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# DESCRIPTION OF SECOND LEVEL WATER QUANTITY MODEL, INCLUDING RESULTS

PROJECTGROUP SOUTHERN PEEL REGION
REPORT No 37

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# 1. INTRODUCTION

In areas different types of activities may be present, each of them having its own impact on the environment. Especially the impact on regional water management caused by agriculture and water supply may interfere. These activities can also interfere with the interest of nature conservation. The need for research on these aspect has resulted in the project : 'Optimization of Regional Water Management in Areas with Conflicting Interests'.

The objective of this project is to develop a system of models to analyse and evaluate alternatives for regional water management. The main interest groups considered in this study are farmers, public water supply companies and nature conservation groups. The objective is therefore to maximize the income from the area, with constraints imposed by the conservation of nature areas, water quality, water supply, etc. ( DRENT, 1981 ).

For the optimization model all effects of production, land-use, water movements, etc have to be related in certain criteria and/or constraints. With these constraints in mind the feasable solutions ( scenario's ) for the area can be calculated. The model concerned must therefore select out of a variety of solutions the optimal solution. Due to the large amount of variables this model requires very simple relationships for all the criteria, otherwise the calculation method will be too complicated and the cost for running such a program excessive. The screening analysis performed in this way will therefore indicate a feasable region and one optimal solution. Because the model can actually select from all the relations given the optimal solution, it is also called the Scenario Generating System ( SGS ).

For the simple, also called first level model, a linear programming technique has been selected. The required linear relations for this first level model have to describe all the effects related to the study area ( eg. relations for production, costs, labour, water movements, etc ). All the constraints in a linearized form have been discussed elsewhere ( ORLOVSKY and VAN WALSUM, 1984 ).

The assumption of linear relations is a very rough estimate for certain variables, but it is the only way to find an optimum with the large number of variables. This optimum from the given linear relations, does not necessarily mean to say the real optimum, because the assumption of linear relations may introduce errors in the used values of certain variables.

Because of this linearization of all relations, the results from the first level model should be verified with more accurate models. The second level models can describe certain processes ( eg. agricultural production, water quantity, water quality, etc ), more accurately because they are simulation models. These models are for the verification by simulation of the outcome from the first level models, and can be used to estimate the various variables more accurately. The result of these calculations may be modified relations for the first level model, e.g. certain variables may be very sensitive in the results, or the assumptions used for the first level models are physically wrong.

The groundwater model described in Chapter 2 and 3 has been developed to simulate the flow of water in the saturated and the unsaturated zone. The effect of irrigation and its impact on the water requirements of the surface water system is also included.

In Chapter 4 the typical input data of the model is discussed and in Chapter 5 the verification of the model, together with some results is given.

# 2. OUTLINE OF SECOND LEVEL MODEL

The second level water quantity model has been developed to simulate the groundwater movements in the study area and to calculate the requirements for sprinkling and subsurface-irrigation. It also gives results of water management on evapotranspiration and groundwater depth.

The existing computerprogram FEMSAT ( VAN BAKEL, 1978 ) was extended for this purpose, to simulate the water quantity aspects. The computerprogram FEMSAT is a quasi-three dimensional finite element model, recently modified to include a fully implicit calculation scheme and various boundary conditions ( QUERNER, 1984, part 1 ). The unsaturated zone formerly not present in this model has now also been included, which has resulted in a special program for the Southern Peel Project ( program FEMSATP ).

## 2.1. Schematization

The southern Peel region is subdivided into 31 subregions, each with relative homogeneous soil properties and hydrogeological schematization ( SMIDT, 1983 ). A subregion is further subdiveded into different areas characterized by its land-use. The area involved is therefore defined by an agricultural activity in growing and processing of a certain crop, or livestock. These areas are called technologies that use land. Technologies that do not use land may be present, but they are not of interest here. Therefore only technologies that use land will apply here whenever reference is made to the term technology. In paragraph 2.2. the different technologies are discussed in more detail.

From each technology only the area involved is known as a percentage of the subregion, and not its geometrical position. These percentages are the outcome of the first level model, or in the case of the present calculations also the situation as per 1982 ( see Chapter 5 ). The total area for a technology may be present as numerous portions of land scattered over a subregion.

For the modelling of the water movements in a second level model, accurate representation of the geohydrological situation is required. Therefore the region has been subdivided into finite elements ( see also

Appendix A ). A number of nodes will then represent one subregions of the study area.

The unsaturated zone has been modelled by means of two reservoirs, one for the root zone and one for the subsoil ( unsaturated zone between root zone and phreatic level ). The reservoir for the root zone simulates the storage of moisture in the root zone with inflow and extractions as rainfall, evapotranspiration, and capillary rise or percolation. If a certain equilibrium moisture content is exceeded, the excess will percolate to the saturated zone. If the moisture content is below the equilibrium moisture content, then the result will be a capillary rise from the saturated zone. From the water balance of the subsoil the height of the phreatic surface is calculated, using a storage coefficient which is dependent on the groundwater depth.

Ideally the flow and retention of water in the unsaturated zone should be calculated for each nodal point and per technology separately because :

- the soil physical properties and the groundwater depth differ per nodal point
- the potential evapotranspiration differs per technology
- the actual evapotranspiration depends on the soil physical unit, technology and hydrological conditions
- the capillary rise depends on the soil physical unit and the groundwater depth
- the root zone depth may be different per technology

With all these specific relations and different flow behaviour in the root zone it would require per nodal point and per technology a model to simulate the unsaturated zone. This would require a great amount of input data and a heavy demand on both computer time and storage. Therefore a simplification has been introduced that per subregion and per technology one model ( reservoir ) is used to calculate moisture content, evapotranspiration and capillary rise ( or percolation ). In this case average hydrological conditions over the subregion are used. For example the amount of capillary rise in a subregion is now dependent on the average groundwater depth. Because the schematization of the subregions is based on more or less homogeneous conditions with respect to groundwater depth and soil types this simplification is justified. This also means that only one soil physical unit per subregion can be present.

The functioning of the surface water system for the summer and winter situation is different, and therefore they require each to be modelled separately according to its special characteristics.

The summer situation is in general characterized by a supply of water. This supply is governed by a certain maximum capacity. Water is extracted from the system for sprinkling and subsurface-irrigation. In the winter situation drainage dominates and an amount of surface runoff can also occur regularly. The ground level over a subregion can vary by some meters. Taking this into account would mean that for each nodal point one model is required, to simulate the interaction between surface water and groundwater, but this would involve a large amount of input data and a heavy demand on computer time. For these reasons simulation for each subregion is used instead.

If the water level in the surface water system over the whole subregion would be taken the same, it would result in ditches with no water and others with a bank full stage. Therefore the water level in a subregion is calculated as a depth below the ground level. For each node the calculated depth below ground level can be translated to a water level relative to the reference datum.

The various water transport and storage processes are thus simulated by three different submodels. They represent the saturated zone, the unsaturated zone, and the surface water system. The various water movements allowed for within the schematization of a subregion and between the three submodels is shown in figure 1. In this figure the summer situation is shown with subsurface-irrigation and a supply of water towards the subregion.

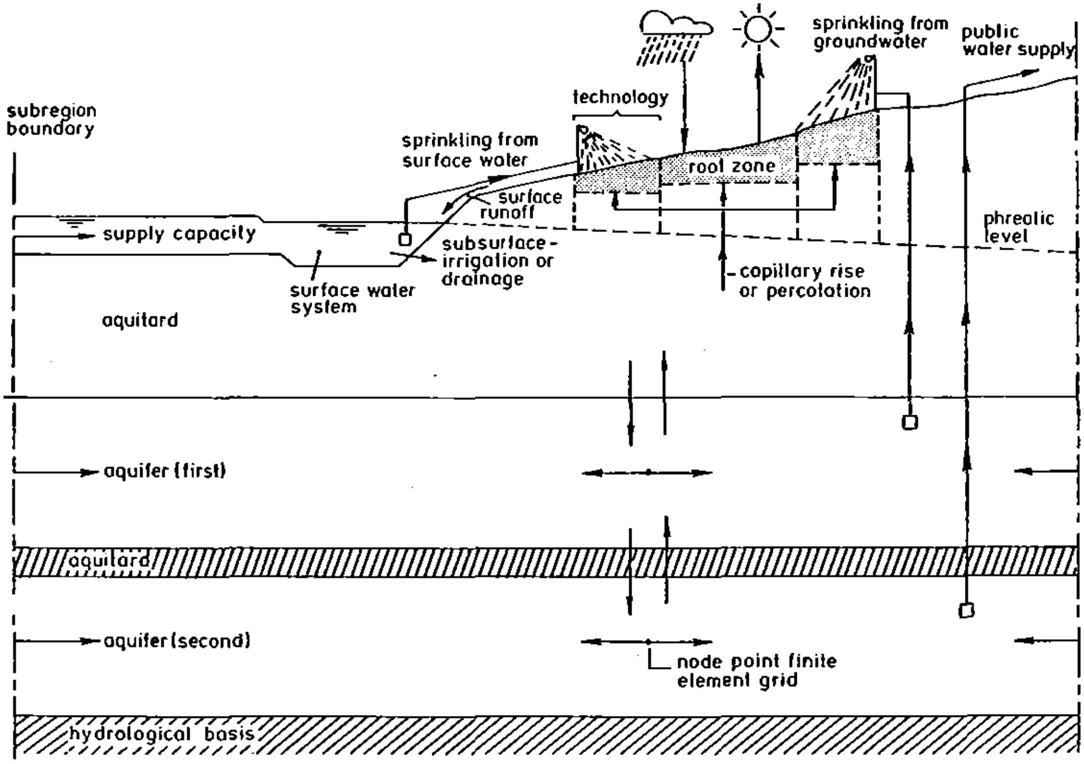


Figure 1 - Schematization of flows in a subregion

## 2.2. Definition of technologies for hydrological calculations

The study area can be subdivided into four main categories of land-use which are important for the calculations of the various water movements. They are :

- agricultural areas
- built-up areas
- nature reserves
- forests

The agricultural technologies defined for the first level model are only for agricultural land-use. In the second level model the water balance of a subregion should take into account all different categories of land-use that take part in the hydrological cycle. Similar criteria as for the agricultural technologies can be defined for built-up areas, nature reserves and forests, so that they can be incorporated in the computermodel.

The built-up areas are split up into areas with an impermeable surface ( e.g. houses, streets, etc ) and the rest. For the impermeable surface areas there is no connection with the unsaturated zone. These areas can be disregarded, because the runoff from these areas is directly transported to the treatment plants ( combined stormwater and foul sewer system ), and the effluent discharges outside the study area. The permeable areas in the towns are considered to have the same characteristics as grassland ( see also table 1 ).

Nature reserves have a vegetation of grass. Forests are distinguished because they have quite different evapotranspiration values and thickness of the root zone.

The agricultural technolgies are subdivided into subtechnologies. These subtechnologies will represent a production level. Each production level is characterized in respect to a water availability condition. Therefore a high production level would mean a greater water demand in the growing season. The demand is achieved by means of sprinkling, where each production level has its own criterium for applying the sprinkler irrigation in terms of available moisture in the root zone. The criteria for irrigation by means of sprinkling are discussed in paragraph 3.2.2.

The different technologies defined for the study area are given in table 1, where the technologies 1 to 7 can have the three subtechnologies dependent on the agricultural production level.

Table 1 - Selected technologies in the Peel area

- glasshouse horticulture
- intensive field horticulture
- extensive field horticulture
- potatoes
- cereals
- maize
- grassland
- built-up areas ( 60 % permeable )
- nature areas
- forest

The criteria and equations for the second level water quantity model are described in the paragraphs 3.1. to 3.3. In paragraph 3.4. a flow chart of the program FEMSATP is given for those parts, where it relates to the described submodels.

# 3. METHOD OF CALCULATION

## 3.1. The saturated zone

### 3.1.1 Calculation of hydraulic head

The calculation of the hydraulic head for a node n is given by QUERNER ( 1984 ). The continuity equation can be written explicitly as :

$$B(n,t) * (\Delta h(n,t) / \Delta t) = \sum_{m} Qnm(n,t) + Qe(n,t) +$$

$$+ \theta \left| \sum_{m} \Delta Qnm(n,t) + ( dQe(n,t) / dh(n,t) ) * \Delta h(n,t) \right| +$$

$$+ Qc(n,t) + \theta * Qc(n,t+\Delta t) \qquad (1)$$

where $\Delta h(n,t)$ is the change of hydraulic head over the timestep, B( ) is the storage coefficient, Qnm( ) is the flow from node n to node m, Qe( ) is the total boundary flows, Qc is the extractions ( e.g. public water supply, sprinkling, and capillary rise ), and $\theta$ is the weighting parameter between timelevels t and t + $\Delta$t.

The first two terms on the right hand side of equation (1) represent the flows to or from node n at time t and the third and fourth term are the actual change in flow over the considered timestep. Equation (1) requires linear relations for the change of flow and hydraulic head over a timestep.

All the boundary conditions must be written as a function of the unknown hydraulic head and in this way can be substituted in equation (1). For the external flow Qe ( e.g. drainage, seepage, etc ) imposed on a layer it has been assumed that it depends on the hydraulic head h(n,t), and that the extraction Qc is independent of the hydraulic head.

The calculation scheme used in equation (1) is the Crank-Nicholson approximation. It uses a central time difference, which is unconditionally stable and will not impose restrictions on the length of the timestep to be used.

### 3.1.2 Average hydraulic head per subregion

After the hydraulic head in each node of the solution domain is calculated with equation (1), the average head per subregion can be calculated with the relation :

$$h(r,t) = \sum_{nr(r)} h(n,t) * xnd(n) \; / \; xt(r) \qquad (2)$$

where xnd(n) is the area of node n and xt(r) is the area of subregion r, and nr(r) is the number of nodes per subregion. For the average ground level of a subregion the same procedure has been followed.

### 3.1.3 Storage coefficient

The storage coefficient used in equation (1), is dependent on the average groundwater depth in a subregion, therefore all nodal points within a subregion have the same storage coefficient given by the function :

$$B(r,t) = f\ \{\ s(r),\ hst(r,t)\ \} \qquad (3)$$

where hst( ) is the groundwater depth and s(r) is the soil physical unit.

The dependency of the root zone depth on the storage coefficient has been neglected. A constant depth of 0.25 m has been used for the relations given by equation (3).

### 3.1.4 Extractions

The extractions from groundwater for irrigation, and the percolation or capillary rise, are calculated on the aggregation level of the subregion. Subsequently the fluxes are attributed to the nodes of a subregion by multiplication with the relative areas of the respective nodes.

Therefore the flux to/from the unsaturated zone can be calculated for each node in a subregion as :

$$vz(n,t) = ( xnd(n) / xt(r) ) ( \sum_{nr(r)} vz(r,j,t) * x(r,j) ) \qquad (4)$$

where x(r,j) is the area of land allocated to technology j.

The sprinkling water extracted from groundwater can be calculated for node n from the total amount required for the subregion, by means of :

$$ig(n,t) = xnd(n) * ig(r,t) / xt(r) \qquad (5)$$

The groundwater used for sprinkling will be assumed to be extracted from one and the same aquifer.

The groundwater extractions for the public water supply are attributed to a single node per subregion, which lies closest to the middle of a subregion.

## 3.2. The unsaturated zone

### 3.2.1 Moisture content in the root zone

A reservoir model is used to simulate the storage of moisture in the root zone. The concept is that water is stored in the root zone to a certain equilibrium. If this equilibrium is exceeded, the excess will percolate to the saturated zone. If the moisture content is below the equilibrium content, then a capillary flux from the saturated zone is possible.

The root zone depth rz is a function of the technology and the soil physical unit. Therefore :

$$rz(r,j) = f \{ j, s(r) \} \qquad (6)$$

In the model a constant root zone has been assumed all year round, with no changes during and over the years.

For each technology in a subregion the change of moisture content of the root zone is calculated with the relation :

$$\Delta v(r,j,t) = (\ p(j,s,t) + 0.9 * igs(r,j,t) - ea(r,j,t)\ )\ \Delta t \tag{7}$$

where p( ) is the net precipitation that will infiltrate into the ground, igs( ) is the net amount of sprinkling from groundwater and surface water, and ea( ) is the actual evapotranspiration. The index r stands for the subregion, j for the technology, and s for the soil physical unit. Due to irregularity in sprinkling it has been assumed that 10 % of the sprinkling is not stored in the root zone, but percolates directly to the saturated zone as given in equation (15). Capillary rise or percolation depends on the actual moisture content in relation to the equilibrium moisture content.

The precipitation is corrected for plant interception and maximum infiltration rate as :

$$p(j,t) = p(t) - p(t) * int(j) \tag{8}$$

and

$$p(j,s,t) = \min \{\ p(j,t)\ ,\ inf(\ s(r)\ )\ \} \tag{9}$$

where p(t) is the actual rainfall, int(j) the interception factor and inf(s) the maximum infiltration rate. Interception is assumed to be present in summer and dependent on the technology. If rainfall exceeds the maximum infiltration rate, this excess is added to the amount of surface runoff. The surface runoff is calculated as part of the flow to the surface water system and given in paragraph 3.3.3. Irrigation by means of sprinkling will be effective if the condition for the considered technology is valid ( see paragraph 3.2.2 ).

The actual evapotranspiration ea( ) is calculated with the relation ( FEDDES and RIJTEMA, 1983 ) :

$$ea(r,j,t) = \alpha \cdot ep(j,t) \tag{10}$$

with

$$\alpha = f\ \{\ v(r,j,t)\ /\ veqo(\ s(r)\ )\ \} \tag{11}$$

where v( ) is the actual moisture content of the root zone, veqo( ) is the equilibrium soil moisture content in the root zone for zero groundwater depth, and s is the index for the soil physical unit. In the approach of Feddes and Rijtema the equilibrium soil moisture content for groundwater depth of 1.0 m was used as a reference for the calculation of the dry up factor. Contrary to this approach the equilibrium soil moisture content for zero groundwater depth is used, because in this way reduction in evapotranspiration due to water logging can be incorporated.

A dry up factor is defined as the ratio actual soil moisture content to the equilibrium soil moisture content for zero groundwater depth. With the defined dry up factor the ratio actual to potential evapotranspiration ( relative evapotr. ) can be determined from figure 2.

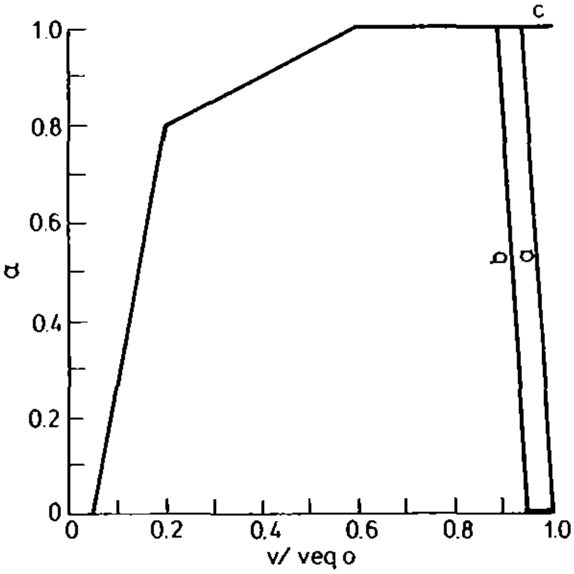


Figure 2 - Relationship for calculation relative evapotranspiration from soil moisture conditions

Figure 2 shows that rootwater uptake is zero when v/veqo is below 0.05 ( wilting point ). When v/veqo is 1.00 ( anaerobiosis point) certain plants will have zero rootwater uptake, which is shown by line a in figure 2. Line b is for plants which are very sensitive on the waterlogging ( e.g. potatoes ). Line c is for nature areas, because it has been assumed that natural vegetation has adapted itself to these wet conditions and a reduction in evapotranspiration will not occur.

The new moisture content in the root zone for time t + Δt is then :

$$v(r,j,t+\Delta t) = v(r,j,t) + \Delta v(r,j,t) \qquad (12)$$

If the moisture content is less than the equilibrium moisture content, then a capillary rise will be effective given by the relation :

$$vz(r,j,t+\Delta t) = f\ \{\ s(r),\ rz(r,j),\ hst(r,t)\ \} \qquad (13)$$

This capillary rise function is the flux underneath the root zone. In equation (13) hst( ) is the average groundwater depth for a standard root zone of 0.25 m. For deeper root zone's, the average groundwater depth is reduced by the difference between actual- and standard root zone depth.

If the moisture content is more than the equilibrium moisture content, it will result in percolation. The amount of percolation ( vz < 0 ) is calculated as :

$$vz(r,j,t+\Delta t) = (\ veq(s(r),t) - v(r,j,t+\Delta t)\ )\ /\ \Delta t \qquad (14)$$

The capillary rise is reduced by the sprinkling, because it cannot all effectively stored in the root zone. Therefore the capillary rise becomes :

$$vz(r,j,t+\Delta t) = vz(r,j,t+\Delta t) - 0.1 * igs(r,j,t) \qquad (15)$$

The new moisture content for the next timestep is now calculated as :

$$v(r,j,t+\Delta t) = v(r,j,t+\Delta t) + vz(r,j,t+\Delta t) * \Delta t \qquad (16)$$

The moisture content of the root zone at equilibrium condition used in equation (14) is calculated with the function :

$$veq(s(r),t) = f\ \{\ s(r),\ rz(r,j),\ hst(r,t)\ \} \qquad (17)$$

In the program the equilibrium moisture contents for the different soil physical units and for a root zone depth of 0.25 m is required as input data. For root zone depths of 0.50 m and 1.00 m correction factors are used. Both the equilibrium moisture content and the correction factors are given in Appendix B.

The measured values for net precipitation and potential evapotranspiration for grassland and forests must be available on a daily base. For a timestep, which in general is seven days, these values where averaged.

The potential evapotranspiration for grassland was derived from open water evapotranspiration muliplied with a factor of 0.8.

The potential evapotranspiration for pine-forest is calculated as the sum of transpiration and interception. An interception reservoir of 2.0 mm and 1.5 mm was taken for the summer and winter period respectively ( WORKING GROUP EVAPORATION, 1984 ).

The potential evapotranspiration for each crop and vegetation type were derived from the values for grassland by converting with known factors per technology in a manner :

$$ep(j,t) = ( f(j,t) * epg(t) ) / 0.8 \qquad (18)$$

where epg(t) is the potential evapotranspiration for grassland. For the different technologies the factors required in equation (18) vary during the growing season between 0.4 and 1.0. For barren land during winter the factor is 0.70.

For each technology in a subregion the above calculations are repeated. For a flow diagram of the calculations performed by the program see paragraph 3.4.

### 3.2.2 Sprinkling

Sprinkling in practise is operated following a rotation scheme along separate fields. The sprinkling is continued as long as the soil moisture content is below a certain level. The second level model cannot allow for a fully realistic simulation of sprinkling according to a rotation scheme, but depending on the production levels of the technologies the sprinkling is operated. A rotational scheme of 7 days per technology has been used, but this can be changed, as it is par of the input data.

For a high production level a high water demand is necessary, which results in frequent sprinkling. The criteria of applying sprinkling depends therefore on the production level and the dry up factor ( equation 11 ). In table 2 the criteria for sprinkling are given. In every timestep subsequent of starting sprinkling a test is included to check if the moisture content does not exceed the criterium for stopping.

Table 2 - Criteria for sprinkling

| production level | dry up factor | |
|---|---|---|
| | start | stop |
| 0 | no sprinkling | |
| 1 | 0.60 | 0.75 |
| 2 | 0.70 | 0.85 |
| 3 | 0.80 | 0.95 |

Allocating the sprinkling capacity to the various technologies in a subregion will be based on priority. Starting with the highest production level and allocating it until all technologies are satisfied or until the capacity constraint is met, such that :

$$igs(r,t) <= \min \left( \left( \sum_{j} igs(r,j,t) \;/\; 0.95 \right) ,\; igm(r,t) \right) \qquad (19)$$

where igs( ) is the total amount of sprinkling water for a subregion and igm(r,t) is the maximum permisseble amount of sprinkling extracted from surface water and groundwater. This maximum capacity follows from :

$$igm(r,t) = ism(r,t-\Delta t) + igmax(r) \qquad (20)$$

where ism( ) is the maximum permissible amount of extractions ( sprinkling ) from surface water and calculated in paragraph 3.3.1, and igmax(r) the maximum extraction from groundwater. The factor 0.95 accounts for losses in the supply and evapotranspiration.

A certain percentage of the area within a subregion is not situated close to the surface water system, and will therefore always be supplied from groundwater. This can be calculated as :

$$ig(r,t) = xg * igs(r,t) \qquad (21)$$

The rest of the required sprinkling will be extracted from the surface water system, if this is allowed. The extraction is :

$$is(r,t) = igs(r,t) - ig(r,t) \qquad (22)$$

The expected extraction amount is( ) is checked with the maximum that is allowed to be extracted from the surface water system. In the case of water shortage in the surface water system the extraction for sprinkling is reduced or even can be zero. The extraction from the surface water system is set to the maximum and the rest must be extracted from groundwater.
Therefore if :

$$is(r,t) \; > \; 0.95 * \min \{ ism(r,t-\Delta t), ismax(r) \}$$

$$is(r,t) = 0.95 * \min ( ism(r,t-\Delta t) , ismax(r) )$$

$$ig(r,t) = igs(r,t) - is(r,t)$$

The factor 0.95 accounts for the evaporation from the surface water system and a need for a minimum amount of water to be present in the system. The extraction from groundwater must be less then the maximum extraction igmax(r).

## 3.3. Surface water system and its interaction with groundwater

### 3.3.1 Water balance of surface water system

The functioning of the surface water system in the summer and winter situation are treated separately.

The summer situation is in general characterized by a supply of water. This supply is governed by a certain maximum capacity. In the winter situation drainage dominates and an amount of surface runoff can also occur regularly.

The summer and winter conditions are shown in figure 3.

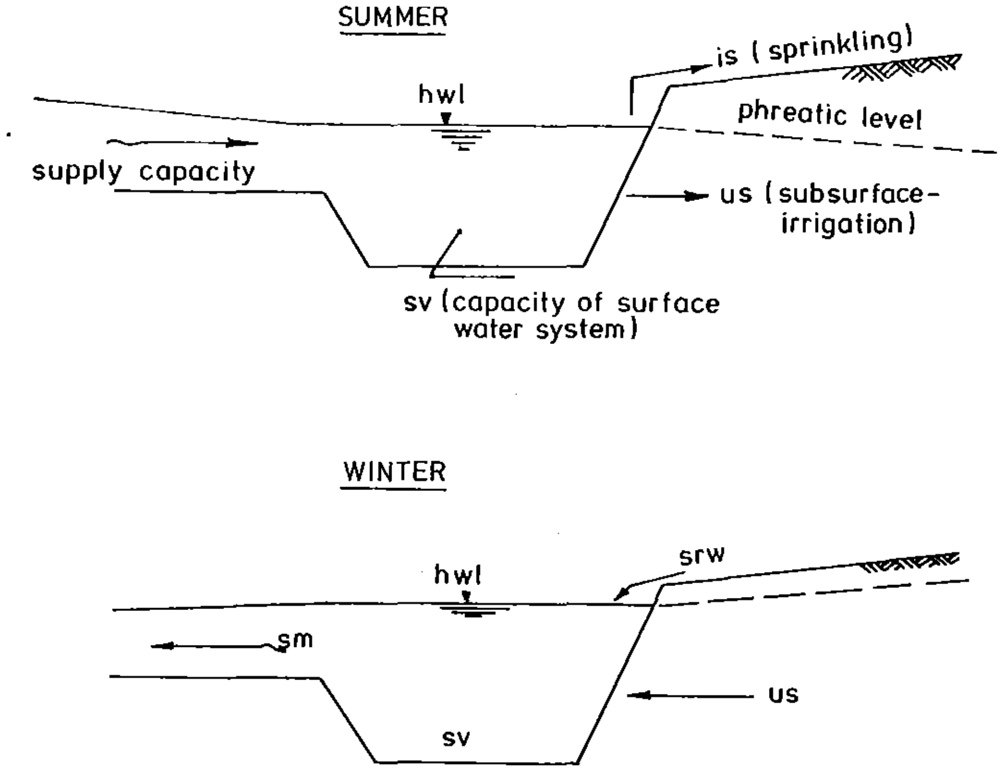


Figure 3 - Schematization of surface water system for summer and winter conditions

The algorithms used for further describing the summer and winter situation are given below.

Summer

The surface water system is modelled as a reservoir with inflows and extractions. The change of storage in this system over a timestep with the assumption that the maximum supply capacity is effective, can be described by :

$$\Delta sv(r,t) = ( smax(r) * spr(t-\Delta t) + srw(r,t) - us(r,t) - is(r,t) ) \Delta t \tag{23}$$

where $smax(r)$ is the maximum surface water supply rate, $spr(\ )$ is the reduction factor for the supply when the maximum supply for the entire region is exceeded ( see equation 26 ), $srw(\ )$ is the surface runoff, $us(\ )$ is the subsurface-irrigation or drainage, and $is(\ )$ the extraction for sprinkling.

The volume of water stored in the surface water system at time t + $\Delta$t would be :

$$sv(r,t+\Delta t) = sv(r,t) + \Delta sv(r,t) \tag{24}$$

Two conditions in summer can occur depending on the volume of water in the system. They are :

- normal situation : $sv(r,t) > vms(r)$

The supply capacity is sufficient to keep the water level at its target level. The supply capacity used for the next timestep is calculated directly from the other external flows.

$$sv(r,t+\Delta t) = vms(r)$$
$$ws(r,t+\Delta t) = wm(r)$$
$$sm(r,t+\Delta t) = us(r,t) - srw(r,t) + is(r,t)$$
$$ism = smax(r) * spr(t-\Delta t)$$

where vms( ) is the maximum storage capacity of the surface water system during summer, wm( ) is the target water level during summer below ground level, ws( ) is the actual water level as a depth below groundlevel, smax(r) is the surface water supply rate, and ism( ) is the maximum extraction for sprinkling for the next timestep.

- shortage of water : $sv(r,t) < vms(r)$

  In this situation the supply capacity is not sufficient to maintain the target level and the water level in the surface water system will drop.
  A lowering of the water level will reduce the amount of subsurface-irrigation, till a new equilibrium situation is reached. With the new storage capacity ( see equation 24 ) the water level can be calculated from a given stage-storage relation.

$$sm(r,t+\Delta t) = smax(r) * spr(t-\Delta t)$$
$$ism(r,t+\Delta t) = sm(r,t+\Delta t) + srw(r,t) - us(r,t)$$
$$ws(r,t+\Delta t) = f\ \{ sv(r,t+\Delta t) \}$$

  The stage-storage relation is given per subregion, and ws( ) is the depth below ground level.

Winter

Now the drainage of water will dominate. The discharge of water from the subregional surface water system is dependent on the weir structures and the capacity of the main outlet channels in the subregion. These effects are simulated with a stage-discharge relation. The supply capacity ( in general drainage ) and the waterlevel are calculated as :

$$sm(r,t+\Delta t) = us(r,t) - srw(r,t)$$

$$ws(r,t+\Delta t) = f\ \{\ sm(r,t+\Delta t)\ \}$$

With the above calculated water level per subregion as a depth below ground level, the actual water level for each node in a subregion can be calculated as :

$$hwl(n,t) = gl(n) - ws(r,t) \tag{25}$$

where hwl( ) is the waterlevel. The reason for this approach is that the ground level over a subregion can vary by some meters. If one level for the surface water system would be taken, it would result in ditches with no water and other with bank full stage. An ideal approach would be by using one reservoir per nodal point, but this would require an excessive amount of input data and computer time.

The supply capacity for the whole region is limited to stmax. If this capacity is exceeded, then the maximum supply capacity per subregion is reduced by a factor :

$$spr(t) = stmax\ /\ \sum_{r} sm(r,t) \tag{26}$$

### 3.3.2 Subsurface-irrigation and drainage

The interaction between the surface water and groundwater system is modelled by means of so-called tertiary and secondary surface water systems. The tertiary system consists of shallow ditches that are intermittently filled with water. The secondary system consists of larger channels, that are nearly always filled with water and the level can be controlled in order to regulate drainage or subsurface-irrigation.

The drainage or subsurface-irrigation is calculated per node and summed over the nodes of a subregion. The equation is :

$$us(r,t) = \sum_{nr(r)} \beta_t(\ ht(n,t) - h(n,t)\ ) + \sum_{nr(r)} \beta_s(\ hs(n,t) - h(n,t)\ ) \tag{27}$$

The first term on the right hand side is the discharge to the tertiary system and the second term is the discharge to the secondary system as shown in figure 4.

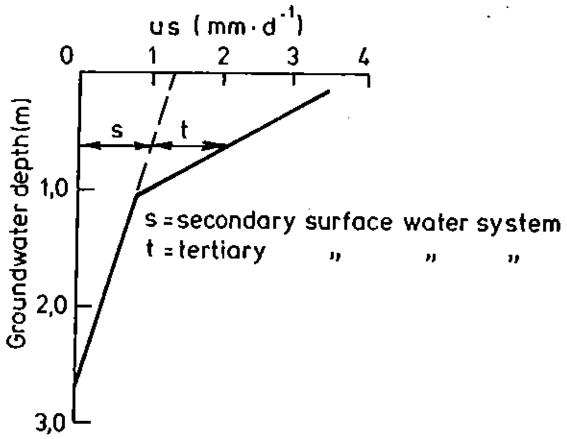


Figure 4 - Typical discharge to surface water system

Depending on whether there is water in the tertiary surface water system or not one can have two conditions for the factor $\beta$ of equation (17) ( the approach for the secondary system is identical ) :

- free draining ditch : ht(n,t) = hbt(n)

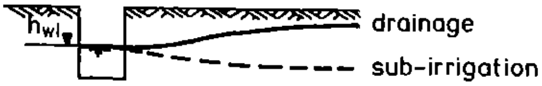
drainage : h(n,t) > hb(n) $\beta_\ell = - 1 / gf * Y_\ell$

no flow : h(n,t) <= hb(n) $\beta_\ell = 0.$

The ditches are in these cases empty, and drainage is possible, but no subsurface-irrigation.

- open-water level in ditch : ht(n,t) = hwl(n,t)

$\beta_\ell = - 1 / gf * Y_\ell$



A water level in the ditches is present, which results in a reduced head for the amount of drainage. In this situation it is possible to have subsurface-irrigation. The water level in the ditch has been set to a level as discussed in paragraph 3.3.1.

In the above relations Y is the drainage resistance, and gf is a geometry factor to convert the hydraulic head midway between two ditches to the average hydraulic head calculated for a nodal point ( see also figure D2 ).

From the density of the ditches in both systems, the drainage resistance is estimated, which is in fact the slope of the lines shown in figure 4. The procedure for estimating the drainage resistance is given in paragraph 4.2.

### 3.3.3 Surface runoff

In the model the surface runoff is computed as shallow subsurface flow and flow over the soil surface to a network of ditches with a drainage base at 0.20 m below ground level. So the surface runoff is computed in a manner analogous to the drainage and subsurface irrigation. Therefore, the relations describing the surface runoff is included in the set of relations describing the interaction between the surface water and the groundwater, as shown in figure 5.

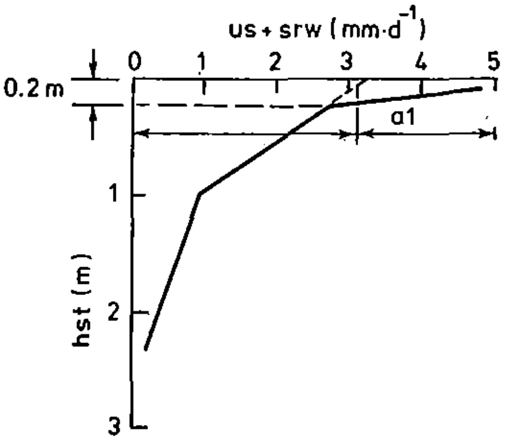


Figure 5 - Typical relation for discharge to surface water system

The distance a1 is the amount of surface runoff and the other part is the normal drainage ( see figure 5 ).

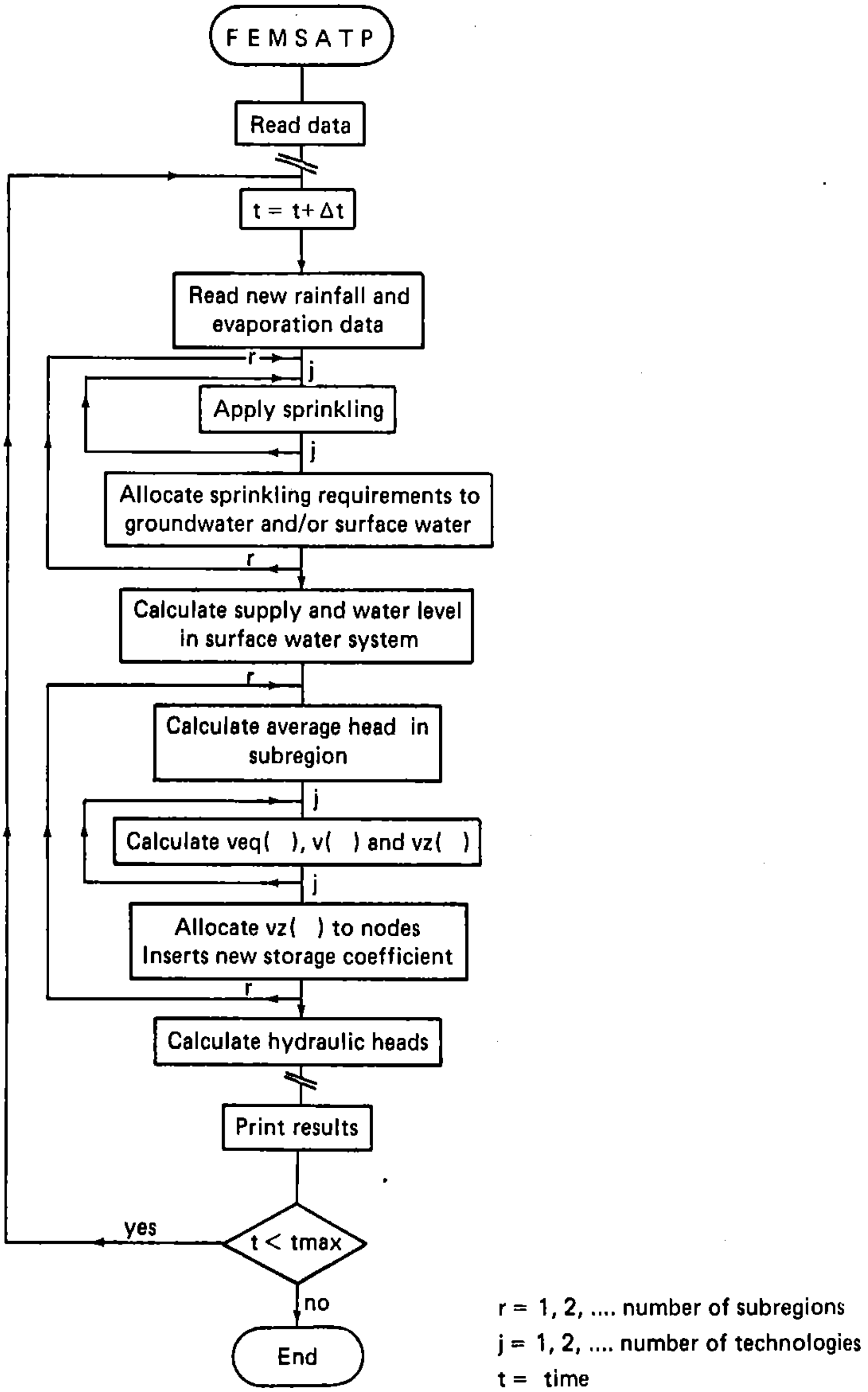


Figure 6 - Flow chart of calculation scheme

## 3.4. Flow chart of calculation scheme

A flow chart of the calculations performed by the three submodels discussed in paragraphs 3.1. to 3.3. is given in figure 6.

## 3.5. Conclusion

The calculation method discussed in the paragraphs 3.1 to 3.3 still uses simple relations to describe the affected variables. From the rigorously linear relations necessary for the first level model, it is now possible to use very non-linear relations.

In particular the relations between change in groundwater depth and capillary rise ( or percolation ) is non-linear and time dependent. The effects of unsteady extractions could also be taken into account.

It is now possible to simulate the evapotranspiration and moisture content in the root zone for each land-use, which results in more realistic values for these variables during the year.

# 4. INPUT OF DATA

The finite element model requires a schematization into a number of layers with homogeneous characteristics, such as aquifers and aquitards. Each layer is subdivided into a finite number of elements ( see also Appendix A ). In an aquifer the flow can be in a horizontal direction. The aquifer layers are enclosed by aquitards in which the flow direction is only vertical.

In the following paragraphs typical aspects, such as soil physical properties, drainage resistance, and surface water system characteristics are discussed.

## 4.1. Hydrological schematization

From field measurements it has been found that the toplayer can be modelled as an aquitard. The second and fourth layers are aquifers, and the third layer is an aquitard. These four layers are present in the Central Slenk area which is on the west side of the Peelrand fault ( see figure 7 ). On the Peel Horst the third and fourth layer are not present and the hydrological basis is below the second layer.

The soil properties of each layer in the Central Slenk and Peel Horst area are given in table 3 ( WIT, 1985; REES VELLINGA and BROERTJES, 1984; HAAIJER, 1984 )

In table 3 the specific storage is the volume of water released or stored in an aquifer or aquitard by a change in hydraulic head.

Table 3 - Soil properties

| layer | layer thickness ( m ) | vertical resistance ( d ) | KD ( $m^2/d$ ) | specific storage ( $m^{-1}$ ) |
|---|---|---|---|---|
| Slenk | | | | |
| 1 | 25 | 100-2500 | - | .0006 |
| 2 | 45-50 | - | 750-3500 | .0006 |
| 3 | 110 | 1500-20000 | - | .0006 |
| 4 | 160 | - | 5500 | .0006 |
| Horst | | | | |
| 1 | 4-25 | 1000-2000 | - | .0006 |
| 2 | 4-34 | - | 200-2000 | .0006 |

## 4.2. Drainage resistance

The drainage resistance has been derived by EERENBEEMT and KARTOREDJO ( 1983 ) from the density of the ditches and brooks. They derived for approximately 150 areas in the study area the average drainage resistance from these densities.

To simplify the derivation of the drainage resistance as a function of the groundwater depth, six different classes of drain density have been distinguished ( classes A to F ). The classes A to F refer to an overall density of ditches and brooks per subregion. Class A has a dense drainage system and class E has hardly any drainage. Class F refers to the two nature reserves in subregion number 16 and 27 ( see figure 7 ). The selected class per subregion is shown in figure 7. In some subregions there is quite a variation of ditch intensity. In these cases the most frequent draïnage class has been selected.

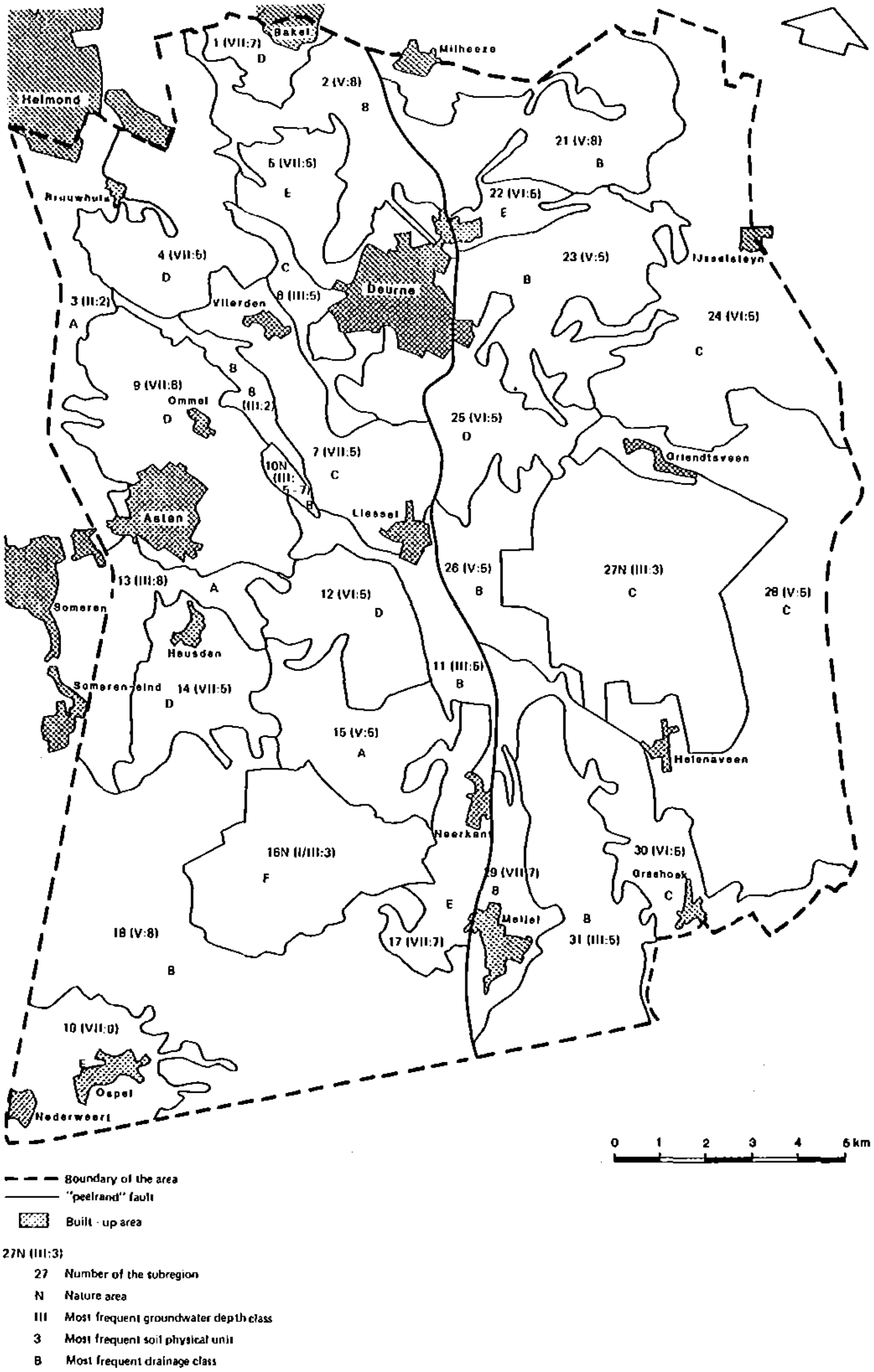


Figure 7 - Adopted drainage classes

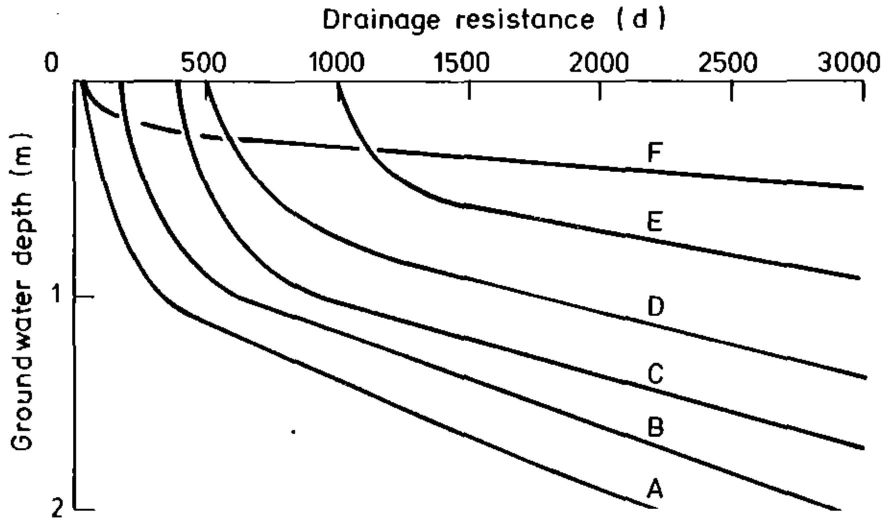


Figure 8 - Classified drainage resistance characteristics

The ditches and brooks were classified in relation to the depths ( ERNST, 1978 ). For each average depth per ditch category the drainage resistance was calculated. An equilivalent drainage resistance for all the categories was calculated for specific depths. The derived drainage resistance as a function of groundwater depth is given in figure 8. In these calculations it has been assumed that all the ditches are free draining. From figure 8 it can be seen that a constant drainage resistance for either tertiary or secondary surface water system would not be realistic, and exponential relations have been derived. For the relations shown in figure 8 the following exponential functions were derived :

$$Y = a * \exp( b * hst(r,t) ) \quad (28)$$

where Y is the drainage resistance ( d ), hst( ) is the groundwater depth, and the constants a and b are dependent on the classes A to F ( see table 4 )

Table 4 - Values of coefficients a and b

| class | a | b |
|---|---|---|
| A | 50 | 1.94 |
| B | 165 | 1.45 |
| C | 325 | 1.20 |
| D | 500 | 1.20 |
| E | 1000 | 1.20 |
| F | 25 | 14.0 |

## 4.3. Surface water system

From the surface water system the following characteristics were required per subregion :

- storage capacity
- maximum supply capacity
- water level ( target ) in summer
- stage-discharge relation for drainage situation

The storage capacity could be derived from the defined ditch density per subregion ( Class A to F ). The maximum supply capacity was determined from field measurements and information from local Water Boards.

The discharge capacity for the winter situation is defined also from the ditch density. For each ditch class the weir width has been calculated, and given in Table 5 ( for classification of codes per subregion see figure 7 ).

Table 5 - Discharge capacity per ditch density class ( m / $km^2$ )

| class | weir width |
|---|---|
| A | .300 |
| B | .120 |
| C | .060 |
| D | .040 |
| E | .035 |
| F | .030 |

The resistance of the channel system has been incorporated in the discharge characteristics as a function of the drainage.

# 5. DISCUSSION OF RESULTS

## 5.1. Verification

In the second level model the hydrological processes are modelled as realistic as possible. The constraints are in general a lack of data and required computational effort, which can influence the results of certain processes to a certain degree. Therefore the verifications are split up in two separate calculations. The concept for the unsaturated zone is verified by comparing it with results from a more accurate model. The hydrological schematization and the input parameters are verified by comparing the results of FEMSATP with field measurements. A sensative analysis on the hydrogeological parameters is done to determine the accuracy of the results. All these aspects are discussed in the following paragraphs 5.1.1 to 5.1.3.

### 5.1.1 Model for unsaturated zone

The simplified calculation method proposed for the water movements in the unsaturated zone ( paragraph 3.2. ) has been placed in a one-dimensional model ( SIMUNS ). For the underlaying saturated zone in this model a relation is defined to describe the flow to the surface water system and the seepage ( see figure 9 ). The computed results of this model could be compared with results from the SWATRE model. This model is a transient one-dimensional finite-difference model for the unsaturated zone with water uptake by roots ( BELMANS, WESSELING and FEDDES, 1983 ).

In the present discussion the comparison will be restricted to the hydraulic heads and water balance terms of the unsaturated zone, calculated for the hydrological year 1975 ( 1 Oct 1974 to 30 Sept 1975 ). The results of the two models are given in table 6, from where it can be seen that their is a reasonable agreement of the calculated results by both models. The model SIMUNS has the tendency to have less evapotranspiration ( 16 - 24 mm ) and less capillary rise ( 1 - 24 mm ). The storage coefficient used for the saturated zone is in the program SIMUNS assumed to be dependent only on the groundwater depth. It should also be dependent on the magnitude of the capillary rise or percolation. If we consider the introduced simplifications of the second level model, these results are satisfactory.

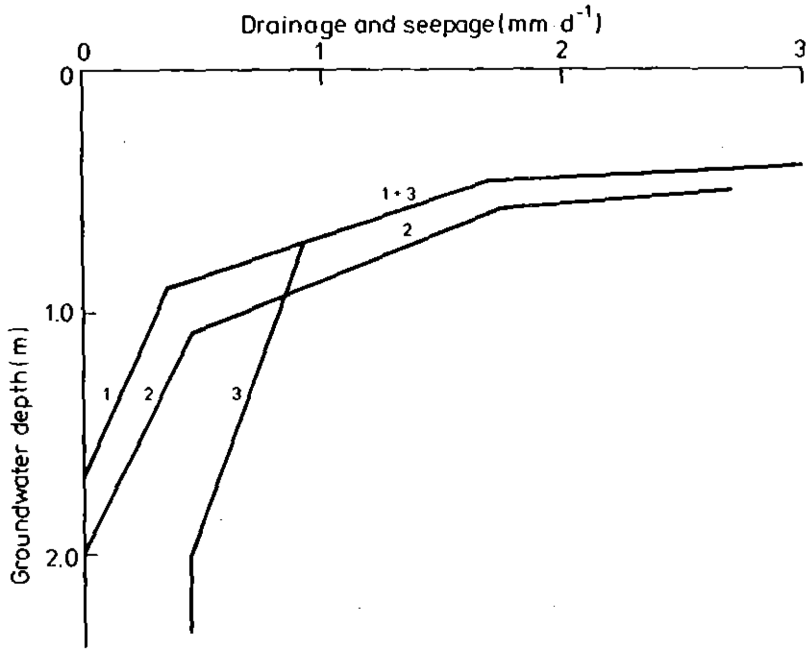


Figure 9 - Boundary conditions for the saturated zone

### 5.1.2 Results of FEMSATP

For the verification of the model the computed results are compared with the measured data of 1982. The land-use, actual technologies, and available sprinkling capacity as present in 1982 could be taken. The technologies used in the calculations and their characteristics are given in Appendix C.

The most important time dependent data are precipitation, potential evapotranspiration, and extractions for public water supply. The precipitation measured by the Royal Dutch Meteorological Office ( KNMI ) was used.

Table 6 - Comparison model results from SIMUNS and SWATRE for grassland with root zone of 0.25 m

| soil unit | bound. cond. fig 8 | groundwater level 1-04-75 (m) | groundwater level 1-10-75 (m) | evapotranspiration (mm) | capillary rise (mm) |
|---|---|---|---|---|---|
| SIMUNS | | | | | |
| 5 | 1 | 0.54 | 1.42 | 400 | 38 |
| 8 | 1 | 0.47 | 1.81 | 423 | 65 |
| 5 | 2 | 0.68 | 1.51 | 386 | 28 |
| 8 | 2 | 0.65 | 1.87 | 415 | 62 |
| 5 | 3 | 0.54 | 1.65 | 391 | 27 |
| 8 | 3 | 0.53 | 2.04 | 405 | 46 |
| SWATRE | | | | | |
| 5 | 1 | 0.54 | 1.26 | 420 | 40 |
| 8 | 1 | 0.47 | 1.70 | 459 | 83 |
| 5 | 2 | 0.68 | 1.37 | 398 | 20 |
| 8 | 2 | 0.65 | 1.78 | 448 | 76 |
| 5 | 3 | 0.54 | 1.52 | 407 | 28 |
| 8 | 3 | 0.53 | 2.14 | 444 | 68 |

The potential evapotranspiration for grassland was calculated from meteorological data. The potential evapotranspiration for the other technologies is calculated in the program by equation (18).

The extractions for public water supply are situated near Vlierden in subregion 7 and near Ospel in subregion 18 ( node 75 and 203, as shown on figure A1 ). The pumpstation situated in subregion 7 extracts water from the shallow aquifer ( second layer ), and the pumpstation in subregion 18 extracts water from the deep aquifer ( fourth layer ). The capacities of both pumpstations are :

| | | | |
|---|---|---|---|
| Vlierden | - | 9630 | $m^3/d$ |
| Ospel | - | 5900 | $m^3/d$ |

The calculations with the FEMSATP model were done for 1981 and 1982. The first year is necessary to start-up the model, so that all parameters have the right values at the start of the actual verification period ( 1982 ).

The verification is done by comparing measured groundwater levels in eight points during the year. These results are discussed in Appendix D, from where it can be concluded that the calculated results in the Slenk area resemble the measured data very good and that in the Horst area some differences occur ( see also figure D3 and D4 of Appendix D for some results )

The calculated levels of the first aquifer for August 1982 are compared with the measured values. In figure 10 the isoline patterns of the calculated and measured levels are given.
The calculated map shows a more regular pattern, because in the case of measured values there may be all kinds of local anomalies and also errors in the measurements. Another difference is the more smooth transition in the calculated values in the neighbourhood of the Peelrand fault. This is caused by the relative coarse nodal network.
In general, however the resemblance between calculated and measured isoline patterns seems satisfactory. In the Horst area the difference between calculated and measured levels is very small ( 0.1 - 0.4 m ). For the Slenk area the same applies as for the Horst area, except in the north-west corner near the region boundary where the differences become greater closer to the boundary ( up to 1.0 m ). A hydrological aspect which perhaps is not included in the model or an error in the boundary condition could be the possible cause of this difference.

### 5.1.3 Sensitivity analysis

Various parameters have been varied to analyse the effect of this variation on the results. The discussion of the results has been restricted to the average standard deviation of the eight measuring points as discussed in Appendix D, the effect on the groundwater levels, and the variation of the waterbalance terms of the unsaturated zone. The results of the sensitivity analysis are given in Appendix E.

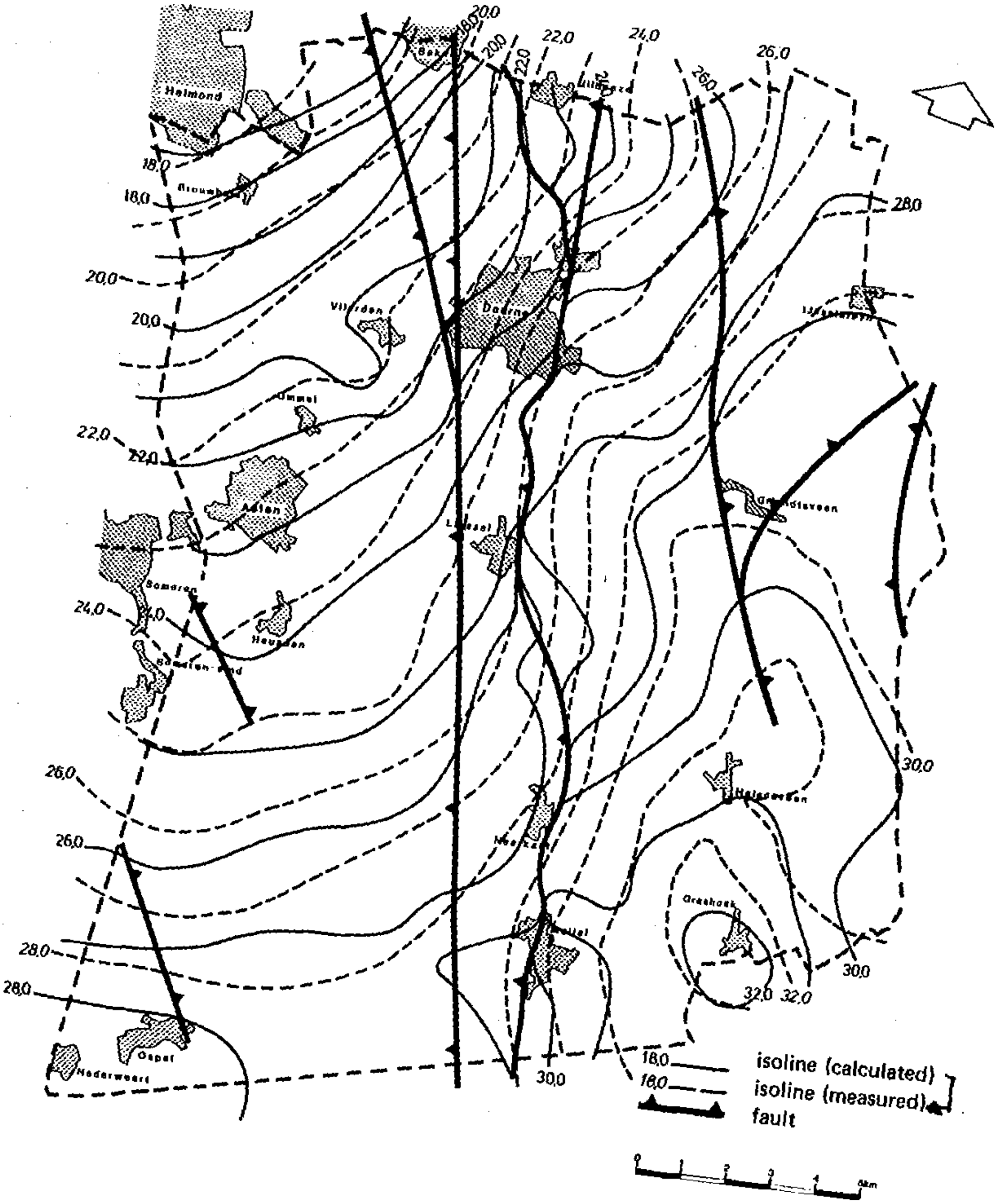


Figure 10 - Measured and calculated hydraulic heads for first aquifer

The conclusions drawn from these results are :

- The variation of groundwater depth at the beginning of the summer half year is more pronounced then at the end of the period.
- The groundwater depth at the beginning of summer is dominated by the drainage resistance.
- The selection of the soil physical unit is important for the correct estimation of the results at the end of the summer period.
- The effect of variation in the geohydrological parameters has hardly any effect on the total sprinkling, actual evapotranspiration, and capillary rise.

## 5.2. Comparison of first- and second level model

With the agricultural technologies present in 1982 the weather year 1975 was used. This year has been selected for the first level model computations, because it is a moderate dry year, with a 10 % occurrence of dryer conditions. The results of both models as far as groundwater levels and waterbalance terms concern, are given in Appendix F.

The deviation in results of first and second level model is rather big, so that an adjustment of the constraints in the first level model is necessary. The main reason for the differences are that both models are based on different sets of data. The first level model is based on data from third level models. These models are separatly run, so the assumed boundary conditions play an important role in the accuracy of these model results.

To overcome the differences in results the first level model input data can be obtained from results of the second level model ( unperturbed waterlevels, evapotranspiration, and capillary rise ).

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# 7. LIST OF SYMBOLS

a - constant
b - constant
B - storage coefficient
D - thickness of aquifer or aquitards
ea - actual evapotranspiration
ep - potential evapotranspiration
epg - potential evapotranspiration of grassland
gf - geometry factor
gl - ground level
h - hydraulic head
ha - mean standard deviation
hb - bottom level of ditch
hc - calculated hydraulic head ( appendix D )
hm - measured hydraulic head
hs - water level in secondary surface water system
hst - groundwater depth
ht - water level in tertiary surface water system
hwl - water level in surface water system
ig - extraction for sprinkling from groundwater
igm - maximum amount of sprinkling
igmax - maximum allowed extraction from groundwater
igs - total amount of sprinkling
inf - maximum infiltration rate
int - plant interception factor
is - extraction for sprinkling from surface water
ism - maximum extraction from surface water for irrigation during timestep
ismax - maximum allowed extraction from surface water for irrigation
j - technology considered
k - number of observations
K - hydraulic conductivity of aquifer layers
n - nodal point of finite element grid
nr - number of nodal points per subregion
p - net precipitation
Qc - extraction for public water supply or sprinkling
Qe - external flow

Qnm - flow beteen node n and adjacent nodes m
r - subregion number
rz - root zone depth
s - index for soil physical unit
sm - supply capacity
smax - maximum supply capacity
spr - reduction factor for supply capacity per subregion
srw - surface runoff
stmax - maximum supply capacity of region
sv - storage capacity of surface water system
t - time
us - subsurface-irrigation or drainage
v - moisture content in the root zone
veq - equilibrium moisture content
veqo - equilibrium moisture content for zero groundwater depth
vms - maximum storage capacity of surface water system during summer
vz - flux between saturated and unsaturated zone
wm - minimum distance of water level in surface water system below ground level
ws - distance of water level in surface water system below ground level
x - area of land allocated to technology j
xg - percentage of subregion area allways irrigated from groundwater
xnd - area of node n
xt - area of subregion r
Y - drainage resistance
Δh - change in head over a timestep
ΔQnm - change in flow between nodes over timestep
Δsv - change in storage capacity of surface water system
Δv - change in moisture content over timestep
Δt - timestep
θ - weighting parameter

# APPENDIX A - Finite element network

For the finite element method it is required to subdivide the study area into elements, either triangular or quadrilateral in shape. Triangular elements have been used here to represent the complex shapes of the region and the subregions.

The nodal points must be positioned in relation to each other, that each node represents an area of land.

The discretization of the study area with the nodal points is shown in figure A1. The study area has been subdivided into 748 elements which has resulted in 404 nodal points.

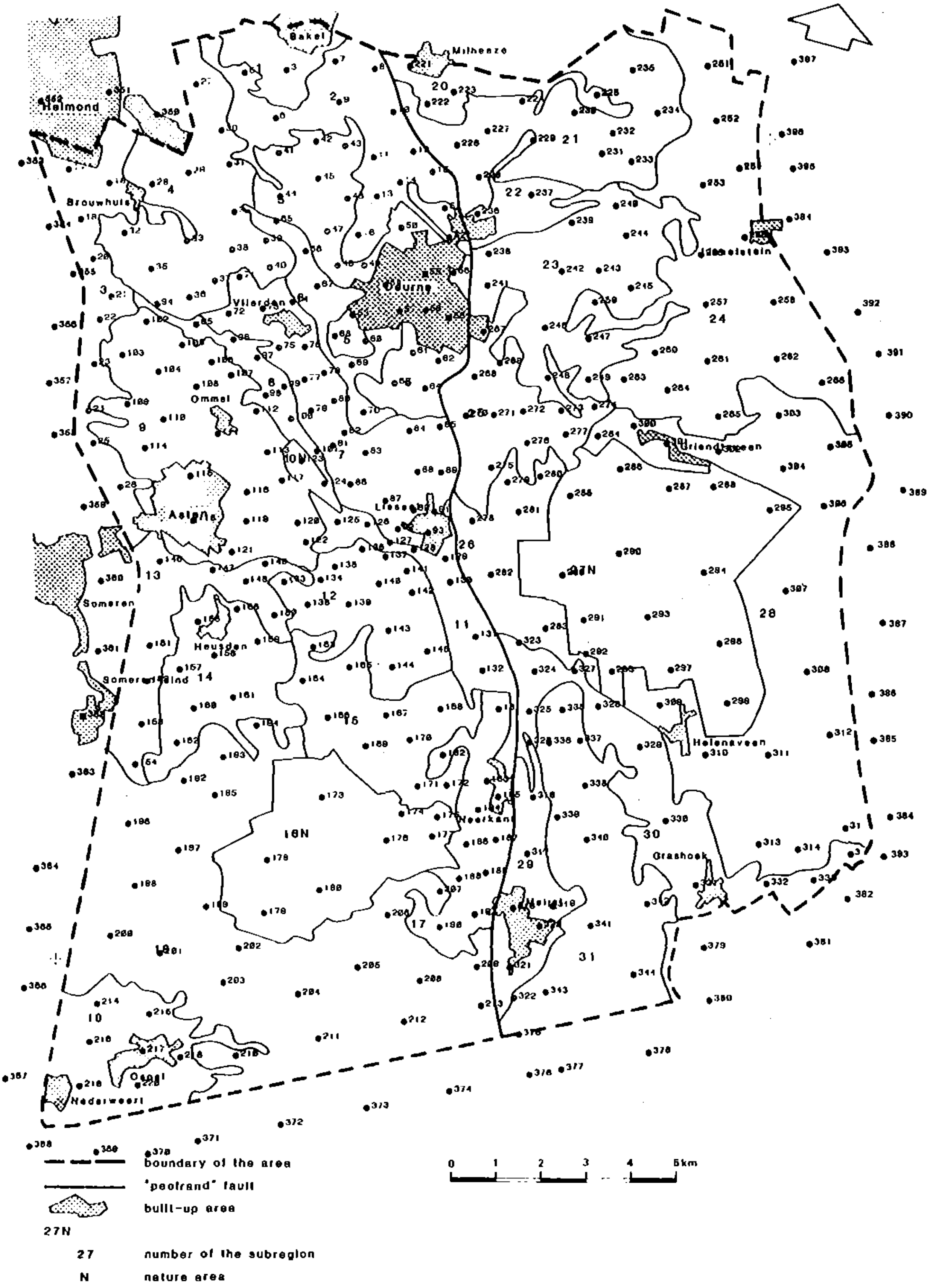


Figure A1 - Finite element network of study area

## APPENDIX B - Soil physical properties

Six different soil physical units are distinguished for the Southern Peel region ( SMIDT, 1983 ). For each soil physical unit the equilibrium moisture content, capillary flux, and storage coefficient have been calculated and given as input data for the computer program. The capillary rise and storage coefficient are calculated with the program CAPSEV ( WESSELING, BLOEMEN and KROONEN, 1984 ). The equilibrium moisture content is calculated from the soil profile data. The values shown in the figures B1 - B3 are based on a root zone depth of 0.25 m.

### Equilibrium moisture content

To account for different root zone depths between technologies a factor per soil physical unit for a depth of 0.50 m and 1.00 m have been included ( see table B1 ). The values given in figure B1 must be multiplied with these factors to derive equilibrium moisture contents for different root zone depths. For other root zone depths the factors are interpolated linearly.

Table B1 - Factor to correct equilibrium moisture content for root zone depth other then 0.25 m

| Soil physical unit | root zone depth 0.50 m | 1.00 m |
|---|---|---|
| 2 | 2.71 | 6.04 |
| 3 | 2.75 | 5.31 |
| 5 | 1.63 | 3.09 |
| 7 | 1.80 | 3.05 |
| 8 | 1.95 | 3.57 |
| 9 | 2.03 | 3.91 |

## Capillary rise

The capillary rise is calculated for a quasi steady-state condition, using a pressure head of -500 cm. The maximum flux is limited to 5 mm/d. To correct the capillary rise for different root zone depths the groundwater depth is adjusted to account for the difference in actual root zone depth, and the standard depth of 0.25 m ( see figure B2 ).

## Storage coefficient

A typical relation for the storage coefficient is shown in figure B3. If the groundwater level is at or above ground level, then the storage coefficient is equal to unity. If the groundwater level is in the root zone then pools of water on the surface will occur. To account for this effect and to maintain numerical stability of the calculation process, the increase from underground storage to storage above the surface has been taken over the last 0.20 m, as shown by the dashed line in figure B3.

For the two nature reserves ( subregion 16 and 27 ) the storage coefficient has been taken constant as 0.25. This is to take into account the storage capacity of the peat, that is present in these areas.

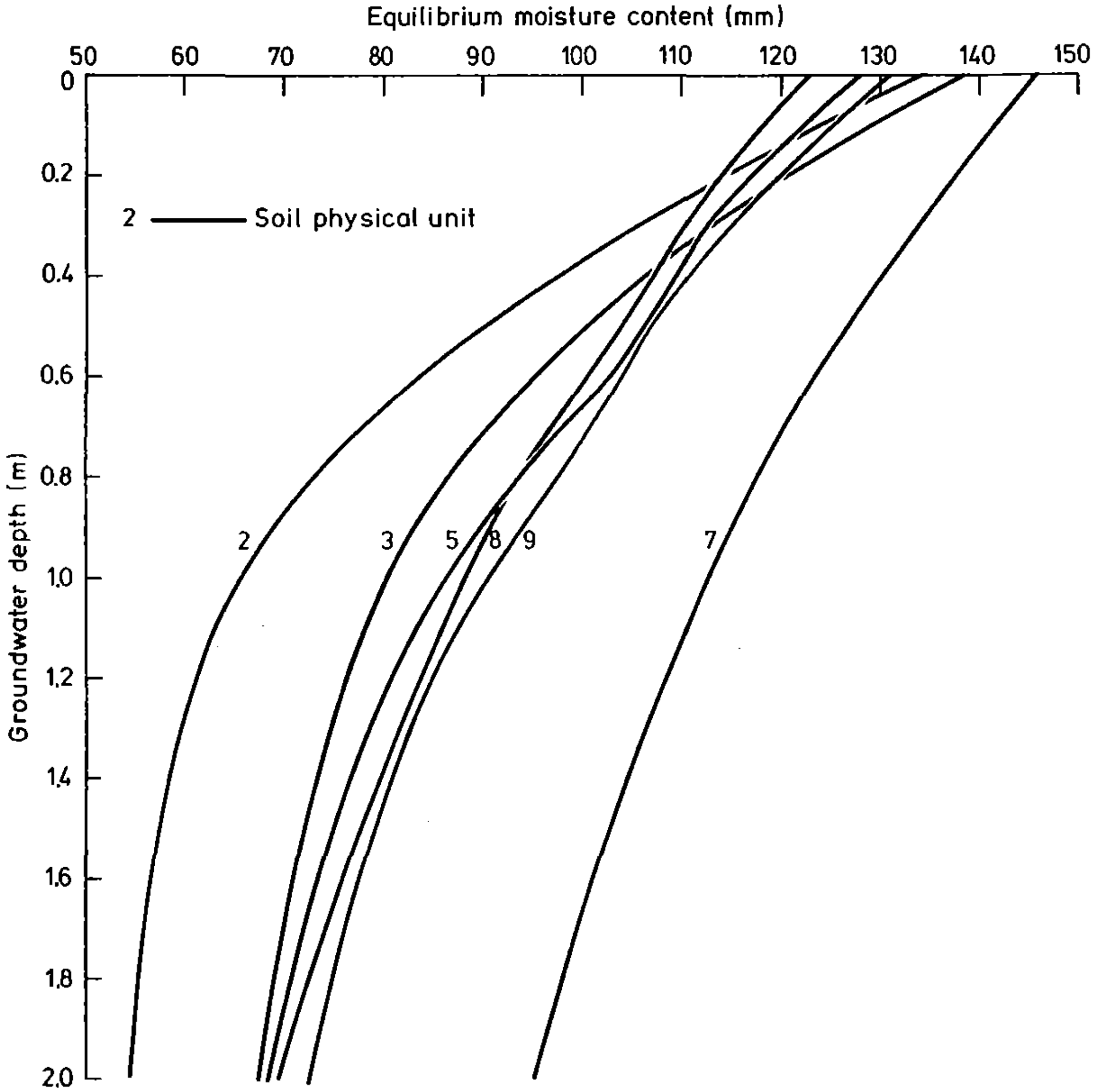


Figure B1 - Equilibrium moisture content for a root zone of 0.25 m

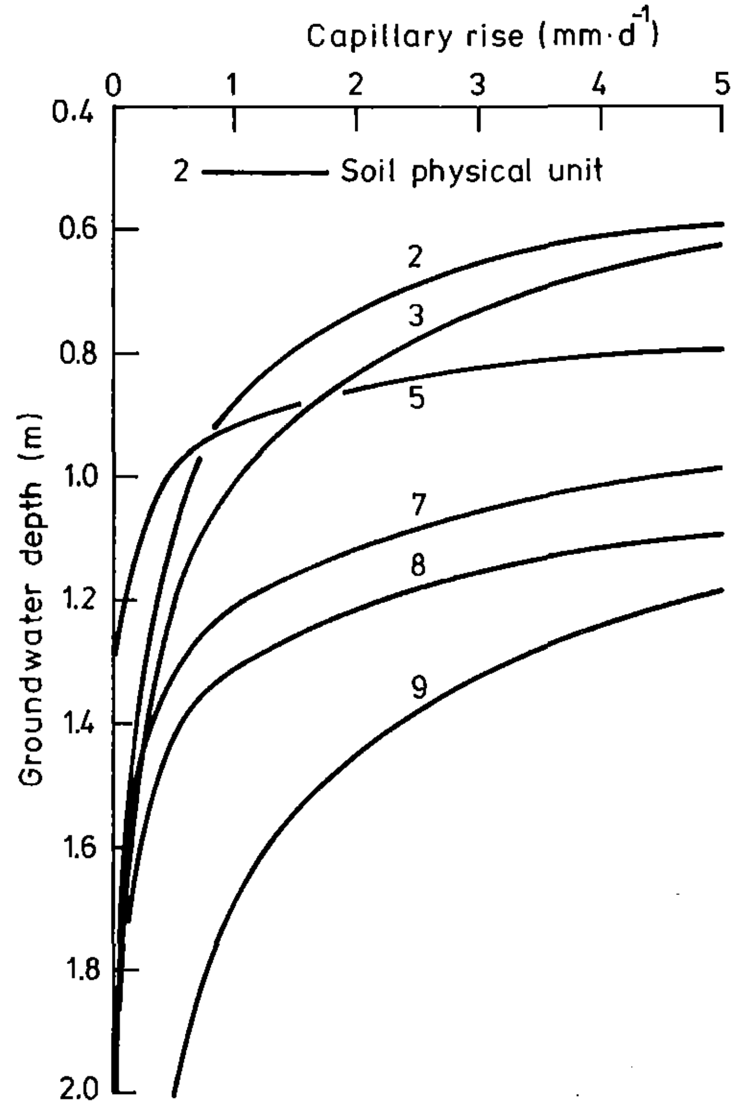


Figure B2 - Capillary rise for a root zone depth of 0.25 m

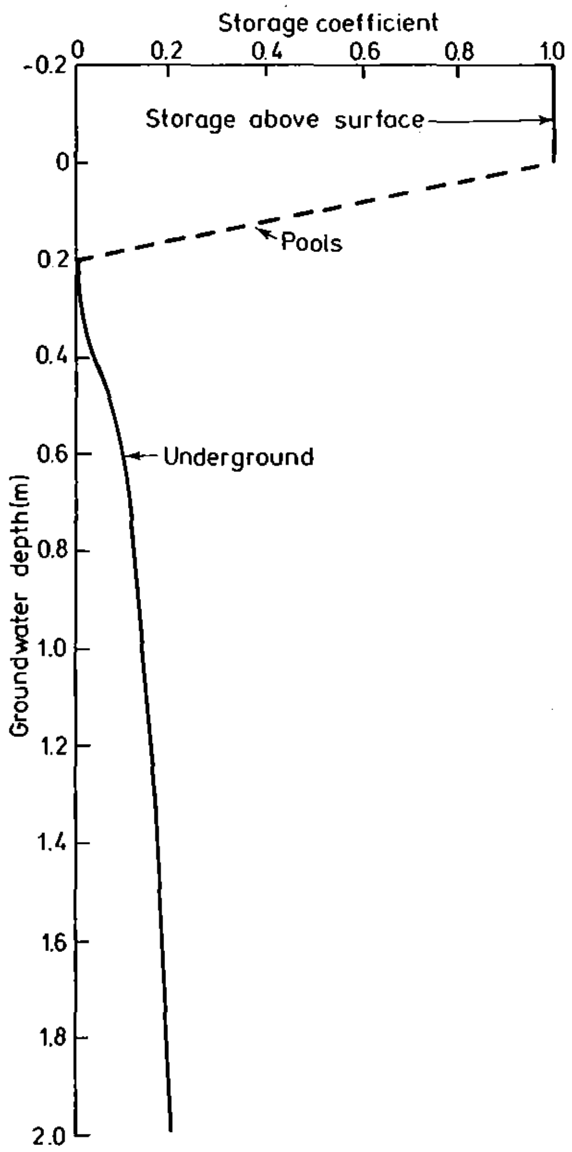


Figure B3 - Typical relation for storage coefficient with root zone depth of 0.25 m

## APPENDIX C - Description of technologies used for calculations

The selected technologies together with the sprinkling intensity, and root zone depth are given in Table C1.

The sprinkling intensity is a gift of 25 mm. For each technology where the sprinkling is started the total area for this technology is irrigated in the number of days given in table C1.

The built-up areas with a permeable surface area are assumed as 60 % of the total area for the towns. The nature areas are defined as regions with a grass vegetation.

Table C1 - Technologies used for calculations

| technology number | description | production level |
|---|---|---|
| 1 | glasshouse horticulture | 0 |
| 2 | int. field horticulture | 2 |
| 3 | ext. field horticulture | 3 |
| 4 | potatoes | 2 |
| 5 | cereals | 1 |
| 6 | maize ( low nitrogen appl. ) | 0 |
| 7 | maize ( med. nitrogen appl. ) | 0 |
| 8 | maize ( high nitrogen appl. ) | 0 |
| 9 | grassland ( high cow density ) | 3 |
| 10 | grassland (low cow densty ) | 0 |
| 11 | built-up areas | 0 |
| 12 | nature areas | 0 |
| 13 | pine-forest | 0 |

## APPENDIX D - Comparison of calculated and measured hydraulic heads

From eight measuring points the hydraulic head is compared with the calculated results. The eight points are shown on figure D1, from these points time-hydraulic head curves where available. The results are analysed by using the mean standard deviation as a measure for the agreement between the measured and calculated values.

From the model results and measured time-hydraulic head values the mean standard deviation has been calculated with the equation :

$$ha = \left( (1/k) * ( hm(i,t) - hc(n,t) + hl(i) ) \right)^{1/2} \qquad (29)$$

where ha is the mean standard deviation, hm( ) is the measured hydraulic head, hc( ) is the calculated hydraulic head, hl(i) is a constant head to convert the measured levels for location i to nodal point n, and k is the number of observations over which the summation is taken.

The measured levels are for a location i, and the calculated results correspond to the average hydraulic head for a nodal point. Therefore hl(i) is used as a conversion. This factor should be time dependent, because it depends on the difference in head between the surface water and the groundwater level midway between two ditches. The position of the observation point in relation to the surface water system is also important, as is shown in figure D2. These aspects have been ignored and the conversion factor has been assumed to be independent of time.

The results of equation (29) for the eight points are given in table D1.

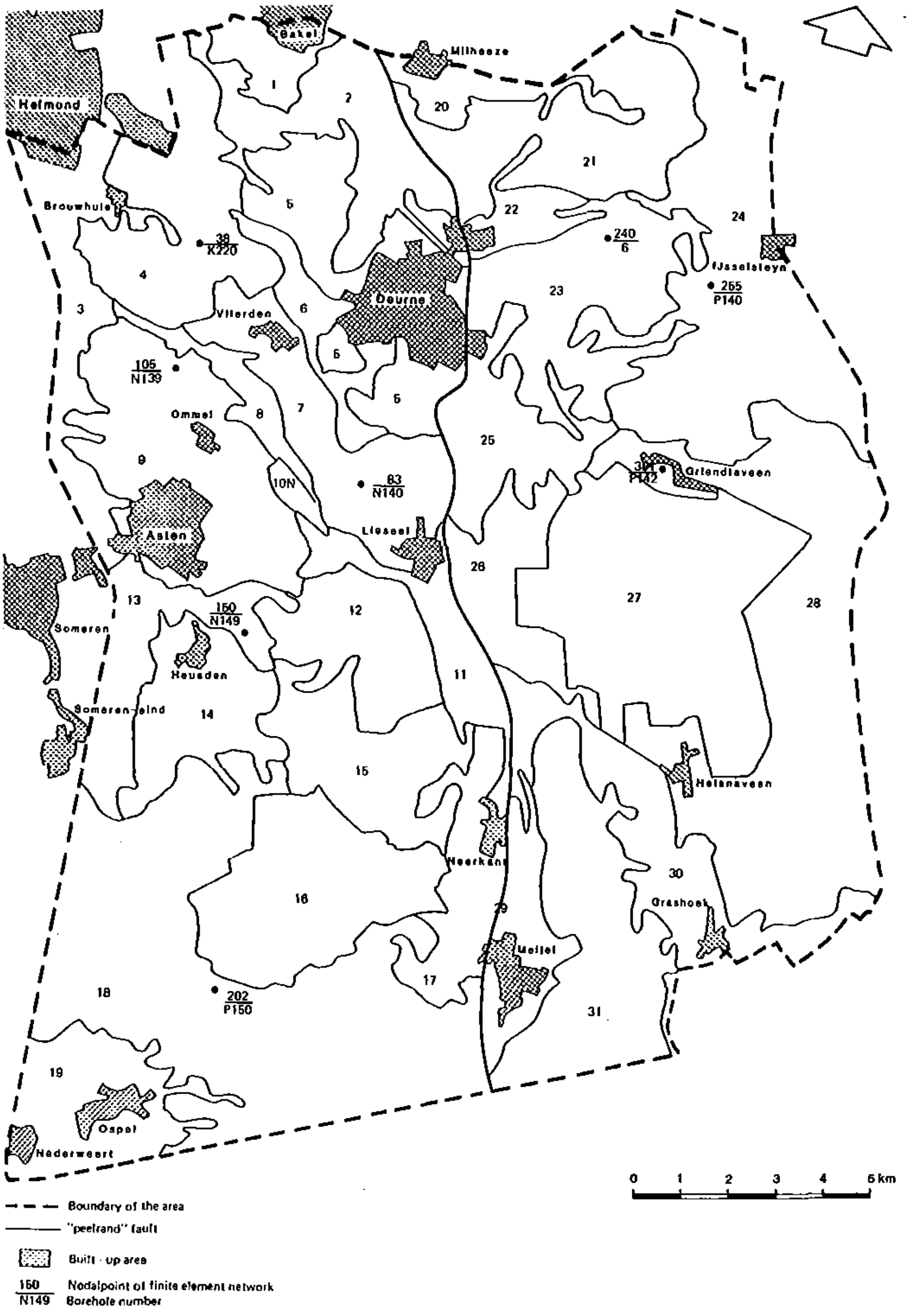


Figure D1 - Location of measuring points

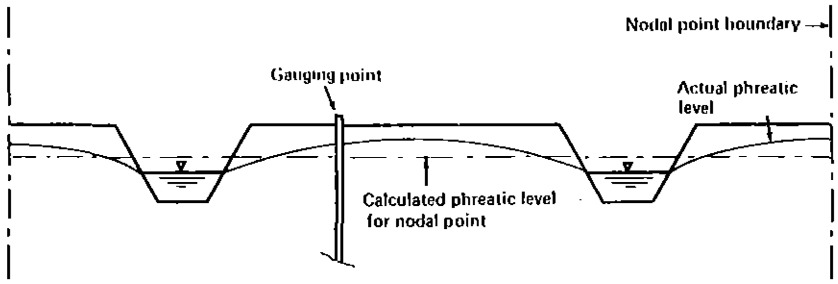


Figure D2 - Correction to relate point measurements to calculated average heads

Table D1 - Mean deviation with minimum, maximum, and average difference in hydraulic head ( layer no 1 - phreatic ; layer no 2 - aquifer )

| nodal point | layer no | ha (m) | hm - hc min | hm - hc max | hm - hc average | hl (m) |
|---|---|---|---|---|---|---|
| 38 | 1 | 0.21 | -0.33 | 0.02 | -0.19 | .0 |
| 83 | 1 | 0.22 | -0.48 | 0.07 | -0.19 | .0 |
| 83 | 2 | 0.21 | -0.43 | 0.09 | -0.15 | .0 |
| 105 | 1 | 0.19 | -0.38 | 0.43 | -0.01 | .0 |
| 105 | 2 | 0.16 | -0.34 | 0.13 | -0.09 | .0 |
| 150 | 1 | 0.18 | -0.37 | 0.25 | -0.09 | .0 |
| 150 | 2 | 0.17 | -0.46 | 0.13 | -0.11 | .0 |
| 202 | 1 | 0.24 | -0.49 | 0.11 | -0.19 | .0 |
| 202 | 2 | 0.46 | -0.66 | 0.02 | -0.42 | .0 |
| 240 | 1 | 0.20 | -0.25 | 0.39 | 0.05 | .0 |
| 255 | 1 | 0.42 | -0.63 | -0.13 | -0.39 | -0.11 |
| 255 | 2 | 0.29 | -0.51 | 0.00 | -0.26 | -0.11 |
| 301 | 1 | 0.30 | -0.61 | 0.18 | -0.23 | .0 |
| 301 | 2 | 0.36 | -0.65 | 0.09 | -0.32 | .0 |
| average |  | 0.26 | -0.47 | 0.13 | -0.19 |  |

The points 38 up to and include 202 are situated in the Slenk area ( left hand side of Peelrand fault ) and the others points are situated in the Horst area ( see figure D1 ). From table D1 it can be seen that the mean standard deviation is smaller in the Slenk area then in the Horst area. The first water bearing layer in the Slenk has relative uniform characteristics and can be modelled satisfactorily by the relative coarse nodal network. In the Horst area the characteristics of the water bearing layer is very irregular in space, caused by the presence of small faults ( REES VELLINGA and BROERTJES, 1984 ). The thickness of the water bearing layer for instance varies from 4 to 25 m.

The calculated and measured results are plotted and shown in figure D3 and D4. From these figures and also the results in table D1 it can be seen that in general the calculated heads are higher then the measured heads, especially in the summer period. The effect of the point measured heads and compared with the average calculated heads for a nodal point contributes to part of these differences.

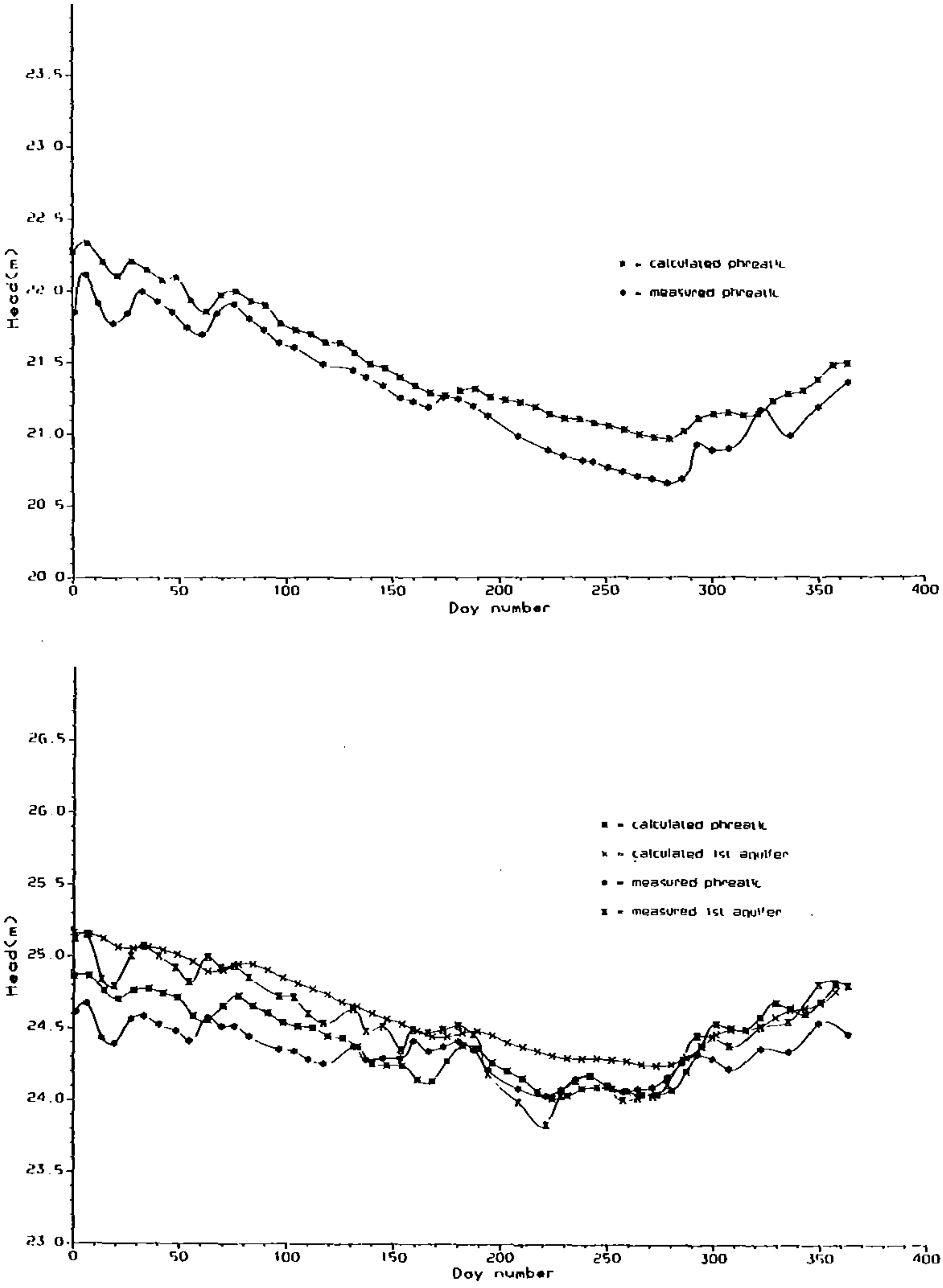
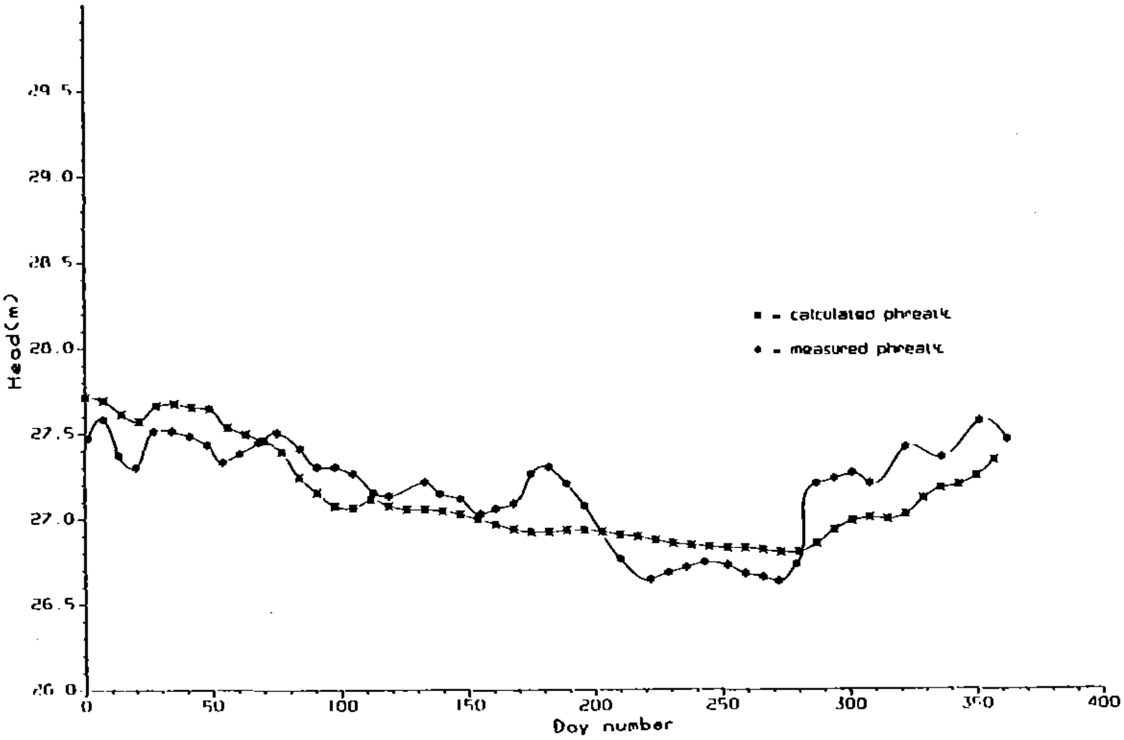


Figure D3 - Measured and calculated heads for point 38 and 150



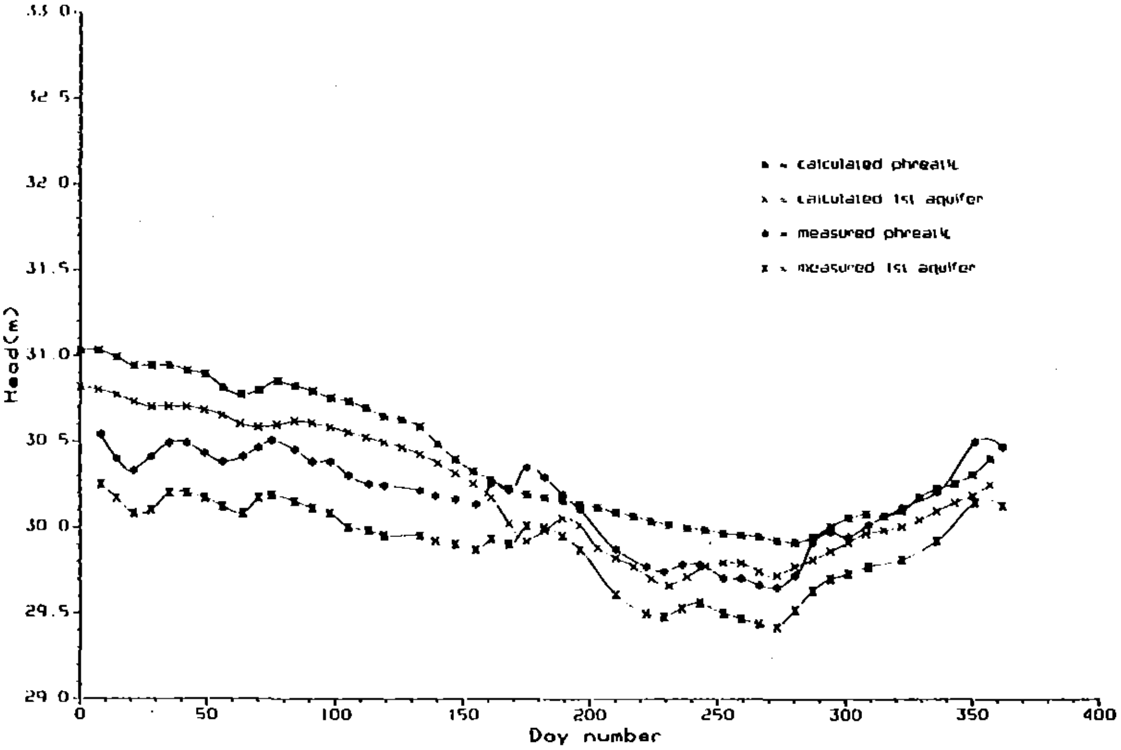


Figure D4 - Measured and calculated heads for point 240 and 255

## APPENDIX E - Results of sensitivity analysis

The parameters which were selected for the sensitivity analysis are given in table E1. The geohydrological parameters of the saturated zone concern the runs 1 - 9 and the parameters of the unsaturated zone concern the runs 10 - 14. The calculation 13 and 14 with a soil physical unit Of 2 and 7 reflect situations with a low and high capillary rise respectively. The equilibrium moisture content of the root zone is for these runs also relative low and high.

The results of the sensitivity analysis in respect of the average standard deviation and the maximum and minimum difference in hydraulic head is given in table E2. The average standard deviation reflects the eight measuring points as shown in figure D1. For all the calculations the conversion factor between measured levels and average hydraulic heads calculated for a nodal point, has been set to zero ( see equation 29 ).

Table E1 - Parameter description of sensitivity analysis

| run | variation | description |
|---|---|---|
| 1 | none | reference run |
| 2 | c - 50 % | hydraulic vertical resistance of top layer |
| 3 | c - 150 % | ,, |
| 4 | KD - 75 % | transmissivity of 2nd layer ( 1 st aquifer ) |
| 5 | KD - 150 % | ,, |
| 6 | Y - lower | drainage resistance class lower |
| 7 | Y - higher | ,, ,, ,, higher |
| 8 | S - 50 % | specific storage |
| 9 | S - 150 % | ,, |
| 10 | vz - 75 % | capillary rise |
| 11 | vz - 150 % | ,, |
| 12 | s - 5 | typical soil physical unit |
| 13 | s - 2 | extreme s.p.u. ( fig B1 and B2 ) |
| 14 | s - 7 | ,, |

Table E2 - Variation of standard deviation and differences in calculated and measured hydraulic heads ( m )

| variation | standard deviation | hm - hc min | hm - hc max | $\Delta h$ average |
|---|---|---|---|---|
| none | 0.273 | -0.49 | 0.11 | 0.20 |
| c - 50 % | 0.269 | -0.46 | 0.12 | 0.20 |
| c - 150 % | 0.289 | -0.51 | 0.11 | 0.22 |
| KD - 75 % | 0.286 | -0.50 | 0.09 | 0.22 |
| KD - 150 % | 0.263 | -0.48 | 0.12 | 0.19 |
| Y - lower | 0.233 | -0.43 | 0.19 | 0.15 |
| Y - higher | 0.366 | -0.65 | 0.02 | 0.32 |
| S - 50 % | 0.257 | -0.46 | 0.12 | 0.19 |
| S - 150 % | 0.287 | -0.51 | 0.10 | 0.22 |
| vz - 75 % | 0.274 | -0.49 | 0.11 | 0.20 |
| vz - 125 % | 0.289 | -0.50 | 0.07 | 0.22 |
| s - 5 | 0.286 | -0.52 | 0.12 | 0.21 |
| s - 2 | 0.310 | -0.56 | 0.07 | 0.24 |
| s - 7 | 0.231 | -0.42 | 0.26 | 0.12 |

The variation in standard deviation, for the runs concerning the geohydrological parameters, is in general small, except when using a higher class for the drainage resistance. The remarkeble smaller deviation when using a lower drainage class, comes from the assumption of one drainage class per subregion. In the vicinity of the measuring point the drainage class can vary quite a bit from the average selected drainage class. Therefore it seems favourable to select a lower drainage resistance for the location of the measuring point, but not for the entire subregion.

The increase or decrease in capillary rise has a very small effect on the standard deviation. The selection of one typical soil physical unit or the unit with extreme hydrological conditions do not show a remarkeble difference from the reference run.

# Table E3 - Variation of groundwater depth per subregion ( 1st April 1982 )

| subregion | groundwater depth ( m ) | | | | |
|---|---|---|---|---|---|
| | initial | minimum | run | maximum | run |
| 1 | 0.78 | 0.61 | 3 | 1.03 | 2 |
| 2 | 0.56 | 0.36 | 7 | 0.74 | 6 |
| 3 | 0.55 | 0.24 | 7 | 0.57 | 3 |
| 4 | 0.65 | 0.28 | 7 | 0.75 | 2 |
| 5 | 0.83 | 0.73 | 7 | 0.94 | 2 |
| 6 | 0.59 | 0.39 | 7 | 0.71 | 6 |
| 7 | 1.18 | 1.05 | 3 | 1.37 | 2 |
| 8 | 0.63 | 0.46 | 7 | 0.79 | 6 |
| 9 | 1.07 | 0.88 | 7 | 1.24 | 2 |
| 10 | 0.43 | 0.18 | 7 | 0.53 | 6 |
| 11 | 0.65 | 0.50 | 7 | 0.80 | 6 |
| 12 | 0.88 | 0.71 | 7 | 0.95 | 2 |
| 13 | 0.63 | 0.39 | 7 | 0.65 | 3 |
| 14 | 1.38 | 1.19 | 7 | 1.55 | 2 |
| 15 | 0.66 | 0.45 | 7 | 0.68 | 4 |
| 16 | 0.04 | 0.04 | 3 | 0.05 | 2 |
| 17 | 0.73 | 0.58 | 3 | 0.97 | 2 |
| 18 | 0.51 | 0.32 | 7 | 0.69 | 6 |
| 19 | 1.56 | 1.39 | 4 | 1.71 | 5 |
| 20 | 1.02 | 0.89 | 7 | 1.17 | 6 |
| 21 | 0.57 | 0.38 | 7 | 0.75 | 6 |
| 22 | 0.87 | 0.67 | 7 | 0.98 | 6 |
| 23 | 0.79 | 0.59 | 7 | 0.80 | 3 |
| 24 | 0.88 | 0.75 | 7 | 1.00 | 6 |
| 25 | 0.95 | 0.82 | 4 | 1.06 | 5 |
| 26 | 0.83 | 0.71 | 7 | 0.94 | 6 |
| 27 | 0.10 | 0.08 | 4 | 0.10 | 2 |
| 28 | 0.65 | 0.47 | 7 | 0.82 | 6 |
| 29 | 1.50 | 1.37 | 4 | 1.64 | 2 |
| 30 | 0.82 | 0.66 | 7 | 0.92 | 6 |
| 31 | 0.68 | 0.52 | 7 | 0.82 | 6 |

Table E4 - Variation of groundwater depth per subregion
( 1st October 1982 )

| subregion | groundwater depth ( m ) | | | | |
|---|---|---|---|---|---|
| | initial | minimum | run | maximum | run |
| 1 | 1.91 | 1.56 | 13 | 2.00 | 4 |
| 2 | 1.39 | 1.16 | 13 | 1.48 | 14 |
| 3 | 0.80 | 0.62 | 7 | 0.82 | 4 |
| 4 | 1.46 | 1.36 | 13 | 1.71 | 14 |
| 5 | 1.76 | 1.69 | 3 | 1.97 | 14 |
| 6 | 1.26 | 1.24 | 9 | 1.64 | 14 |
| 7 | 1.99 | 1.91 | 3 | 2.18 | 14 |
| 8 | 1.15 | 1.11 | 7 | 1.45 | 14 |
| 9 | 1.89 | 1.72 | 13 | 2.00 | 2 |
| 10 | 1.18 | 1.01 | 13 | 1.32 | 14 |
| 11 | 1.23 | 1.22 | 4 | 1.53 | 14 |
| 12 | 1.65 | 1.59 | 13 | 1.84 | 14 |
| 13 | 1.09 | 0.97 | 7 | 1.13 | 3 |
| 14 | 2.17 | 2.05 | 3 | 2.28 | 2 |
| 15 | 1.09 | 1.03 | 13 | 1.25 | 14 |
| 16 | 0.67 | 0.63 | 3 | 1.10 | 12 |
| 17 | 1.99 | 1.71 | 13 | 2.06 | 2 |
| 18 | 1.60 | 1.28 | 12 | 1.72 | 14 |
| 19 | 2.99 | 2.54 | 13 | 3.18 | 5 |
| 20 | 2.43 | 1.96 | 13 | 2.51 | 8 |
| 21 | 1.47 | 1.23 | 12 | 1.50 | 4 |
| 22 | 1.99 | 1.87 | 13 | 2.13 | 14 |
| 23 | 1.38 | 1.37 | 7 | 1.65 | 14 |
| 24 | 1.78 | 1.73 | 13 | 2.00 | 14 |
| 25 | 1.94 | 1.81 | 4 | 2.18 | 14 |
| 26 | 1.58 | 1.51 | 4 | 1.91 | 14 |
| 27 | 0.69 | 0.66 | 4 | 1.38 | 14 |
| 28 | 1.41 | 1.35 | 7 | 1.77 | 14 |
| 29 | 2.42 | 2.27 | 4 | 2.56 | 2 |
| 30 | 1.77 | 1.71 | 4 | 2.01 | 14 |
| 31 | 1.44 | 1.40 | 13 | 1.76 | 14 |

The effect of the sensitivity analysis on the groundwater depth is shown in table E3 and E4. For each subregion the extreme groundwater depth calculated from the sensitivity analysis is given. The run numbers refer to the type of parameter variation as described in table E1.

For the beginning of the summer half year the drainage resistance gives in most subregions the extreme variation in groundwater depth ( run 6 or 7 ). For the end of the summer half year the selected soil physical unit gives the extreme variation in groundwater depth ( see table E4 ).

The variation in sprinkling, evapotranspiration, and capillary rise for the entire region is given in table E5. These results are for the summer half year of 1982. They show clearly that variation of the geohydrological parameters has no significant effect on the overall water balance terms, except the variation of the drainage resistance on the amount of sprinkling. The variation of the parameters for the unsaturated zone ( capillary rise and soil physical units ) has a more pronounced effect on these water balance terms. The evapotranspiration for instance varies from +12 % to -7 % ( related to reference run ). The variation of the water balace terms per subregion are even more pronounced. This is shown in table E6. Considering the evapotranspiration on a subregional level the maximum increase is 25 % and the maximum decrease is 40 % ( see table E6 ).

Table E5 - Variation of water balance terms ( entire region ) for the unsaturated zone ( summer period of 1982 )

| variation | sprinkling ig + is ( mm ) | evapotr. agriculture ( mm ) | capillary rise ( mm ) |
|---|---|---|---|
| none | 51 | 436 | 87 |
| c - 50 % | 52 | 432 | 84 |
| c - 150 % | 51 | 437 | 88 |
| KD - 75 % | 50 | 437 | 88 |
| KD - 150 % | 51 | 434 | 86 |
| Y - lower | 56 | 432 | 84 |
| Y - higher | 42 | 427 | 84 |
| S - 50 % | 53 | 433 | 82 |
| S - 150 % | 49 | 437 | 91 |
| vz - 75 % | 52 | 440 | 89 |
| vz - 125 % | 44 | 416 | 84 |
| s - 5 | 56 | 424 | 72 |
| s - 2 | 55 | 406 | 67 |
| s - 7 | 23 | 488 | 141 |

Table E6 - Extreme variation ( % ) of water balance terms per
subregion in relation to reference run
( summer period of 1982 )

| variation | sprinkling |  | evapotr. |  | capillary rise |  |
|---|---|---|---|---|---|---|
|  | incr. | decr. | incr. | decr. | incr. | decr. |
| none | 0 | 0 | 0 | 0 | 0 | 0 |
| c - 50 % | 55 | 33 | 1 | 13 | 10 | 66 |
| c - 150 % | 31 | 35 | 2 | 1 | 25 | 17 |
| KD - 75 % | 33 | 31 | 2 | 2 | 15 | 28 |
| KD - 150 % | 32 | 22 | 3 | 2 | 30 | 13 |
| Y - lower | 68 | 5 | 5 | 4 | 23 | 22 |
| Y - higher | 0 | 113 | 11 | 14 | 34 | 93 |
| S - 50 % | 21 | 0 | 1 | 2 | 3 | 21 |
| S - 150 % | 7 | 33 | 2 | 1 | 22 | 3 |
| vz - 75 % | 72 | 2 | 14 | 3 | 67 | 26 |
| vz - 125 % | 0 | 62 | 2 | 22 | 35 | 127 |
| s - 5 | 187 | 18 | 13 | 35 | 24 | 181 |
| s - 2 | 180 | 55 | 7 | 40 | 16 | 166 |
| s - 7 | 77 | 277 | 25 | 12 | 192 | 104 |

# APPENDIX F - Results of first- and second level model

In the present discussion the comparison will be restricted to the hydraulic heads and water balance terms, calculated for the hydrological year 1975 ( 1 Oct 1974 to 30 Sept 1975 ).

## Groundwater levels

In the first level model the groundwater depth at the beginning, or end of summer is calculated from an initial given groundwater depth at those particular times without any extractions, and added the change in level calculated from influence matrices ( van WALSUM, 1983 and ORLOVSKY and van WALSUM, 1984 ). The change in the groundwater depth is a result of withdrawal for public water supply, extraction for irrigation, and subsurface-irrigation.

In the second level model the groundwater depth is calculated by means of simulation. In table F1 the groundwater depth per subregion for beginning of summer ( 1 April 1975 ) and for the end of summer ( 1 October 1975 ) calculated with both models are given. From this table it can be seen that the groundwater level for April 1975, calculated with the second level model is around 0.10 - 0.20 m lower, then the results from the first level model. At the end of summer the results of both models do not show a clear difference.

The groundwater levels for the first level model are based on calculations with the SWATRE model. These depths are too low for the beginning of summer. The results of these calculations are dependent on the assumed flux through the lower boundary of this model.

## Water balance terms

The most important terms in this respect are the actual evapotranspiration ea, irrigation from groundwater ig, and irrigation from surface water is. In table F2 the results are given. Evaluation of these figures leads to a number of conclusions :

- The evapotranspiration calculated with the second level model is in general a bit lower than the evapotranspiration calculated with the first level model. The computed results with the first level model are entirely based on evapotranspiration data for potatoes, whereas the second level model differentiates between the actual technologies The second level model also allows for effects other then contributed by the agricultural technologies. For instance the evapotranspiration from nature reserves and built-up areas.
  The second level model calculates also lower evapotranspiration because it uses less sprinkling and has lower groundwater levels at the beginning of summer.

- The total amount of sprinkling in the second level model is lower. The high values ( in some cases ) calculated with the first level model are partly a result of the linearized relations. The change in phreatic level, caused by extraction from groundwater and change in capillary rise, has resulted in the considerable differences. In reality this mechanism is evidently not so effective. Most of the extracted water comes from phreatic storage. Possible other reasons for the high values for sprinkling in the first level model, are the higher values for potential evapotranspiration and the possibility of the second level model to use the available water stock in the root zone. A more detailed analysis of this subject is necessary.

Table F1 - Average groundwater depth per subregion ( m )

| subregion | first level model | | second level model | |
|---|---|---|---|---|
| no | Apr 75 | Oct 75 | Apr 75 | Oct 75 |
| 1 | 0.36 | 1.81 | 0.54 | 1.85 |
| 2 | 0.30 | 1.73 | 0.40 | 1.29 |
| 3 | 0.42 | 1.30 | 0.50 | 0.73 |
| 4 | 0.38 | 1.59 | 0.42 | 1.30 |
| 5 | 0.39 | 1.64 | 0.56 | 1.52 |
| 6 | 0.39 | 1.42 | 0.26 | 1.17 |
| 7 | 0.41 | 1.77 | 0.86 | 1.79 |
| 8 | 0.41 | 1.42 | 0.46 | 1.04 |
| 9 | 0.31 | 2.23 | 0.82 | 1.77 |
| 10 | 0.38 | 1.45 | 0.26 | 1.03 |
| 11 | 0.37 | 1.39 | 0.53 | 1.19 |
| 12 | 0.38 | 1.38 | 0.73 | 1.54 |
| 13 | 0.30 | 1.77 | 0.53 | 0.99 |
| 14 | 0.36 | 1.61 | 1.20 | 2.07 |
| 15 | 0.36 | 1.32 | 0.59 | 1.03 |
| 16 | - | - | - | - |
| 17 | 0.39 | 1.84 | 0.47 | 1.86 |
| 18 | 0.30 | 1.78 | 0.38 | 1.52 |
| 19 | 0.30 | 2.17 | 1.41 | 2.71 |
| 20 | 0.34 | 2.36 | 0.78 | 2.27 |
| 21 | 0.49 | 1.87 | 0.43 | 1.39 |
| 22 | 0.55 | 1.45 | 0.67 | 1.83 |
| 23 | 0.55 | 1.51 | 0.68 | 1.33 |
| 24 | 0.55 | 1.73 | 0.75 | 1.64 |
| 25 | 0.56 | 1.47 | 0.72 | 1.75 |
| 26 | 0.55 | 1.45 | 0.71 | 1.45 |
| 27 | - | - | - | - |
| 28 | 0.55 | 1.51 | 0.56 | 1.37 |
| 29 | 0.36 | 1.83 | 1.25 | 2.25 |
| 30 | 0.55 | 1.45 | 0.61 | 1.61 |
| 31 | 0.55 | 1.41 | 0.57 | 1.35 |

Table F2 - Evapotranspiration and sprinkling quantities calculated for summer period of 1975 ( mm )

| subr. | first level model | | second level model | |
|---|---|---|---|---|
| no | ea | is + ig | ea | is + ig |
| 1 | 452 | 20 | 474 | 18 |
| 2 | 433 | 13 | 416 | 8 |
| 3 | 375 | 25 | 472 | 2 |
| 4 | 385 | 19 | 433 | 2 |
| 5 | 402 | 47 | 405 | 58 |
| 6 | 408 | 64 | 429 | 23 |
| 7 | 421 | 57 | 386 | 57 |
| 8 | 406 | 87 | 438 | 40 |
| 9 | 436 | 36 | 391 | 46 |
| 10 | - | - | - | - |
| 11 | 411 | 63 | 436 | 41 |
| 12 | 421 | 53 | 408 | 58 |
| 13 | 437 | 42 | 411 | 0 |
| 14 | 410 | 61 | 366 | 70 |
| 15 | 389 | 19 | 455 | 18 |
| 16 | - | - | - | - |
| 17 | 445 | 10 | 471 | 4 |
| 18 | 434 | 32 | 396 | 1 |
| 19 | 417 | 2 | 447 | 0 |
| 20 | 511 | 0 | 465 | 31 |
| 21 | 425 | 26 | 411 | 7 |
| 22 | 396 | 36 | 389 | 53 |
| 23 | 376 | 45 | 419 | 62 |
| 24 | 438 | 131 | 397 | 93 |
| 25 | 410 | 68 | 392 | 62 |
| 26 | 405 | 68 | 415 | 59 |
| 27 | - | - | - | - |
| 28 | 404 | 67 | 424 | 54 |
| 29 | 452 | 17 | 443 | 41 |
| 30 | 388 | 33 | 378 | 32 |
| 31 | 380 | 19 | 404 | 18 |