50	-100	-200	-500	-1000	-2500	-16000
1	0-7	0.85	0.81	0.77	0.74	0.69	0.62	0.53	0.46	0.38	0.26
	8-19	0.93	0.89	0.86	0.84	0.78	0.67	0.32	0.15	0.11	0.06
	>19	0.41	0.35	0.28	0.22	0.14	0.09	0.07	0.06	0.05	0.03
2	0-22	0.85	0.81	0.77	0.74	0.69	0.62	0.53	0.46	0.38	0.26
	23-66	0.93	0.89	0.86	0.84	0.78	0.67	0.32	0.15	0.11	0.06
	>66	0.41	0.35	0.28	0.22	0.14	0.09	0.07	0.06	0.05	0.03
3	0-30	0.47	0.43	0.40	0.37	0.30	0.24	0.18	0.14	0.10	0.07
	>30	0.37	0.34	0.29	0.22	0.14	0.09	0.06	0.05	0.04	0.02
4	0-40	0.55	0.50	0.47	0.45	0.41	0.36	0.30	0.25	0.20	0.14
	>40	0.39	0.35	0.32	0.29	0.22	0.16	0.13	0.11	0.09	0.06
5	0-30	0.46	0.43	0.41	0.39	0.34	0.28	0.20	0.17	0.13	0.08
	>30	0.34	0.33	0.31	0.29	0.22	0.16	0.11	0.08	0.06	0.04
6	0-30	0.48	0.44	0.41	0.38	0.32	0.26	0.21	0.17	0.13	0.08
	>30	0.36	0.33	0.30	0.27	0.20	0.14	0.10	0.08	0.06	0.03

Table 2** **Unsaturated conductivity as a function of the pressure head for the different layers of the soil physical units. Values in cm.d^{-1}.

Soil physical unit	Layer depth (cm b.s.s.)	Pressure head (cm)						
		0	-5	-10	-50	-100	-1000	-10000
1	0-7	1.80E+1	9.80E+0	5.80E+0	1.50E-1	4.70E-2	9.00E-5	5.00E-6
	8-19	8.50E+0	1.50E+0	7.50E-1	1.50E-1	5.00E-2	1.60E-3	4.00E-5
	>19	8.50E+0	4.00E+0	1.00E+0	1.20E-1	4.20E-2	1.20E-3	3.00E-5
2	0-22	1.80E+1	9.80E+0	5.80E+0	1.50E-1	4.70E-2	9.00E-5	5.00E-6
	23-66	8.50E+0	1.50E+0	7.50E-1	1.50E-1	5.00E-2	1.60E-3	4.00E-5
	>66	8.50E+0	4.00E+0	1.00E+0	1.20E-1	4.20E-2	1.20E-3	3.00E-5
3	0-30	1.69E+2	1.40E+2	4.14E+1	2.44E+0	7.20E-1	1.25E-2	2.18E-4
	>30	3.00E+2	1.57E+2	7.90E+1	1.16E+1	4.51E-1	3.98E-5	1.58E-6
4	0-40	2.31E+2	1.36E+2	3.98E+1	2.30E+0	6.75E-1	1.15E-2	1.95E-4
	>40	7.00E+1	4.12E+1	2.43E+1	3.49E-1	1.74E-3	1.58E-4	6.28E-6
5	0-30	2.40E+2	7.55E+1	2.34E+1	1.54E+0	4.78E-1	9.75E-3	1.99E-4
	>30	7.00E+1	4.58E+1	2.99E+1	9.98E-1	1.42E-2	1.58E-4	6.28E-6
6	0-30	1.32E+2	7.55E+1	2.34E+1	1.54E+0	4.78E-1	9.75E-3	1.99E-4
	>30	1.00E+0	4.58E+1	2.99E+1	9.98E-1	1.42E-2	1.58E-4	6.28E-6

Table 3** **Equilibrium soil moisture content of the root zone calculated with CAPSEV for a root zone depth of 25 cm, for six soil physical units. Values in mm.

Groundwater depth (m b.s.s.)	Soil physical unit					
	1	2	3	4	5	6
0.0	193.4	212.2	116.1	146.8	114.7	122.1
0.2	187.9	206.7	109.3	135.4	109.4	115.0
0.4	174.7	196.1	101.8	125.3	102.8	106.0
0.6	166.6	188.3	94.4	118.5	96.0	100.2
0.8	159.7	183.3	84.1	112.2	89.7	92.6
1.0	153.8	178.3	76.8	107.5	85.0	86.0
1.2	147.8	173.5	71.5	103.4	80.7	81.0
1.4	143.2	169.4	67.9	99.8	76.4	77.3
1.6	139.2	165.9	64.8	96.5	72.6	74.0
1.8	135.3	162.4	62.1	93.8	69.5	71.3
2.0	131.7	159.5	59.8	91.4	66.6	68.9

Table 4** **Equilibrium soil moisture content of the root zone calculated with CAPSEV for a root zone depth of 50 cm, for six soil physical units. Values in mm.

Groundwater depth (m b.s.s.)	Soil physical unit					
	1	2	3	4	5	6
0.0	295.3	441.8	208.3	272.6	205.5	244.2
0.2	289.8	436.4	201.5	261.2	200.3	237.0
0.4	269.6	422.4	190.3	243.6	191.4	223.6
0.6	242.6	404.6	171.0	226.1	180.1	207.7
0.8	220.5	392.7	144.6	213.2	168.6	194.4
1.0	202.6	382.6	123.9	199.7	157.1	180.6
1.2	188.5	372.8	111.5	189.2	146.0	168.5
1.4	178.0	362.8	102.6	180.4	136.3	159.3
1.6	170.6	352.7	96.2	173.0	128.0	152.2
1.8	163.9	344.3	90.7	166.6	121.0	146.1
2.0	157.9	336.4	86.0	161.2	114.9	140.8

Table 5 ***Equilibrium soil moisture content of the root zone calculated with CAPSEV for a root zone depth of 100 cm, for six soil physical units. Values in mm.***

Groundwater depth (m b.s.s.)	Soil physical unit 1	2	3	4	5	6
0.0	499.1	717.1	392.7	461.6	375.3	423.1
0.2	493.5	711.7	385.9	450.2	370.1	416.0
0.4	473.3	697.7	374.7	432.5	361.2	402.5
0.6	442.9	678.3	353.7	412.2	349.4	383.8
0.8	401.5	652.5	315.8	387.4	333.6	359.8
1.0	352.2	615.7	271.5	355.5	314.3	331.4
1.2	308.0	579.6	230.1	325.7	291.9	308.2
1.4	274.6	548.3	196.6	296.8	268.8	289.5
1.6	251.0	522.1	175.3	273.3	247.0	275.5
1.8	233.5	500.9	160.0	254.9	229.0	261.1
2.0	220.1	484.3	148.2	240.2	213.8	245.2

Table 6 ***Capillary rise calculated with CAPSEV for a root zone depth of 25 cm, for six soil physical units. Values in*** $mm.d^{-1}$.

Groundwater depth (m b.s.s.)	Soil physical unit 1	2	3	4	5	6
0.0	5.00	5.00	5.00	5.00	5.00	5.00
0.2	5.00	5.00	5.00	5.00	5.00	5.00
0.4	5.00	5.00	5.00	5.00	5.00	5.00
0.6	5.00	5.00	5.00	5.00	5.00	5.00
0.8	2.40	2.56	2.22	5.00	5.00	5.00
1.0	1.32	1.30	0.26	4.66	2.20	3.35
1.2	0.78	0.76	0.10	1.07	0.59	1.79
1.4	0.49	0.45	0.10	0.36	0.24	1.05
1.6	0.31	0.28	0.10	0.17	0.13	0.66
1.8	0.19	0.16	0.10	0.10	0.10	0.43
2.0	0.10	0.10	0.10	0.10	0.10	0.30

Table 7 ***Phreatic storage coefficient (dimensionless) calculated with CAPSEV for a root zone depth of 25 cm, for six soil physical units.***

Groundwater depth (m b.s.s.)	Soil physical unit 1	2	3	4	5	6
0.2	0.15	0.15	0.03	0.04	0.02	0.03
0.4	0.15	0.15	0.05	0.07	0.02	0.05
0.6	0.24	0.15	0.11	0.08	0.04	0.11
0.8	0.22	0.18	0.18	0.13	0.12	0.32
1.0	0.24	0.23	0.22	0.27	0.10	0.12
1.2	0.25	0.27	0.24	0.19	0.13	0.13
1.4	0.26	0.29	0.25	0.23	0.16	0.15
1.6	0.28	0.28	0.25	0.25	0.18	0.17
1.8	0.28	0.28	0.37	0.25	0.19	0.19
2.0	0.28	0.28	0.37	0.37	0.19	0.19

Table 8 ***Rooting depths of the technologies (in m), for six soil physical units.***

Technology	Soil physical unit 1	2	3	4	5	6
Arable land, non-sprinkled	0.25	0.25	0.35	0.50	0.25	0.50
Maize, non-sprinkled	0.25	0.25	0.40	0.80	0.30	0.80
Grassland, non-sprinkled	0.20	0.20	0.30	0.50	0.25	0.60
Arable land, sprinkled	0.25	0.25	0.35	0.50	0.25	0.50
Maize, sprinkled	0.25	0.25	0.40	0.80	0.30	0.80
Grassland, sprinkled	0.20	0.20	0.30	0.50	0.25	0.60
Deciduous forest	1.00	1.00	1.00	1.00	1.00	1.00
Pine forest	1.00	1.00	1.00	1.00	1.00	1.00
Nature area	0.30	0.30	0.30	0.50	0.25	0.60

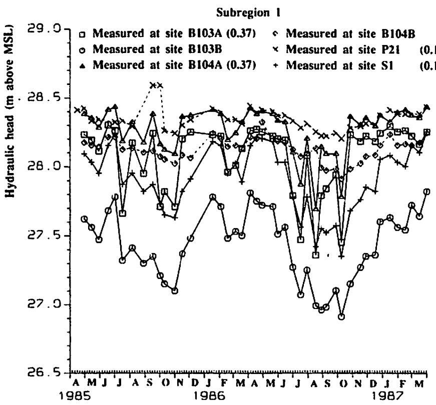
ANNEX 2 Measured and simulated water-level trajectories

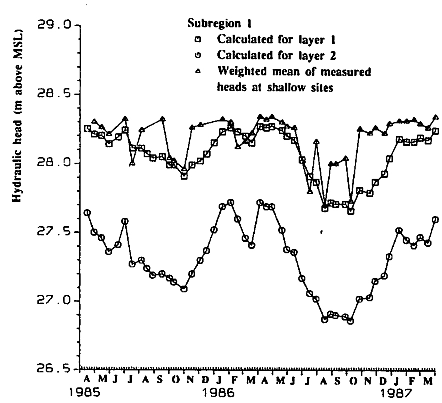
The water level data have been divided into three subsets:
1. Data for the *Groote Peel*, for the period 1/4/1985 - 1/4/1987
2. Data for the *Groote Peel*, for the period 1/4/1987 - 15/9/1989
3. Data for the surrounding area, for the period 1/4/1985 - 1/4/1987

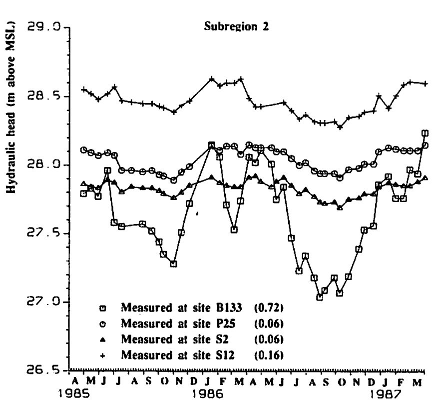
The division into periods is due to the fact that as from April 1 1987 a cutback in the monitoring program came into effect, leading to a reduction of the number of measurement sites. The location map of the measurement sites can be found in Joosten and Bakker (1987).

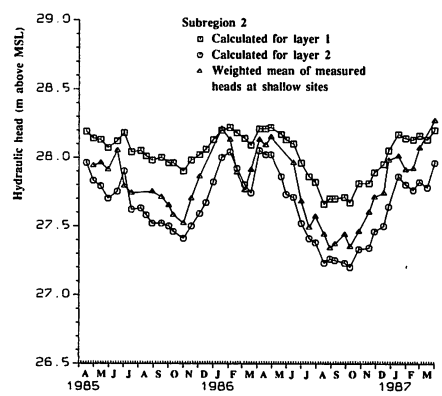
2.1 Data for the *Groote Peel*, for the period 1/4/1985 - 1/4/1987

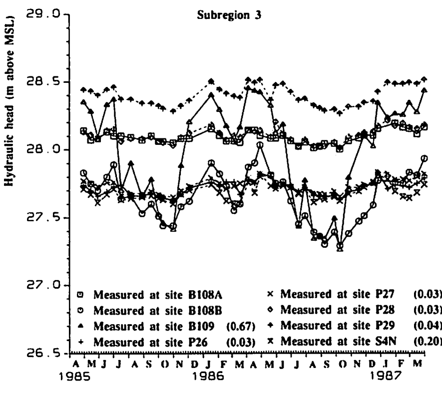
In the left-hand column of the subsequent pages the measured trajectories are given for the sites within the 16 subregions. In the right-hand column the corresponding trajectories are given of the simulated hybrid water level and the weighted mean of the measured trajectories. The used weights for calculating the weighted mean are listed on the plots in the left-hand column.

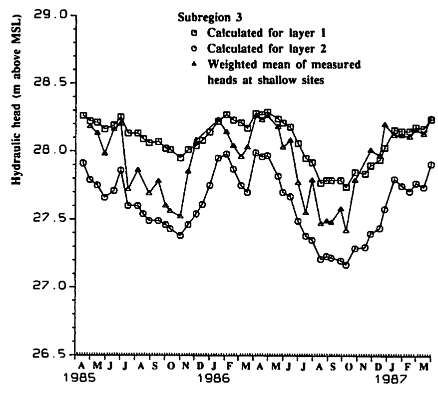


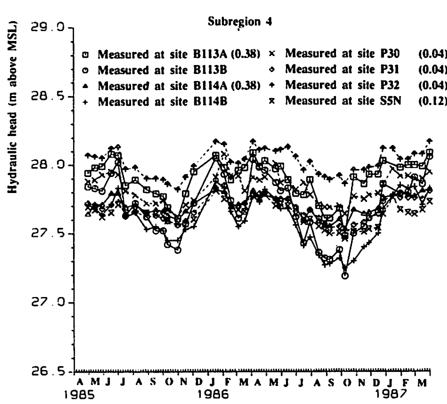


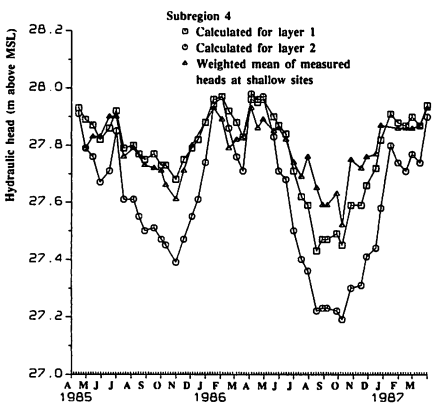


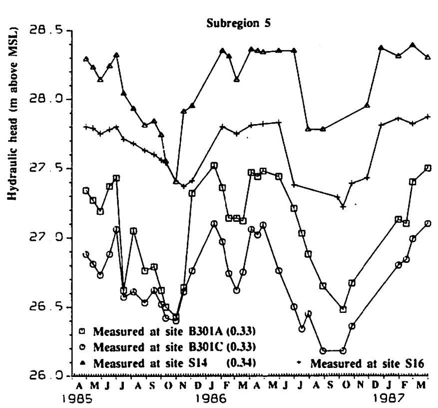


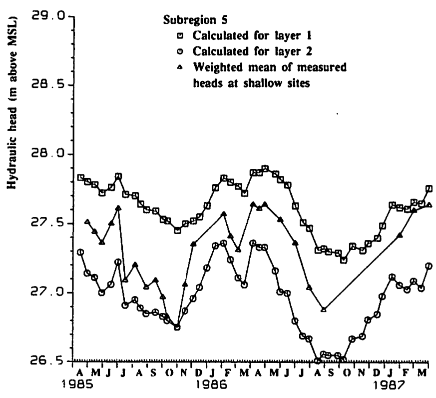

Subregion 3
Hydraulic head (m above MSL)
Measured at site B108A
Measured at site B108B
Measured at site B109 (0.67)
Measured at site P26 (0.03)
Measured at site P27 (0.03)
Measured at site P28 (0.03)
Measured at site P29 (0.04)
Measured at site S4N (0.20)
1985
1986
1987

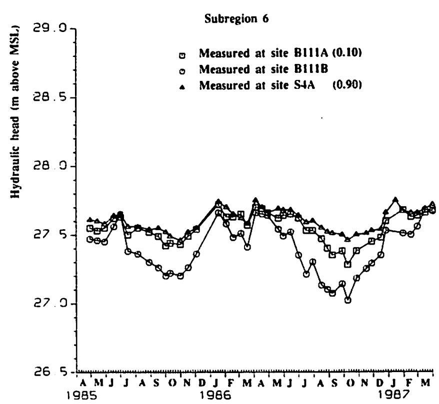

Subregion 3
Calculated for layer 1
Calculated for layer 2
Weighted mean of measured heads at shallow sites
Hydraulic head (m above MSL)
1985
1986
1987

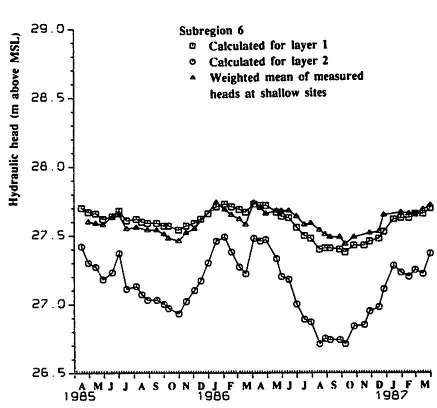

Subregion 4
Hydraulic head (m above MSL)
Measured at site B113A (0.38)
Measured at site B113B
Measured at site B114A (0.38)
Measured at site B114B
Measured at site P30 (0.04)
Measured at site P31 (0.04)
Measured at site P32 (0.04)
Measured at site S5N (0.12)
1985
1986
1987

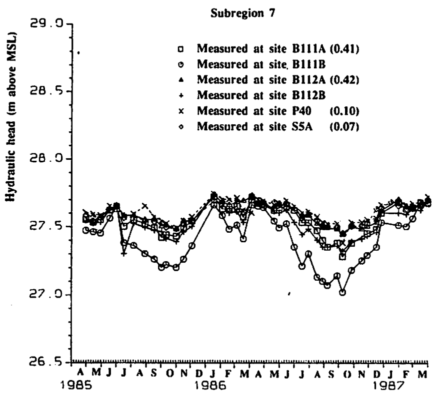

Subregion 4
Calculated for layer 1
Calculated for layer 2
Weighted mean of measured heads at shallow sites
Hydraulic head (m above MSL)
1985
1986
1987

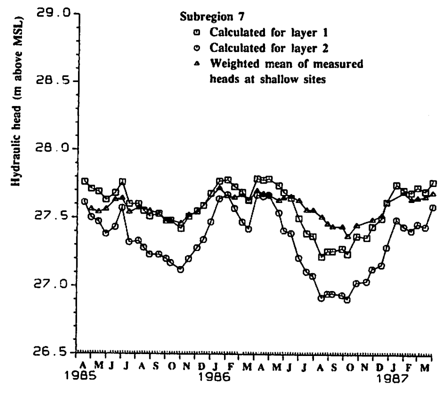

Subregion 5
Hydraulic head (m above MSL)
Measured at site B301A (0.33)
Measured at site B301C (0.33)
Measured at site S14 (0.34)
Measured at site S16
1985
1986
1987

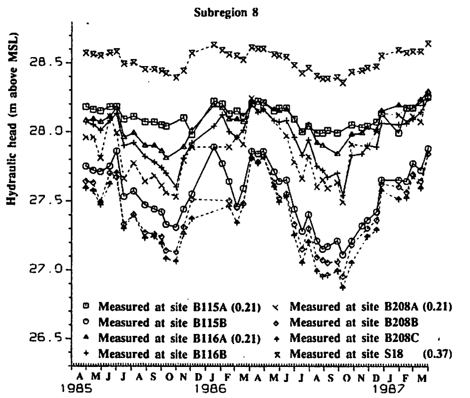

Subregion 5
Calculated for layer 1
Calculated for layer 2
Weighted mean of measured heads at shallow sites
Hydraulic head (m above MSL)
1985
1986
1987

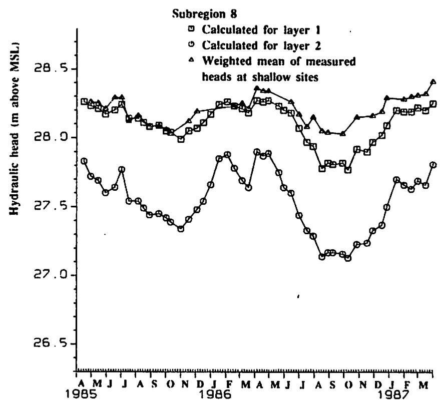

Subregion 6
Hydraulic head (m above MSL)
Measured at site B111A (0.10)
Measured at site B111B
Measured at site S4A (0.90)
1985
1986
1987

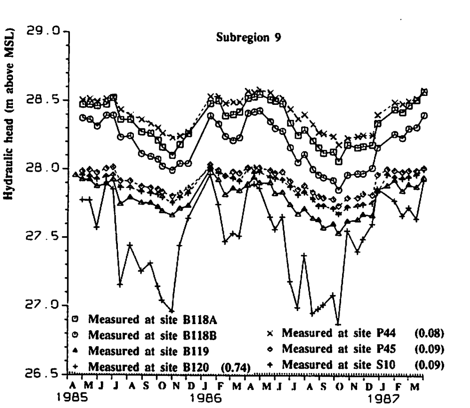

Subregion 6
Calculated for layer 1
Calculated for layer 2
Weighted mean of measured heads at shallow sites
Hydraulic head (m above MSL)
1985
1986
1987

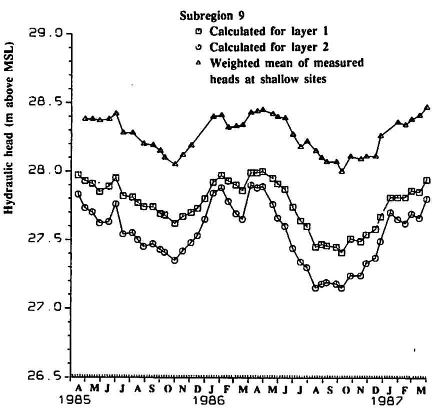

Subregion 7
Measured at site B111A (0.41)
Measured at site B111B
Measured at site B112A (0.42)
Measured at site B112B
Measured at site P40 (0.10)
Measured at site S5A (0.07)
Hydraulic head (m above MSL)
A M J J A S O N D J F M A M J J A S O N D J F M
1985 1986 1987

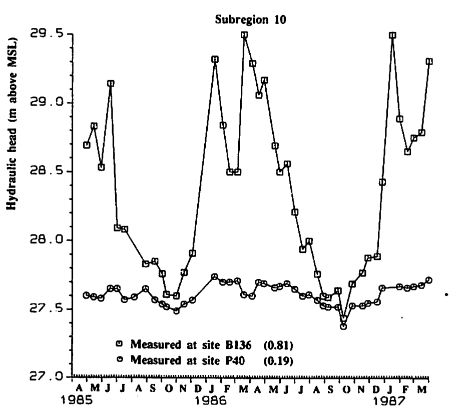

Subregion 7
Calculated for layer 1
Calculated for layer 2
Weighted mean of measured heads at shallow sites
Hydraulic head (m above MSL)
A M J J A S O N D J F M A M J J A S O N D J F M
1985 1986 1987

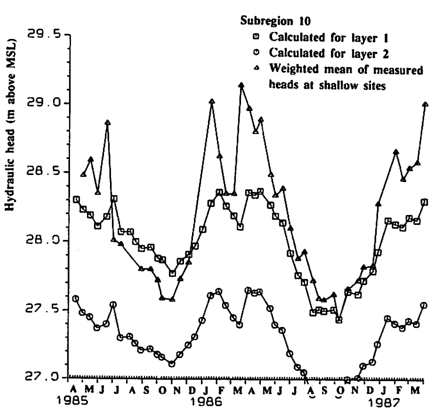

Subregion 8
Measured at site B115A (0.21)
Measured at site B115B
Measured at site B116A (0.21)
Measured at site B116B
Measured at site B208A (0.21)
Measured at site B208B
Measured at site B208C
Measured at site S18 (0.37)
Hydraulic head (m above MSL)
A M J J A S O N D J F M A M J J A S O N D J F M
1985 1986 1987

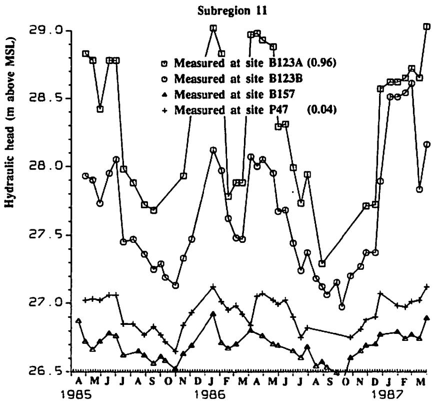

Subregion 8
Calculated for layer 1
Calculated for layer 2
Weighted mean of measured heads at shallow sites
Hydraulic head (m above MSL)
A M J J A S O N D J F M A M J J A S O N D J F M
1985 1986 1987

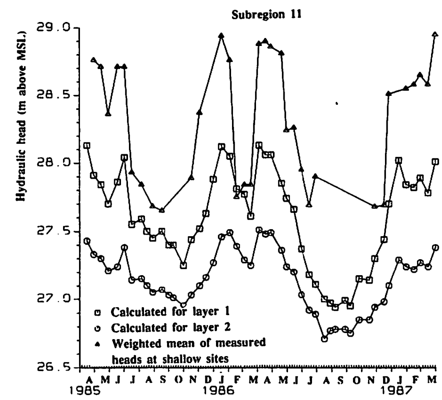

Subregion 9
Measured at site B118A
Measured at site B118B
Measured at site B119
Measured at site B120 (0.74)
Measured at site P44 (0.08)
Measured at site P45 (0.09)
Measured at site S10 (0.09)
Hydraulic head (m above MSL)
A M J J A S O N D J F M A M J J A S O N D J F M
1985 1986 1987

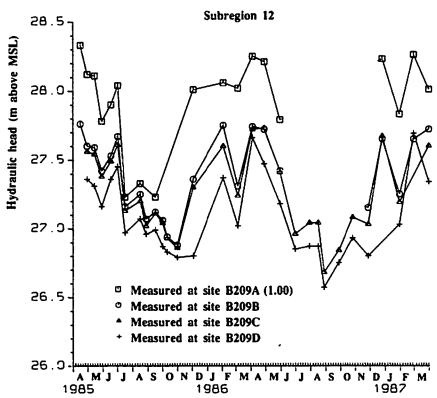

Subregion 9
Calculated for layer 1
Calculated for layer 2
Weighted mean of measured heads at shallow sites
Hydraulic head (m above MSL)
A M J J A S O N D J F M A M J J A S O N D J F M
1985 1986 1987

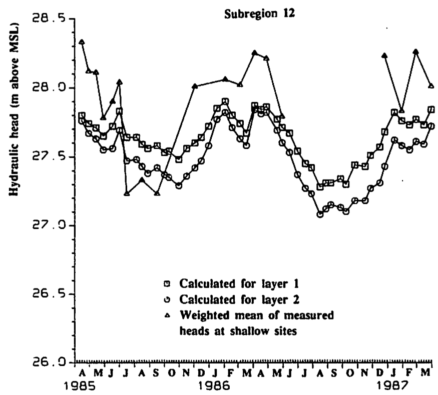

Subregion 10
Measured at site B136 (0.81)
Measured at site P40 (0.19)
Hydraulic head (m above MSL)
A M J J A S O N D J F M A M J J A S O N D J F M
1985 1986 1987

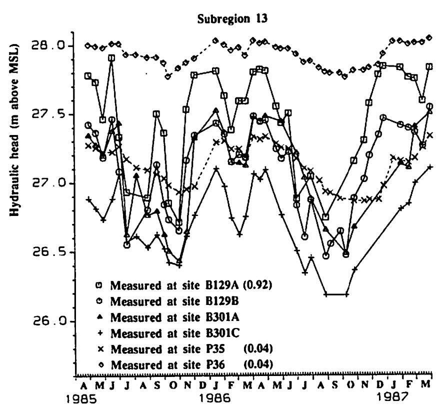

Subregion 10
Calculated for layer 1
Calculated for layer 2
Weighted mean of measured heads at shallow sites
Hydraulic head (m above MSL)
A M J J A S O N D J F M A M J J A S O N D J F M
1985 1986 1987

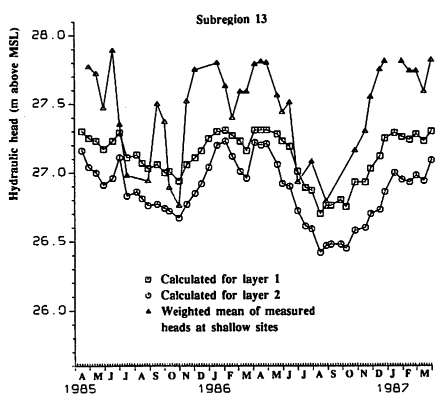

Subregion 11
Measured at site B123A (0.96)
Measured at site B123B
Measured at site B157
Measured at site P47 (0.04)
Hydraulic head (m above MSL)
29.0
28.5
28.0
27.5
27.0
26.5
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

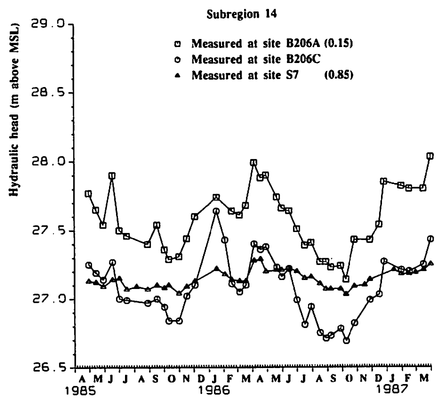

Subregion 11
Calculated for layer 1
Calculated for layer 2
Weighted mean of measured heads at shallow sites
Hydraulic head (m above MSL)
29.0
28.5
28.0
27.5
27.0
26.5
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

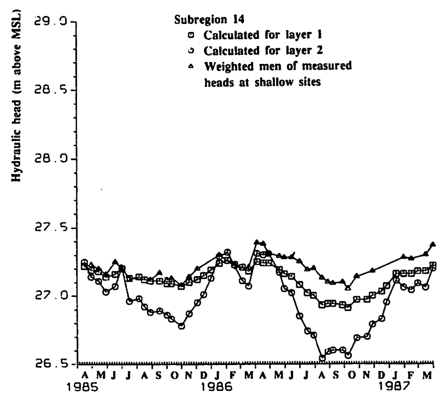

Subregion 12
Measured at site B209A (1.00)
Measured at site B209B
Measured at site B209C
Measured at site B209D
Hydraulic head (m above MSL)
28.5
28.0
27.5
27.0
26.5
26.0
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

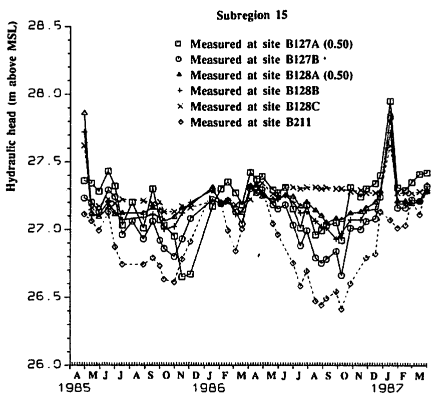

Subregion 12
Calculated for layer 1
Calculated for layer 2
Weighted mean of measured heads at shallow sites
Hydraulic head (m above MSL)
28.5
28.0
27.5
27.0
26.5
26.0
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

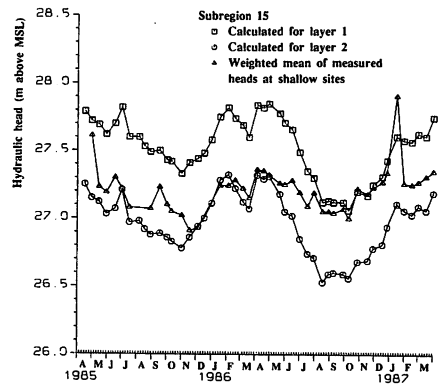

Subregion 13
Measured at site B129A (0.92)
Measured at site B129B
Measured at site B301A
Measured at site B301C
Measured at site P35 (0.04)
Measured at site P36 (0.04)
Hydraulic head (m above MSL)
28.0
27.5
27.0
26.5
26.0
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

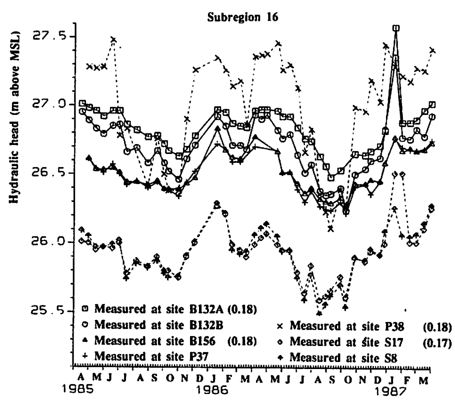

Subregion 13
Calculated for layer 1
Calculated for layer 2
Weighted mean of measured heads at shallow sites
Hydraulic head (m above MSL)
28.0
27.5
27.0
26.5
26.0
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

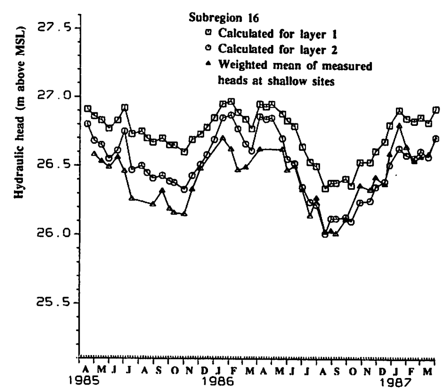

Subregion 14
Measured at site B206A (0.15)
Measured at site B206C
Measured at site S7 (0.85)
Hydraulic head (m above MSL)
29.0
28.5
28.0
27.5
27.0
26.5
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

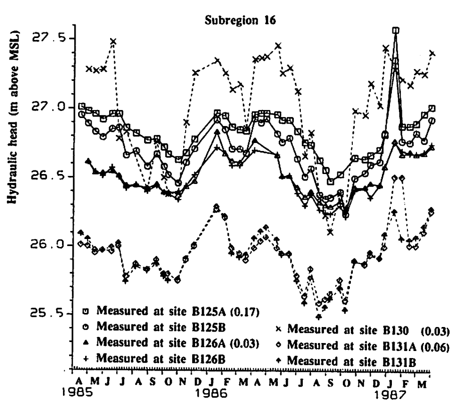

Subregion 14
Calculated for layer 1
Calculated for layer 2
Weighted men of measured heads at shallow sites
Hydraulic head (m above MSL)
29.0
28.5
28.0
27.5
27.0
26.5
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987


Subregion 15
Measured at site B127A (0.50)
Measured at site B127B
Measured at site B128A (0.50)
Measured at site B128B
Measured at site B128C
Measured at site B211
Hydraulic head (m above MSL)
28.5
28.0
27.5
27.0
26.5
26.0
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987


Subregion 15
Calculated for layer 1
Calculated for layer 2
Weighted mean of measured heads at shallow sites
Hydraulic head (m above MSL)
28.5
28.0
27.5
27.0
26.5
26.0
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

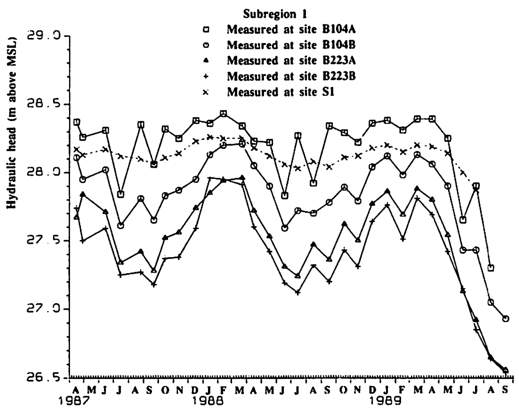

Subregion 16
Hydraulic head (m above MSL)
27.5
27.0
26.5
26.0
25.5
Measured at site B132A (0.18)
Measured at site B132B
Measured at site B156 (0.18)
Measured at site P37
Measured at site P38 (0.18)
Measured at site S17 (0.17)
Measured at site S8
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

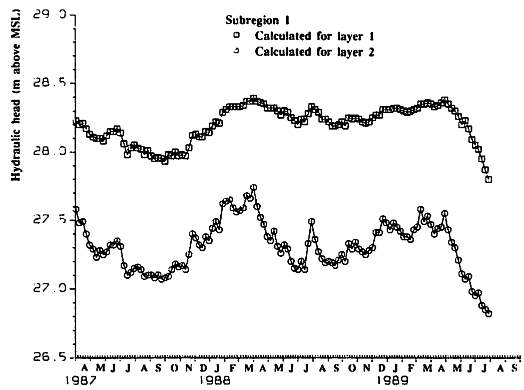

Subregion 16
Calculated for layer 1
Calculated for layer 2
Weighted mean of measured heads at shallow sites
Hydraulic head (m above MSL)
27.5
27.0
26.5
26.0
25.5
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

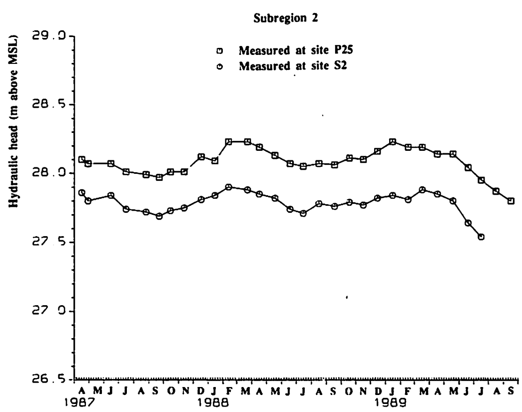

Subregion 16
Hydraulic head (m above MSL)
27.5
27.0
26.5
26.0
25.5
Measured at site B125A (0.17)
Measured at site B125B
Measured at site B126A (0.03)
Measured at site B126B
Measured at site B130 (0.03)
Measured at site B131A (0.06)
Measured at site B131B
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

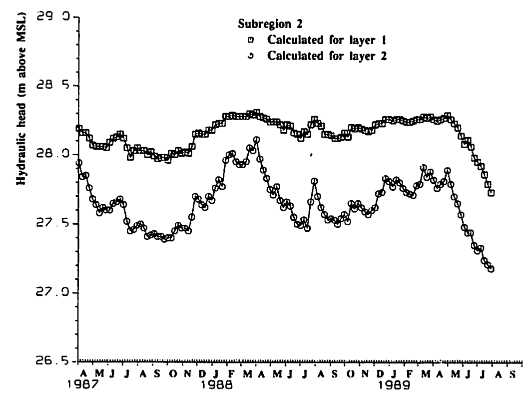
2.2 Data for the *Groote Peel*, for the period 1/4/1987 - 15/9/1989

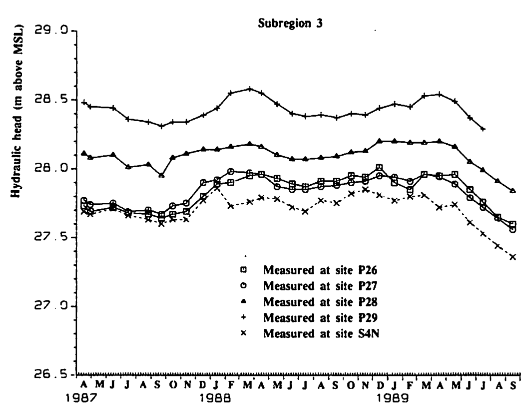
Due to the reduction of the amount of measurement sites from April 1 1987 onwards, some of the sites used for computing the weighted mean are not available for the period 1/4/1987 - 15/9/1989. Because the use of other sites was considered to be confusing the weighted mean has been left out altogether for this period.

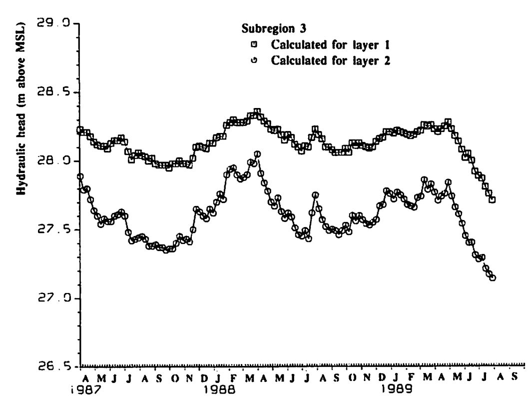


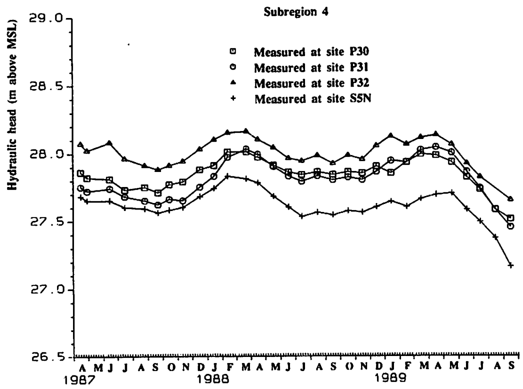


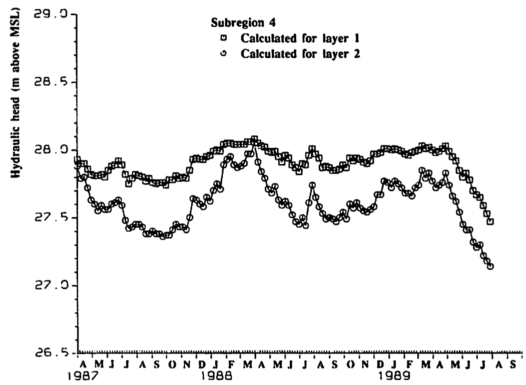


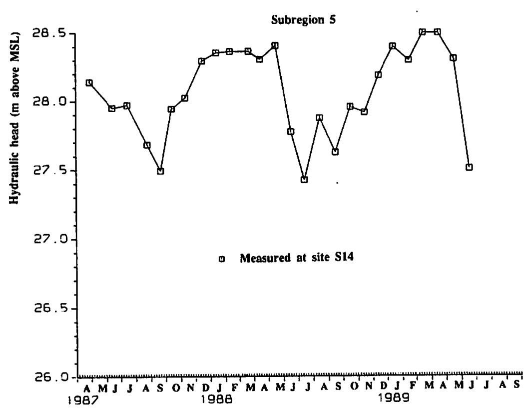


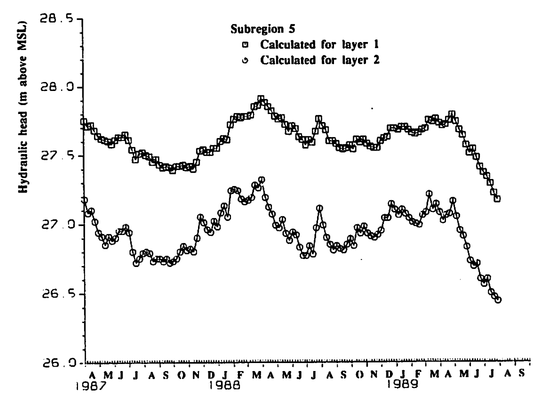


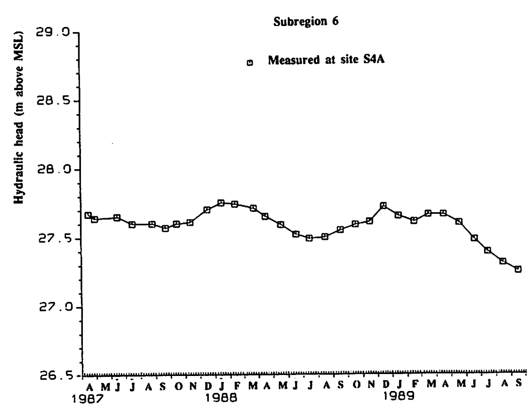


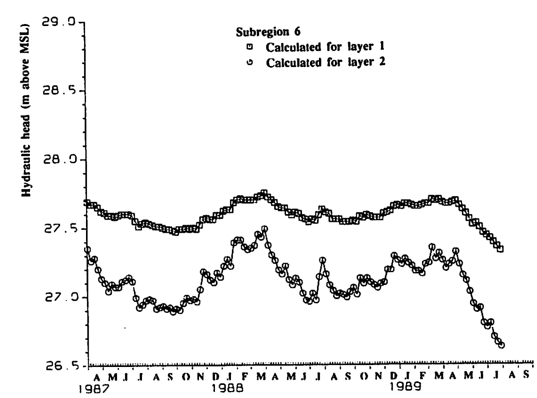

Subregion 4
Measured at site P30
Measured at site P31
Measured at site P32
Measured at site S5N
Hydraulic head (m above MSL)
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987
1988
1989

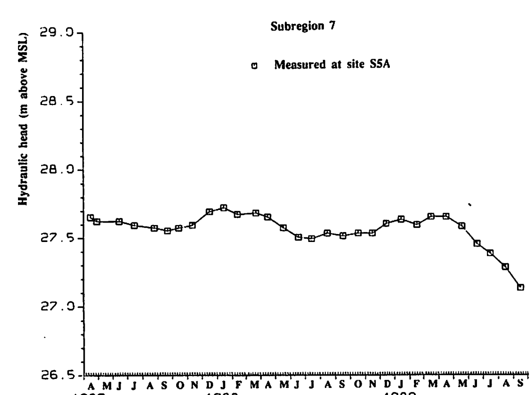

Subregion 4
Calculated for layer 1
Calculated for layer 2
Hydraulic head (m above MSL)
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987
1988
1989

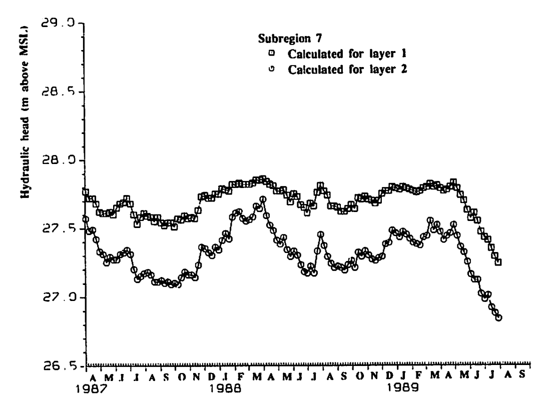

Subregion 5
Measured at site S14
Hydraulic head (m above MSL)
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987
1988
1989

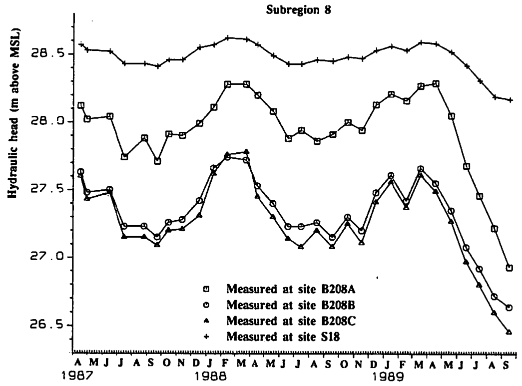

Subregion 5
Calculated for layer 1
Calculated for layer 2
Hydraulic head (m above MSL)
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987
1988
1989

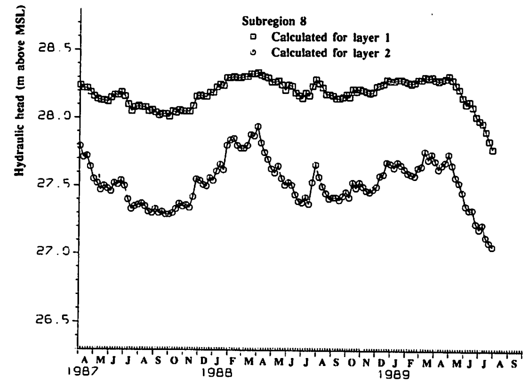

Subregion 6
Measured at site S4A
Hydraulic head (m above MSL)
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987
1988
1989

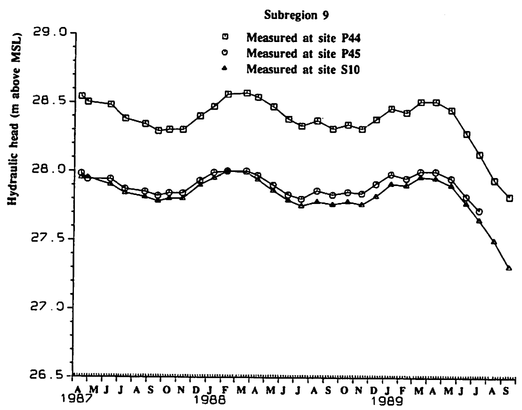

Subregion 6
Calculated for layer 1
Calculated for layer 2
Hydraulic head (m above MSL)
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987
1988
1989

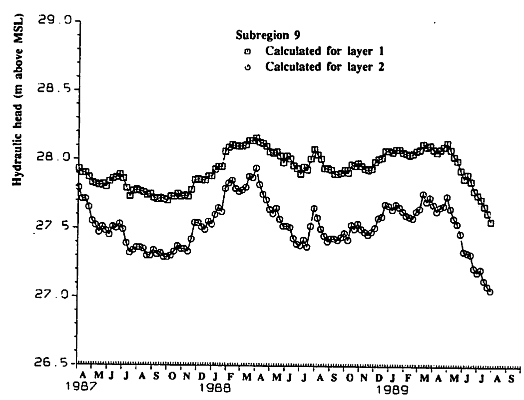

Subregion 7
Measured at site S5A
Hydraulic head (m above MSL)
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987
1988
1989

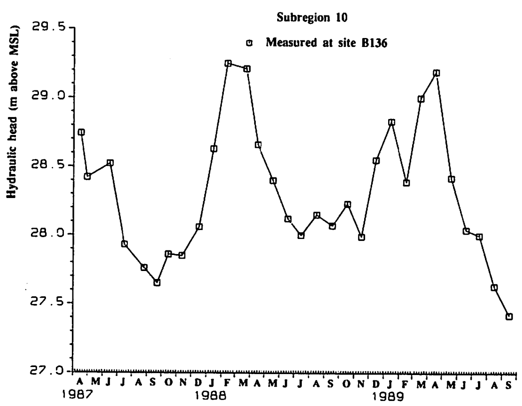

Subregion 7
Calculated for layer 1
Calculated for layer 2
Hydraulic head (m above MSL)
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987
1988
1989

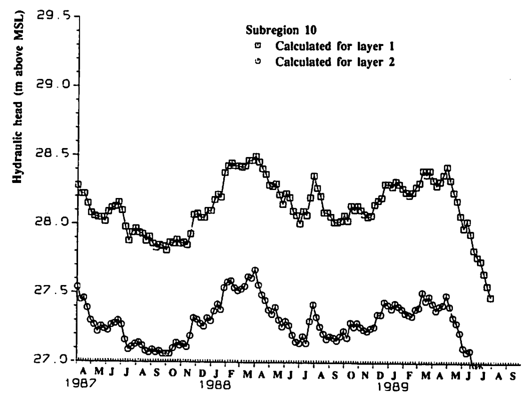

Subregion 8
Hydraulic head (m above MSL)
28.5
28.0
27.5
27.0
26.5
Measured at site B208A
Measured at site B208B
Measured at site B208C
Measured at site S18
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987 1988 1989

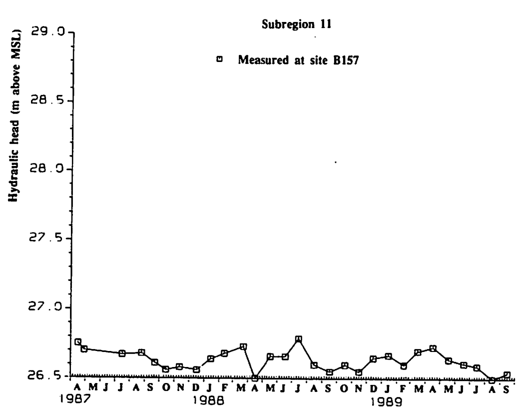

Subregion 8
Calculated for layer 1
Calculated for layer 2
Hydraulic head (m above MSL)
28.5
28.0
27.5
27.0
26.5
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987 1988 1989

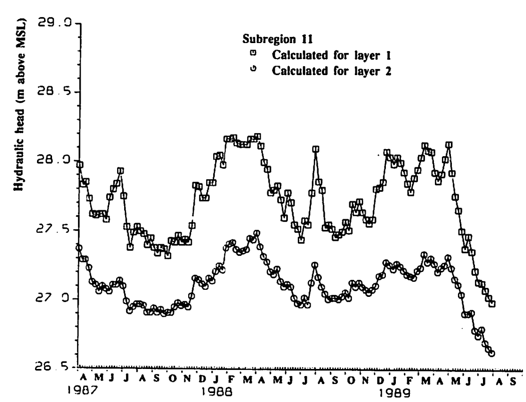

Subregion 9
Measured at site P44
Measured at site P45
Measured at site S10
Hydraulic head (m above MSL)
29.0
28.5
28.0
27.5
27.0
26.5
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987 1988 1989

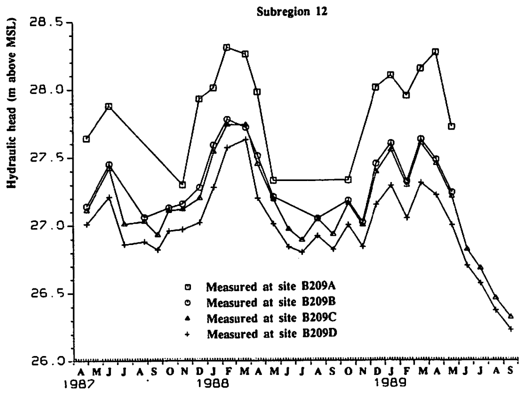

Subregion 9
Calculated for layer 1
Calculated for layer 2
Hydraulic head (m above MSL)
29.0
28.5
28.0
27.5
27.0
26.5
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987 1988 1989

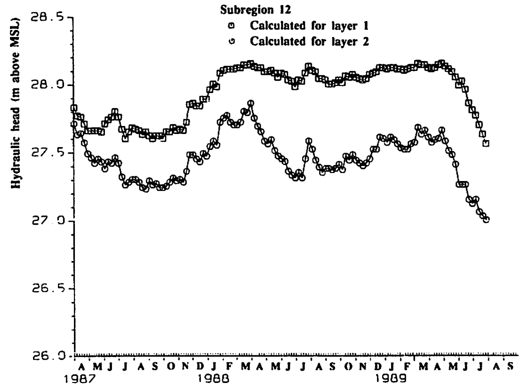

Subregion 10
Measured at site B136
Hydraulic head (m above MSL)
29.5
29.0
28.5
28.0
27.5
27.0
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987 1988 1989

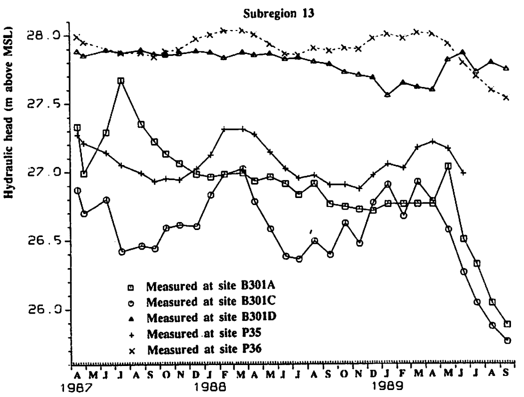

Subregion 10
Calculated for layer 1
Calculated for layer 2
Hydraulic head (m above MSL)
29.5
29.0
28.5
28.0
27.5
27.0
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987 1988 1989

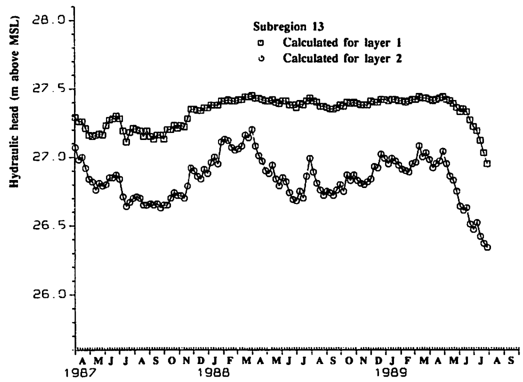

Subregion 11
Measured at site B157
Hydraulic head (m above MSL)
29.0
28.5
28.0
27.5
27.0
26.5
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987 1988 1989

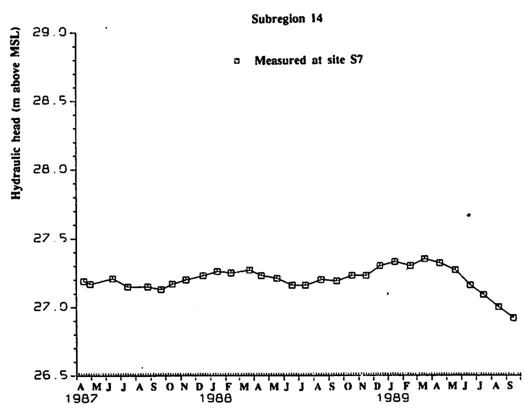

Subregion 11
Calculated for layer 1
Calculated for layer 2
Hydraulic head (m above MSL)
29.0
28.5
28.0
27.5
27.0
26.5
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987 1988 1989

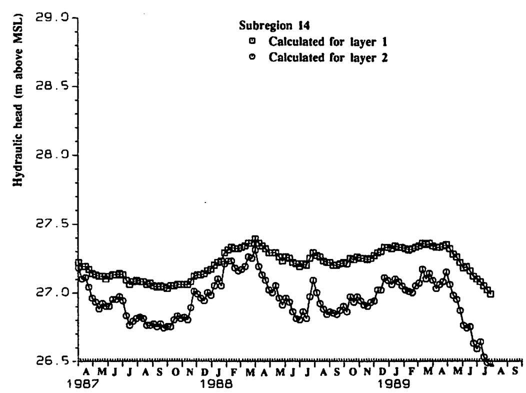

Subregion 12
Hydraulic head (m above MSL)
Measured at site B209A
Measured at site B209B
Measured at site B209C
Measured at site B209D
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1987
1988
1989

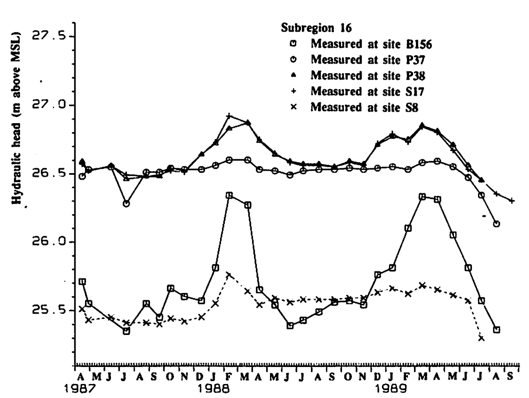

Subregion 12
Calculated for layer 1
Calculated for layer 2
Hydraulic head (m above MSL)
1987
1988
1989

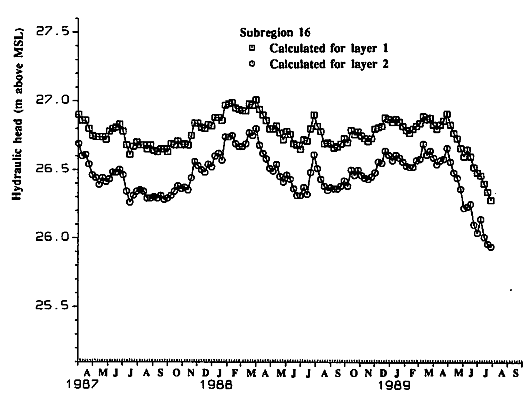

Subregion 13
Hydraulic head (m above MSL)
Measured at site B301A
Measured at site B301C
Measured at site B301D
Measured at site P35
Measured at site P36
1987
1988
1989


Subregion 13
Calculated for layer 1
Calculated for layer 2
Hydraulic head (m above MSL)
1987
1988
1989

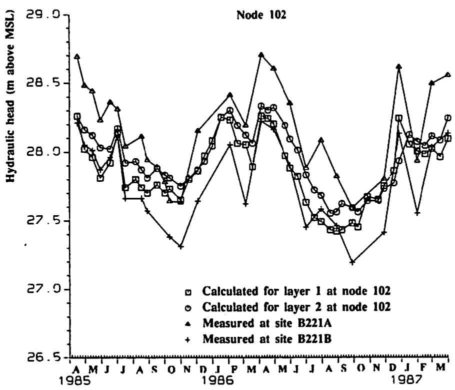

Subregion 14
Measured at site S7
Hydraulic head (m above MSL)
1987
1988
1989

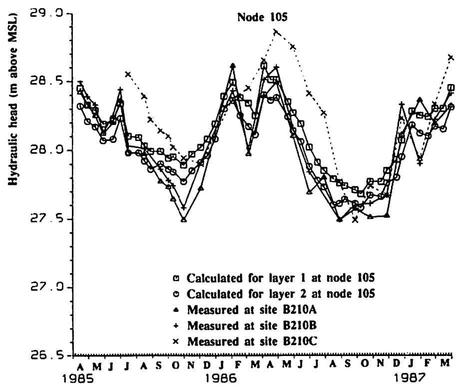

Subregion 14
Calculated for layer 1
Calculated for layer 2
Hydraulic head (m above MSL)
1987
1988
1989

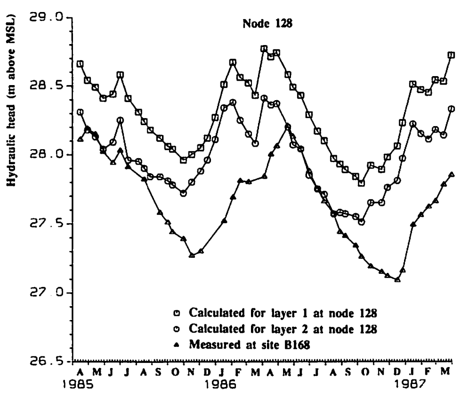

Subregion 16
Measured at site B156
Measured at site P37
Measured at site P38
Measured at site S17
Measured at site S8
Hydraulic head (m above MSL)
1987
1988
1989

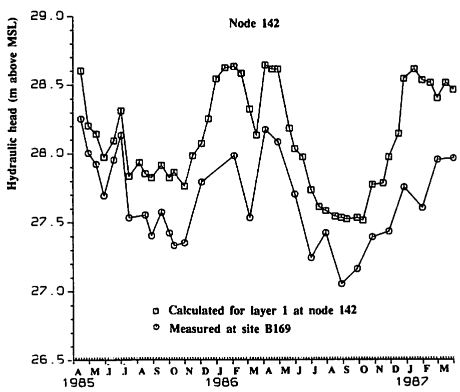

Subregion 16
Calculated for layer 1
Calculated for layer 2
Hydraulic head (m above MSL)
1987
1988
1989

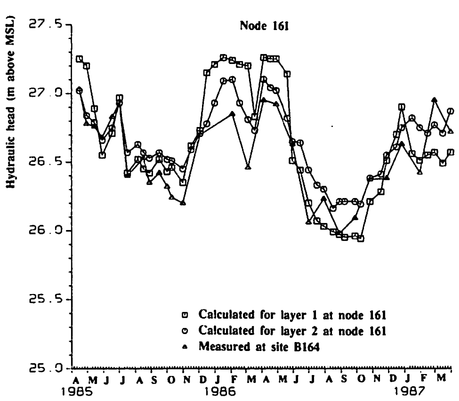
2.3. Data for the surrounding area, for the period 1/4/1985 - 1/4/1987

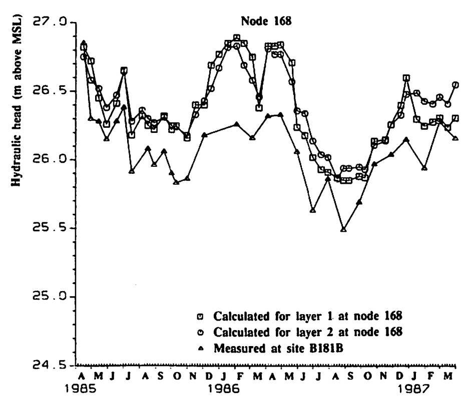


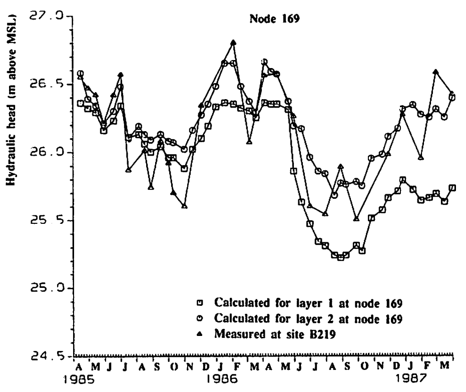


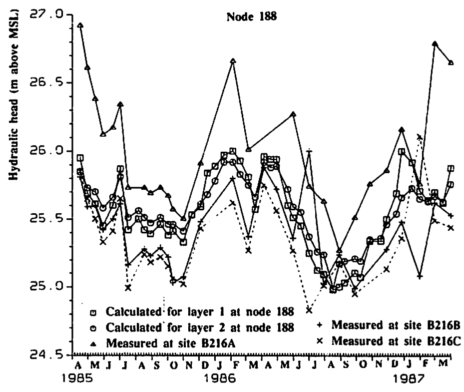


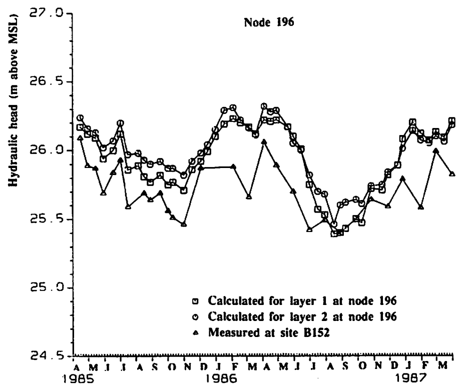


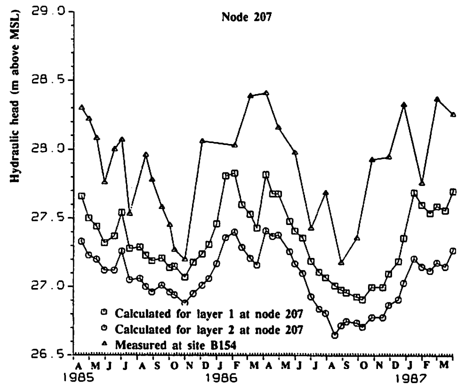


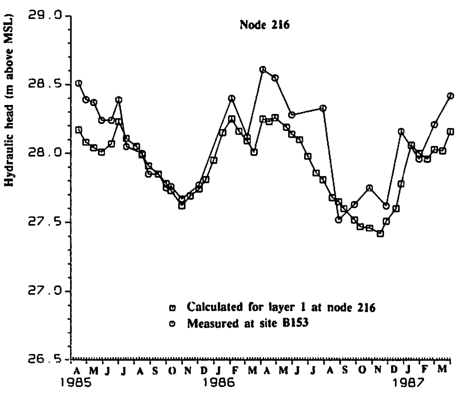


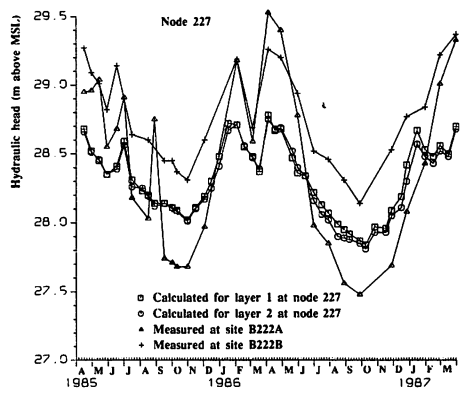

Node 169
Hydraulic head (m above MSL)
Calculated for layer 1 at node 169
Calculated for layer 2 at node 169
Measured at site B219
1985
1986
1987

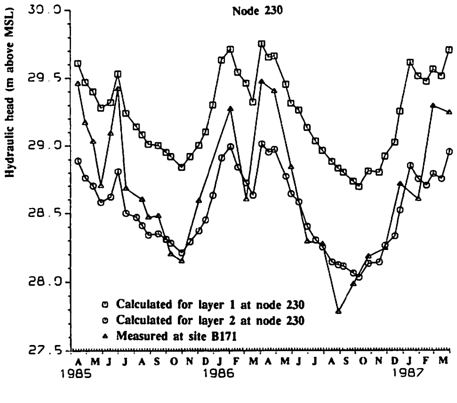

Node 188
Hydraulic head (m above MSL)
Calculated for layer 1 at node 188
Calculated for layer 2 at node 188
Measured at site B216A
Measured at site B216B
Measured at site B216C
1985
1986
1987

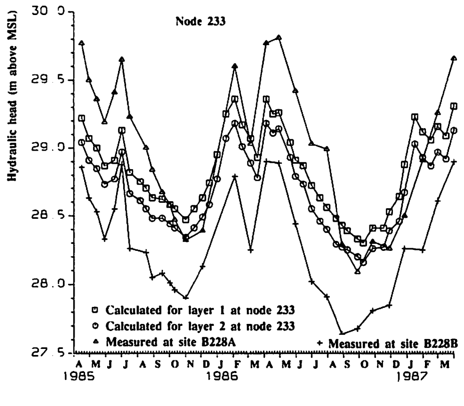

Node 196
Hydraulic head (m above MSL)
Calculated for layer 1 at node 196
Calculated for layer 2 at node 196
Measured at site B152
1985
1986
1987

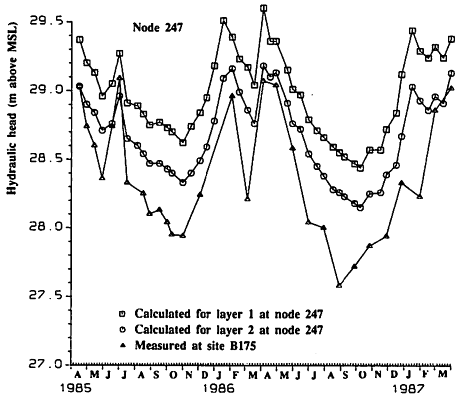

Node 207
Hydraulic head (m above MSL)
Calculated for layer 1 at node 207
Calculated for layer 2 at node 207
Measured at site B154
1985
1986
1987

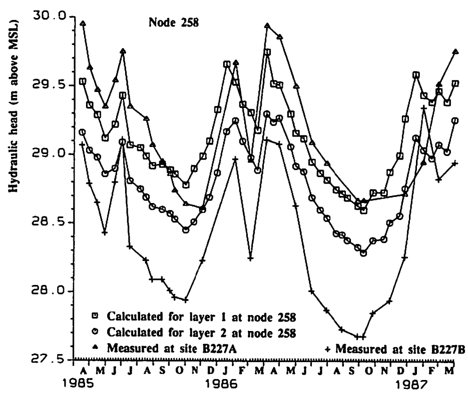

Node 216
Hydraulic head (m above MSL)
Calculated for layer 1 at node 216
Measured at site B153
1985
1986
1987

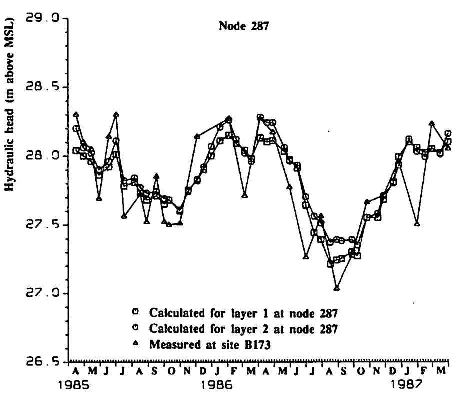

Node 227
Hydraulic head (m above MSL)
Calculated for layer 1 at node 227
Calculated for layer 2 at node 227
Measured at site B222A
Measured at site B222B
1985
1986
1987

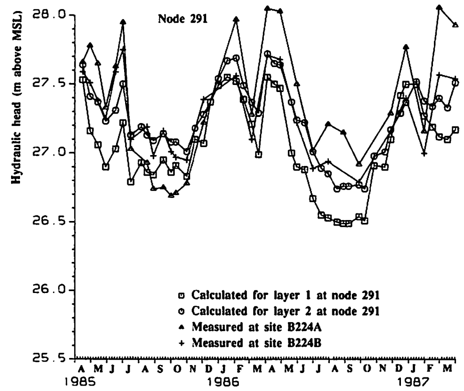

Node 230
Hydraulic head (m above MSL)
30.0
29.5
29.0
28.5
28.0
27.5
Calculated for layer 1 at node 230
Calculated for layer 2 at node 230
Measured at site B171
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

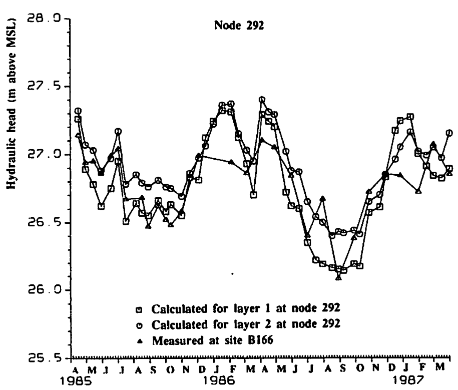

Node 233
Hydraulic head (m above MSL)
30.0
29.5
29.0
28.5
28.0
27.5
Calculated for layer 1 at node 233
Calculated for layer 2 at node 233
Measured at site B228A
+ Measured at site B228B
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

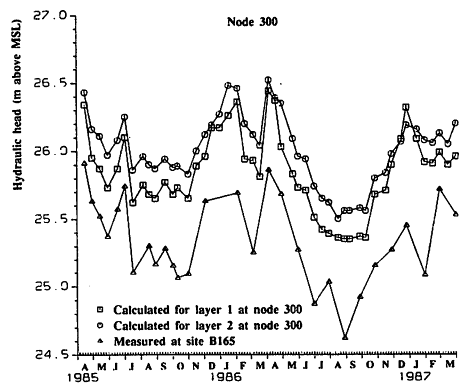

Node 247
Hydraulic head (m above MSL)
29.5
29.0
28.5
28.0
27.5
27.0
Calculated for layer 1 at node 247
Calculated for layer 2 at node 247
Measured at site B175
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

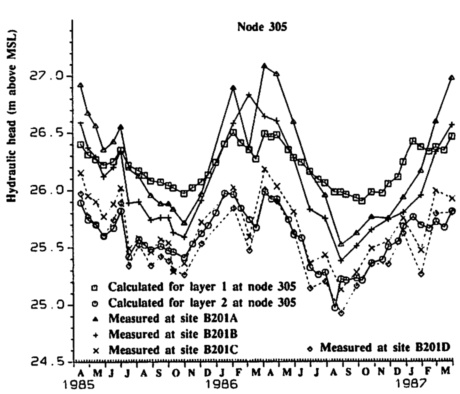

Node 258
Hydraulic head (m above MSL)
30.0
29.5
29.0
28.5
28.0
27.5
Calculated for layer 1 at node 258
Calculated for layer 2 at node 258
Measured at site B227A
+ Measured at site B227B
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

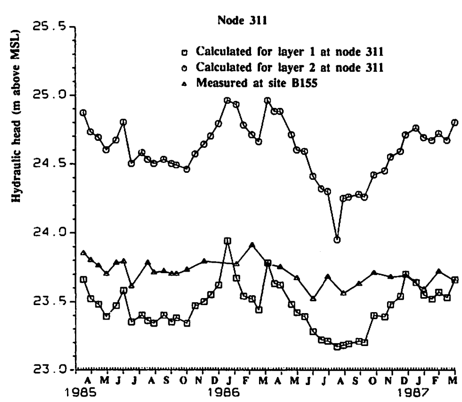

Node 287
Hydraulic head (m above MSL)
29.0
28.5
28.0
27.5
27.0
26.5
Calculated for layer 1 at node 287
Calculated for layer 2 at node 287
Measured at site B173
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

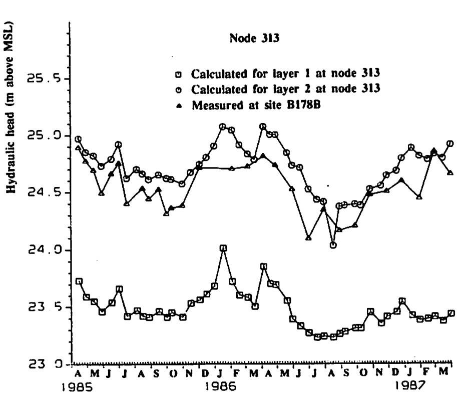

Node 291
Hydraulic head (m above MSL)
28.0
27.5
27.0
26.5
26.0
25.5
Calculated for layer 1 at node 291
Calculated for layer 2 at node 291
Measured at site B224A
+ Measured at site B224B
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

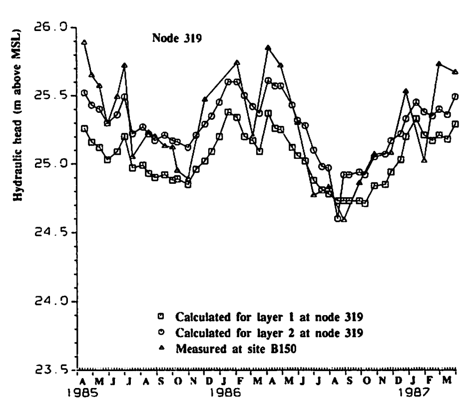

Node 292
Hydraulic head (m above MSL)
28.0
27.5
27.0
26.5
26.0
25.5
Calculated for layer 1 at node 292
Calculated for layer 2 at node 292
Measured at site B166
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

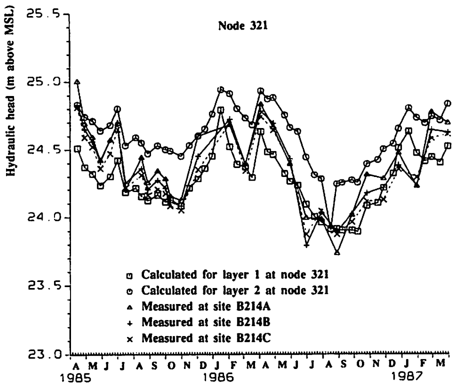

Node 300
Hydraulic head (m above MSL)
27.0
26.5
26.0
25.5
25.0
24.5
Calculated for layer 1 at node 300
Calculated for layer 2 at node 300
Measured at site B165
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

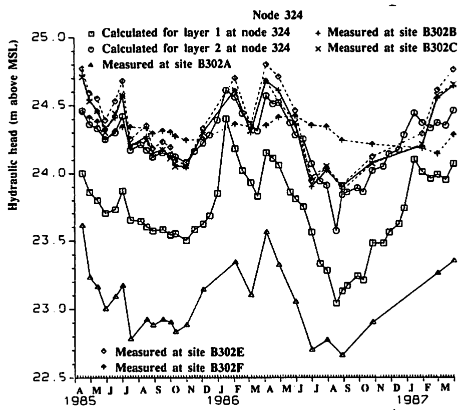

Node 305
Hydraulic head (m above MSL)
27.0
26.5
26.0
25.5
25.0
24.5
Calculated for layer 1 at node 305
Calculated for layer 2 at node 305
Measured at site B201A
Measured at site B201B
Measured at site B201C
Measured at site B201D
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

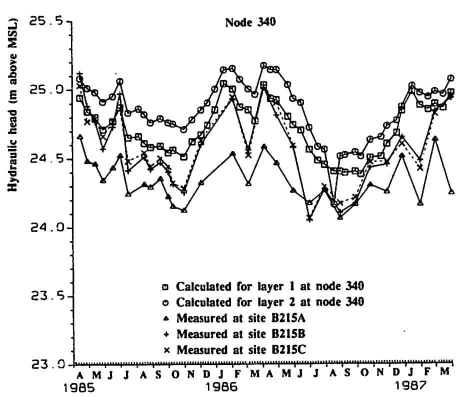

Node 311
Hydraulic head (m above MSL)
25.5
25.0
24.5
24.0
23.5
23.0
Calculated for layer 1 at node 311
Calculated for layer 2 at node 311
Measured at site B155
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

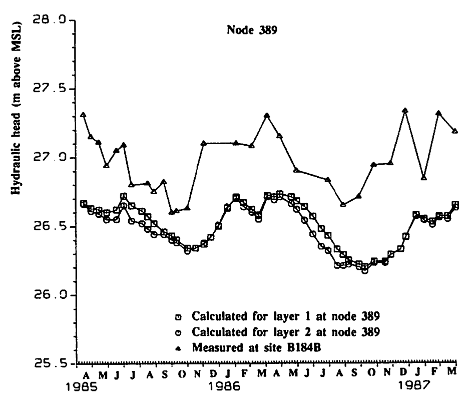

Node 313
Hydraulic head (m above MSL)
25.5
25.0
24.5
24.0
23.5
23.0
Calculated for layer 1 at node 313
Calculated for layer 2 at node 313
Measured at site B178B
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

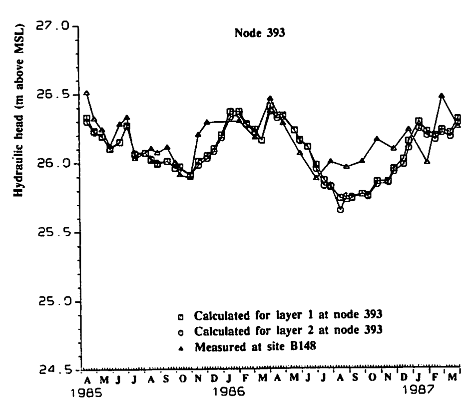

Node 319
Hydraulic head (m above MSL)
26.0
25.5
25.0
24.5
24.0
23.5
Calculated for layer 1 at node 319
Calculated for layer 2 at node 319
Measured at site B150
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987


Node 321
Hydraulic head (m above MSL)
25.5
25.0
24.5
24.0
23.5
23.0
Calculated for layer 1 at node 321
Calculated for layer 2 at node 321
Measured at site B214A
Measured at site B214B
Measured at site B214C
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987


Node 324
Hydraulic head (m above MSL)
25.0
24.5
24.0
23.5
23.0
22.5
Calculated for layer 1 at node 324
Calculated for layer 2 at node 324
Measured at site B302A
Measured at site B302B
Measured at site B302C
Measured at site B302E
Measured at site B302F
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987


Node 340
Hydraulic head (m above MSL)
25.5
25.0
24.5
24.0
23.5
23.0
Calculated for layer 1 at node 340
Calculated for layer 2 at node 340
Measured at site B215A
Measured at site B215B
Measured at site B215C
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987


Node 389
Hydraulic head (m above MSL)
28.0
27.5
27.0
26.5
26.0
25.5
Calculated for layer 1 at node 389
Calculated for layer 2 at node 389
Measured at site B184B
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987


Node 393
Hydraulic head (m above MSL)
27.0
26.5
26.0
25.5
25.0
24.5
Calculated for layer 1 at node 393
Calculated for layer 2 at node 393
Measured at site B148
A M J J A S O N D J F M A M J J A S O N D J F M
1985
1986
1987

ANNEX 3 Calculation of the infiltration resistance of the tertiary surface water system

The used method for calculating the infiltration resistance of the tertiary system consists of two steps:

- calculation of the infiltration resistance of the individual nodes, under the assumption that all the ditches within the nodal influence area can be reached by surface water supply;
- aggregation of the resistances of the nodes within a subregion to a representative subregional value, taking into account that only part of the tertiary system can be reached by surface water that has been imported through the secondary channels.

In the area surrounding the *Groote Peel* the drainage resistance of the nodes where no subsurface drainage has been installed is of the order of 1000 d. Such a high resistance means that the undrained nodes contribute only in a minor way towards the infiltration of externally supplied surface water. For this reason the value has simply been set equal to the drainage resistance.

The drainage resistance of the drained nodes is assumed to be 70 d; the average drain depth is about 80 cm b.s.s. and the average drain distance is about 10 m. (That this distance has been chosen so small is because of the local presence of loam lenses in the shallow subsoil.) When the drains are used for infiltration, the flow resistance is for two reasons higher than in the drainage situation:

- increased entry resistance owing to partial clogging of the drain slots by particles that have been transported in suspended form by the infiltration water;
- the increased resistance as a consequence of the hollow water table (which reduces the area that is available for flow through a vertical cross-section).

The increased resistance owing to partial clogging can only be estimated in a very rough manner. An important point to bear in mind is that the considered drains are not only used for infiltration, but alternatively for infiltration during the summer and drainage during the winter. This means that in the drainage situation some of the clogging is removed again by the exfiltrating water. Since the estimate of the resistance due to partial clogging is anyhow very rough, it does not have much point to estimate the increased resistance of the reduced cross-section in a sophisticated manner. So the used value of 120 d (70% higher than the drainage resistance 70 d) is simply based on 'expert judgement'.

For arriving at a infiltration resistance that is representative for a subregion, the assumption has been made that the reachability of the tertiary channels (and drains) is limited to strips of 100 m in breadth, on both sides of the secondary channels that become water bearing in the situation that the supply schemes are implemented. An inventory was made of the reachable fractions of subregions – though the distinction was of course made between the undrained and the drained reachable fraction. These fractions were then used for calculating an equivalent substitution resistance for the subregion as a whole:

$$\frac{1}{R_s} = \frac{F_d}{120} + \frac{F_o}{R_o}$$

implying

$$R_s = \frac{1}{(F_d/120 + F_o/R_o)}$$

where:

- R_s - substitution infiltration resistance of the nodes within a subregion (d)
- F_d - fraction of the subregion that is within the 100 m strips along the water bearing secondary channels and that is drained (-);
- F_o - fraction of the subregion that is within the 100 m strips along the water bearing secondary channels and that is undrained (-);
- R_o - representative resistance of the undrained nodes within a subregion (d)