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Modelling the interactions between transient saturated and unsaturated groundwater flow

Off-line coupling of LGM and SWAP

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Het rapport in het kort

Modellering van de interactie tussen de waterstroming in de bodem en het grondwater. Koppeling van LGM en SWAP.

Het Landelijk Grondwatermodel (LGM) en een één-dimensionaal model van de hydrologie van de onverzadigde zone (SWAP) zijn gekoppeld. Met dit gecombineerde model kunnen de waterstromen in het bodem- en grondwatersysteem, alsmede de stromingen vanuit het grondwater naar het oppervlaktewater, berekend worden. Het model kan zodoende de hydrologische invoer leveren voor studies naar de belasting van grond- en oppervlaktewater met nutriënten en gewasbeschermingsmiddelen. Een andere mogelijke toepassing van het model is de simulatie van de variatie van de grondwaterstand in de tijd. Om de seizoensdynamiek correct te kunnen berekenen, worden zowel LGM als SWAP dynamisch toegepast. Het model kan op verschillende schalen worden toegepast. De prestaties van het model zijn getoetst in een studie in het Beerze Reusel gebied. In het algemeen bleek dat de overeenkomst tussen de gemiddelde diepte van het grondwaterpeil, zoals berekend met SWAP, goed overeenkwam met de gemiddelde diepte van het grondwaterpeil, zoals berekend met LGM. Ook bleek dat beide modellen de seizoensdynamiek op dezelfde wijze simuleren. Een aanvullende studie moet aantonen in hoeverre de berekende grondwaterpeilen overeenkomen met de gemeten grondwaterpeilen. Deze studie moet aangeven of het gecombineerde model de hydrologische basis kan leveren voor verdrogingstudies en waterkwaliteitsberekeningen, zoals die door het Milieu- en Natuurplanbureau worden uitgevoerd.

Trefwoorden: hydrologie; SWAP; LGM; grondwater; oppervlaktewater; koppeling; model

Abstract

Modelling the interactions between transient saturated and unsaturated groundwater flow. Off-line coupling of LGM and SWAP

The groundwater flow model for the Netherlands (LGM), and a one-dimensional model of soil water flow (SWAP) were coupled. With this combined model, it is possible to calculate fluxes and residence times of nutrients and pesticides in both the unsaturated zone and the phreatic aquifer. The model can also predict the seasonal dynamics of the groundwater table. In order to correctly simulate these seasonal dynamics, both LGM and SWAP are used in transient mode. The performance of the model was tested in a regional-scale model application. There was generally a good agreement between the mean depth of the groundwater table, as simulated with SWAP, and the mean depth of the groundwater depth as simulated by LGM. The seasonal dynamics of the groundwater table were, however, underestimated by LGM. Further investigation showed that correct transfer of the phreatic storage coefficient was the key factor for correctly predicting the seasonal dynamics of the groundwater table. With the correct storage coefficient, the correspondence between the groundwater heads simulated by SWAP and the groundwater heads simulated by LGM were nearly perfect. An additional study should show whether there is also a good agreement with observed groundwater heads. Results from this study can be used to conclude upon the applicability of the adopted methodology for both ecohydrological studies and water quality assessments as required by the Netherlands Environmental Assessment Agency.

Key words: hydrology; groundwater; surface-water; LGM, SWAP; modelling; coupling; transient

Contents

Samenvatting

Dit rapport beschrijft de koppeling tussen het Landelijk Grondwatermodel (LGM) en een één-dimensionaal model van de hydrologie van de onverzadigde zone, SWAP. Met dit gecombineerde model kunnen de waterstromen in het bodem- en grondwatersysteem, alsmede de stromingen vanuit het grondwater naar het oppervlaktewater, berekend worden. Het model kan zodoende de hydrologische invoer leveren voor studies naar de belasting van grond- en oppervlaktewater met nutriënten en gewasbeschermingsmiddelen. Een andere mogelijke toepassing van het model is de voorspelling van de variatie van de grondwaterstand in de tijd, bijvoorbeeld gedurende het jaar. Informatie over deze jaarlijkse fluctuaties is met name van belang in studies naar de effecten van verdroging op ecosystemen, waar de diepte van de grondwaterstand in het begin van het groeiseizoen gebruikt wordt als een indicator voor de vochttoestand. Om de seizoensdynamiek correct te kunnen berekenen, worden zowel LGM als SWAP dynamisch toegepast; de uitwisseling van gegevens tussen beide modellen vindt per decade plaats. Aangezien verdrogingstudies in het algemeen een groot ruimtelijk detail vereisen, zijn procedures geïmplementeerd om de resultaten van het gecombineerde model met een hoge ruimtelijke resolutie beschikbaar te maken. De ruimtelijke schematisatie van het model is daarom flexibel gemaakt; de basisgegevens worden hierbij via GIS procedures rechtstreeks naar effectieve modelparameters vertaald. De prestaties van het model zijn getoetst in een studie in het Beerze Reusel gebied. In het algemeen bleek dat de overeenkomst tussen de gemiddelde diepte van het grondwaterpeil, zoals berekend met SWAP, goed overeenkwam met de gemiddelde diepte van het grondwaterpeil, zoals berekend met LGM. Het bleek echter ook dat de seizoensdynamiek onderschat werd door LGM. Nadere studie leerde dat dit veroorzaakt werd doordat de zogenaamde freatische bergingscoëfficiënt onjuist van SWAP naar LGM werd overgedragen. Nadat dit hersteld was, was er een nagenoeg perfecte overeenkomst tussen de grondwaterstand berekend door SWAP en de grondwaterstand berekend door LGM. Toetsing aan gemeten grondwaterpeilen heeft nog niet plaatsgevonden. Een aanvullende studie, waarin de resultaten van het gecombineerde model met grondwaterstanden gemeten in het Nederlandse zandgebied worden vergeleken, kan op korte termijn worden uitgevoerd. Deze studie moet aangeven of het gecombineerde model de hydrologische basis kan leveren voor verdrogingstudies en waterkwaliteitsberekeningen, zoals door het Milieu- en Natuurplanbureau worden uitgevoerd.

Summary

An offline coupling was established between the groundwater flow model for the Netherlands, LGM, and a one-dimensional model of soil water flow, SWAP. With this combined model, it is possible to calculate fluxes and residence times of chemicals (particularly nutrients and pesticides) in both the unsaturated zone and the phreatic aquifer. Because the model considers interactions with local surface-water systems, the model can be used to predict fluxes of these chemicals into surface waters as well. Another possible application of the model is the prediction of the seasonal dynamics of the groundwater table, which is particularly important in ecohydrological studies, where the depth of the groundwater table at the start of the growing season is an important indicator of water availability. In order to correctly simulate these seasonal dynamics, both LGM and SWAP are run in transient mode, with a coupling time-step of 10 days. Procedures have been implemented to make the final results available at a very high spatial resolution, which is a requirement for ecohydrological studies. Regardless the grid size, GIS procedures convert the basic model parameters available in the LGM database into effective model input parameters. The performance of the combined model was tested in a regional-scale model application. There was generally a good agreement between the mean depth of the groundwater table, as simulated with SWAP, and the mean depth of the groundwater depth as simulated by LGM. The seasonal dynamics of the groundwater table were, however, underestimated by LGM. Further investigation showed that correct transfer of the phreatic storage coefficient was the key factor for correctly predicting the seasonal dynamics of the groundwater table. After adaptation of the calculation of this coefficient, the correspondence between the groundwater heads simulated by SWAP and the groundwater heads simulated by LGM were nearly perfect. The model has not yet been validated against observed groundwater heads; this should be done in an additional study to be carried out soon. Results of this study can be used to conclude upon the applicability of the LGM-SWAP model as the hydrological modelling tool for both ecohydrological studies and water quality assessments as required by the Netherlands Environmental Assessment Agency.

1. Introduction

1.1 General introduction

The Groundwater Model for the Netherlands (LGM) is a model for the simulation of quantity and quality aspects of saturated groundwater systems. The model has been developed by the National Institute of Public Health and the Environment, RIVM (Pastoors, 1992; Kovar *et al.*, 1992) and was applied in various studies. The focus in these studies was on effects of groundwater abstractions on the geohydrological system (Leijnse and Pastoors, 1996). Later, studies were carried out to quantify contamination of drinking water abstraction wells with nutrients and pesticides (Kovar *et al.*, 1998; Kovar *et al.*, 2000; Uffink and Van der Linden, 1998; Tiktak *et al.*, 2004). Since the mid nineties, attention in the policy arena shifted from drinking water to ecohydrological studies and to diffuse source pollution of the shallow groundwater and local surface waters by nutrients and pesticides. These problems require an adapted model approach, in which the mutual relationships between the unsaturated zone, the saturated zone and local surface waters are considered. For this reason, RIVM, Alterra and RIZA together developed the hydrological component of the nutrient fate model STONE (Wolf *et al.*, 2003). This model consists of an offline coupling between the unsaturated zone model SWAP (Van Dam, 2000) and the National Groundwater Model (De Lange, 1996). Although this model has successfully been used in the evaluation of the Dutch Manure Policy (RIVM, 2004), it suffered from a number of limitations:

- the model showed an unrealistic, long-term trend in the groundwater table for approximately 10% of the cases;
- the model could not reproduce the seasonal dynamics of the groundwater table, which is required for ecohydrological studies;
- the spatial schematisation of the model was fixed. It was therefore not possible to make local refinements, which are needed for ecohydrological studies and regional studies.

To mitigate to these problems, RIVM decided to accomplish an offline coupling between the Groundwater Model for the Netherlands (LGM, version 4) and the SWAP model (version 2.0.9d). The most important additional requirements for this model are:

- the model should be able to correctly describe both the long-term trend and the seasonal dynamics of the groundwater table;
- the model should be operational at different spatial scales, using finite-element grids of any required spatial resolution.

1.2 Overview of report

After this general introduction, an overview of the model and the coupling procedure is given in chapter 2. The spatial schematisation and the model parameterisation is discussed in chapter 3. Chapter 4 and 5 describe some model applications. In chapter 4, the combined model is applied in a catchment. The aim of this application was to test the performance of the coupling procedure. Chapter 5 describes the application of the model at the national scale. An important aim of this application was to test the ability of the model to operate at different spatial scales, with local grid refinements. Final conclusions and recommendations are reported in chapter 6. A user manual of the model is published in a separate report (Tiktak *et al.*, 2004).

1.3 Perspectives

Due to its flexible set-up, the current model can be used at different spatial scales. The following model outputs are calculated in a consistent way:

- long-term trends and seasonal dynamics of fluxes of water into the shallow groundwater and local surface waters;
- long-term trends and seasonal dynamics of hydrological state variables, the most important one being the groundwater table.

The model can provide the hydrological base for desiccation studies and ecohydrological studies. The model can also provide inputs for such studies as the evaluation of the 'Dutch Manure Policy' and the evaluation of the 'Policy Plan Sustainable Crop Protection'.

2. Model description

2.1 Theory of the Groundwater Model for the Netherlands (LGM)

The Groundwater Model for the Netherlands (LGM version 4) is a model for the simulation of quantity and quality aspects of saturated groundwater systems. LGM was developed by the National Institute of Public Health and the Environment, RIVM (Pastoors, 1992; Kovar *et al.*, 1992) and applied in various studies (for example, Leijnse and Pastoors, 1996; Kovar *et al.*, 1998; Kovar *et al.*, 2000).

LGM simulates groundwater flow in a saturated multi-aquifer geohydrogical system consisting of a series of aquifers separated by aquitards. The flow in the system is assumed to be quasi three-dimensional, namely two-dimensional horizontal flow in aquifers and vertical flow in aquitards. LGM is based on the numerical technique of finite elements. The elements are quadrilaterals and triangles. The model can be applied for any user-selected grid density, the grid density being dependent on the specific conditions of the problem to be solved. The grid can be locally refined, for example within a well capture area or in the vicinity of rivers. Figure 2.1 shows schematically the basic features of the LGMs finite element implementation, namely the grid nodes, the elements, and the node influence areas, A_{inf} (m^2).

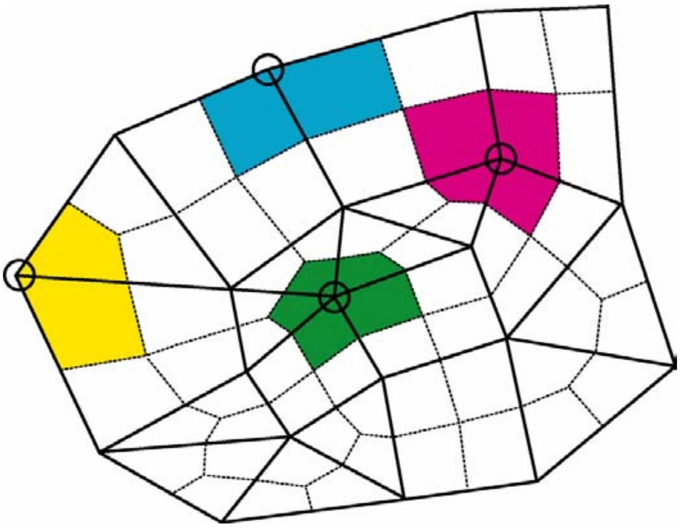


Figure 2.1. Example of a finite element grid for LGM, containing nodes, elements and node influence areas A_{inf} (dashed lines). Influence areas are highlighted at four nodes.

The basic module of LGM calculates groundwater heads in aquifers, the flux across the aquitards, the flux between the top aquifer and rivers, and the flux between the top aquifer and the small-scale surface water system (ditches, drains, brooks). The latter flux is referred to as the topsystem flux.

In the current study, LGM was applied in transient mode, with two time-variable inputs, the groundwater recharge rate, q_{re} (m d^{-1}), and the storage coefficient of the top aquifer, μ (-). All other input data, such as groundwater heads along the model periphery, groundwater abstraction rates, river water levels, and drainage levels in the small-scale surface water systems, were kept constant in time.

Figure 2.2 depicts the geohydrological system in the Groundwater Model for the Netherlands. Although usually five aquifers are used for national studies, for simplicity the figure is restricted to two aquifers. LGM calculates, as a function of time, the groundwater heads in the first and second aquifers, respectively. An essential part of the schematisation is that the uppermost aquifer (aquifer 1) is phreatic. The latter means that the uppermost aquifer is not overlain by a semi-pervious layer. This implies that the upper boundary of the uppermost aquifer is at the ground surface. Depending on the occurrence and depth of the first aquitard, three situations can be distinguished:

- regions where no aquifer occurs immediately below ground level, such as in peat-clay polder areas shown in the left part of figure 2.2. In these cases, a very thin dummy top aquifer will be modelled with negligible horizontal flow. This horizontal flow does not make part of any (sub)regional flow. It is markedly local in nature, being shallow groundwater flow to the nearest ditches. Obviously, groundwater abstractions are not permitted in this dummy top aquifer;
- regions where both the top aquifer and the separating aquitard exist, as shown in the central part of figure 2.2. The modelled top aquifer stretches between the aquitard top and the ground surface;
- regions where only one thick aquifer exists from the base up to the ground level, but the separating aquitard is missing. This is shown in the rightmost part of figure 2.2. In this case a dummy aquitard (with small hydraulic resistance c_1) has to be introduced, thus splitting the actual aquifer into the top aquifer and aquifer 2. In those regions LGM will calculate the groundwater head $\varphi_{1,lgm} \approx \varphi_{2,lgm}$. It is possible that the calculated groundwater head $\varphi_{1,lgm}$ can be below the bottom level of the top aquifer, as is shown in figure 2.2.

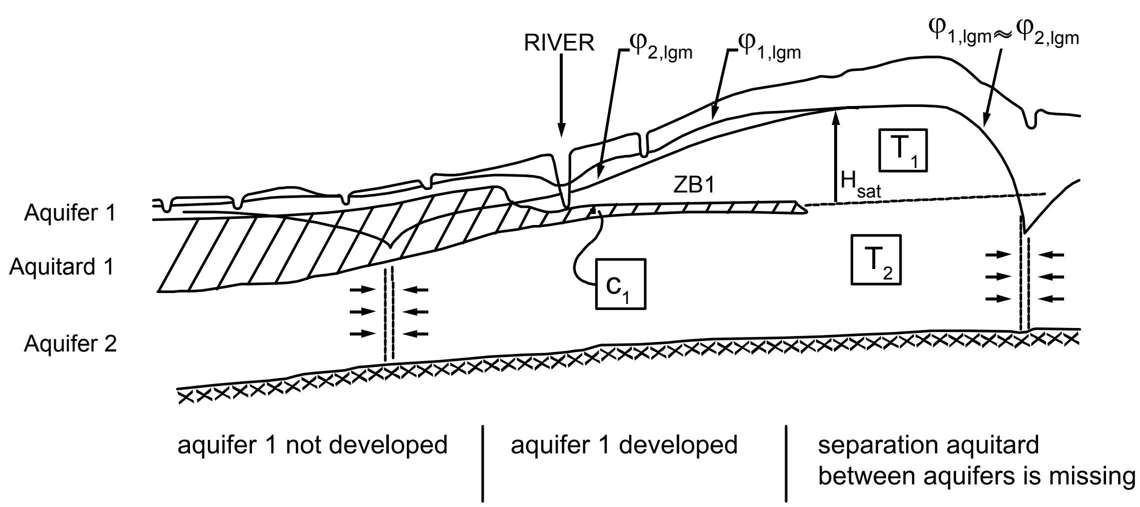


Figure 2.2. Sketch of the geohydrological system of the Groundwater Model for the Netherlands. c_1 is the hydraulic resistance of the separating aquitard and T_1 and T_2 are the transmissivities of the aquifers.

Unlike the transmissivity T_2 (m^2 d^{-1}), which is a user-given input value, the transmissivity T_1 (m^2 d^{-1}) of the top aquifer (aquifer 1) depends on the current value of the calculated groundwater head $\varphi_{1,lgm}$. T_1 follows from the equation:

$$T_1 = kH_{sat} = k\left(\varphi_{1,\lg m} - Z_{T1}\right) \tag{2.1}$$

where k (m d^{-1}) is the horizontal hydraulic conductivity within the top aquifer, H_{sat} (m) is the saturated thickness of the top aquifer, and Z_{T1} is the height of the bottom of the uppermost aquifer. The value of the saturated thickness H_{sat} is minimised to 0.1 m to ensure that T_1 remains a small positive value, which on its turn implies negligible horizontal flow in the top aquifer.

In LGM, two types of surface waters are distinguished, namely rivers and small surface waters. Small surface waters are represented by a lumped 'top-system relationship' and are diffuse in nature. On the other hand, in the finite element grid of LGM, rivers follow their actual location in space.

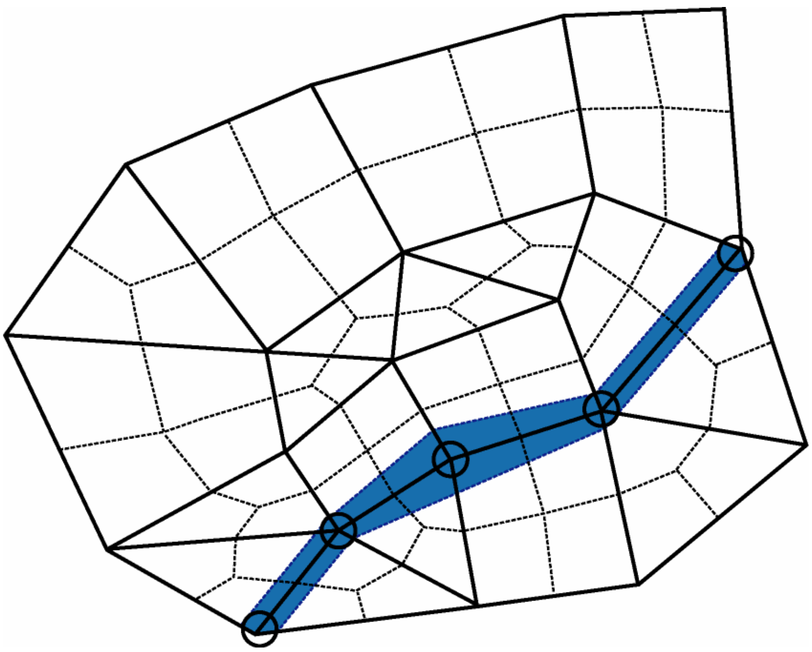


Figure 2.3. Rivers in LGM, coinciding with element sides. Dashed lines delineate the node influence areas (see also figure 2.1).

The rivers represent large (wide) river courses, like the Rhine and its major branches. They also include large canals, like the 'Amsterdam Rijn Channel'. Figure 2.3 illustrates the location of a river, the river being located along the element sides between five nodes. All river-related parameters can be variable along the water course. Those parameters are the river width, the hydraulic resistance of the river bottom, and the river-water level. In each river node, the flux between the top aquifer and the river, Q_{riv} is defined by:

$$Q_{riv} = A_{riv}\left(h_{riv} - \varphi_{1,\lg m}\right)/\, c_{riv} \tag{2.2}$$

where Q_{riv} (m^3 d^{-1}) is the flux from the river to the groundwater in the top aquifer, A_{riv} (m^2) is the surface area of the river within the influence area of a node, h_{riv} (m) is the water level of the river, and c_{riv} (d) is the hydraulic resistance of the river bottom. As mentioned before, though LGM allows the river-water level h_{riv} to be specified variable in time, in this study we have used a time invariant water level.

The topsystem flux relation regards the interactions between the top aquifer and the small-scale surface waters (ditches, drains, brooks). The topsystem flux q_{ts} (m d^{-1}) is assumed to be constant within an influence area of a node, the total topsystem flux Q_{ts} [m^3 d^{-1}] at a node being expressed by $Q_{ts} = A_{inf}\, q_{ts}$. Figure 2.4 illustrates the shape of the topsystem relation for LGM. The relation is composed of a series of topsystem points, each topsystem point being defined by a groundwater head h_{ts} and a flux q_{ts} occurring at h_{ts}. Values of q_{ts} smaller than zero and q_{ts} larger than zero indicate a drainage and infiltration situation, respectively. The multiple piecewise relations in figure 2.3 are created by concatenating a series of separate flux-head relationships existing in a given node, for example the relation for the primary system (see page 21 for definitions of drainage systems), the relation for the secondary system, and the relation for the surface drainage. Note that the number of points in the topsystem relation for LGM is identical at all grid nodes. Consequently, if no relation exists in a node or the relation is less complex than in other nodes, dummy topsystem points are introduced to preserve the same number of topsystem points for all nodes.

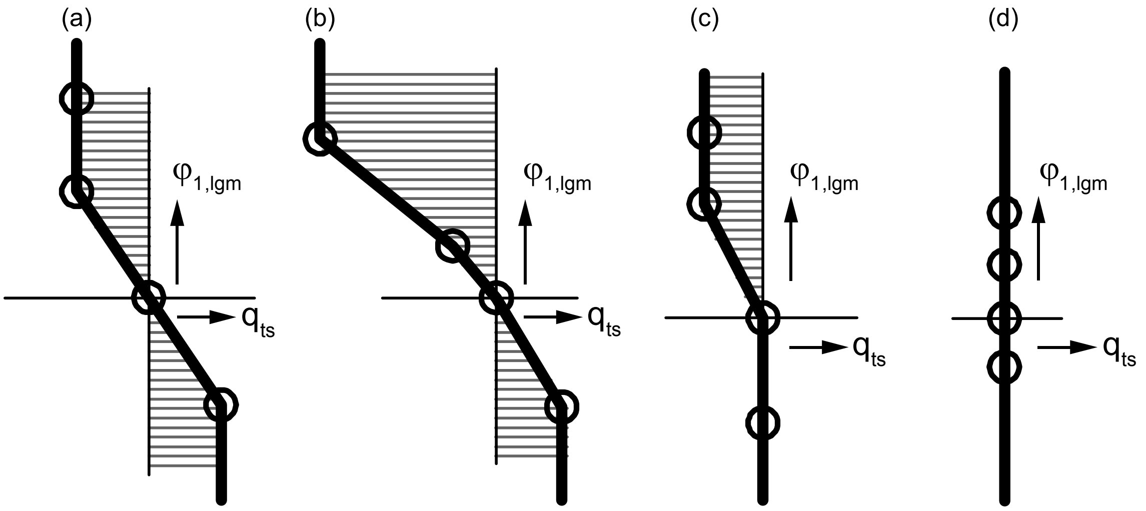


Figure 2.4. Examples of shape of the topsystem flux relation in LGM, each with four topsystem points: (a) one drainage/infiltration system with one dummy point on top, (b) one drainage/infiltration system combined with one drainage system, (c) one drainage system with two dummy points, and (d) absence of any infiltration and drainage system (four dummy points, each with q_{ts}*=0).*

2.2 Theory of SWAP

The Soil Water Atmosphere Plant (SWAP version 2.0.9d) model is a one-dimensional, dynamic, multi-layer model. An extensive overview of the SWAP model is given by Van Dam *et al*. (1997) and Van Dam (2000).

The SWAP model (Van Dam, 2000) uses a finite-difference method to solve Richard's equation. The hydraulic properties are described by closed form functions as proposed by Van Genuchten (1980). The upper boundary of the model interacts with the atmosphere, and is situated at the top of the crop canopy (figure 2.5). Daily rainfall fluxes are input to the model; the reference evapotranspiration rate is calculated from daily temperature and radiation data, according to Makkink (1957). The lower boundary of the system is used to interact with the regional groundwater system and was located at a depth of 13 m below soil surface. In this study, a Cauchy type of boundary condition was chosen, which is further described in section 2.3). The lateral boundary of the system consist of local surface water systems that interact with the groundwater. In SWAP, a maximum of five different classes of local drainage systems can be considered. All drainage systems are spatial distributed and have a linear relationship between drainage flux and groundwater level.

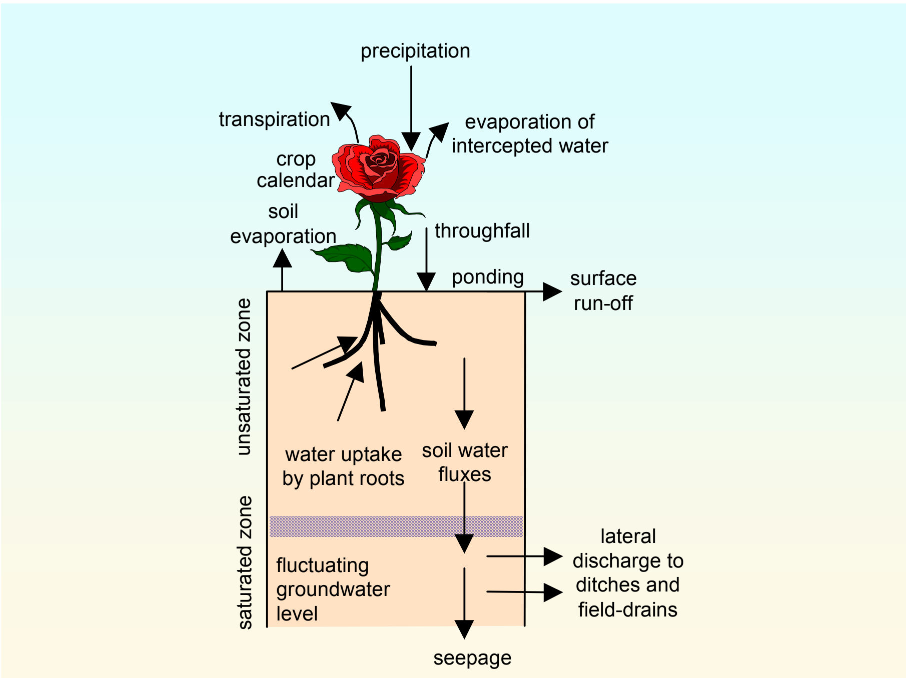


Figure 2.5. Overview of processes included by SWAP, as such considered in the coupled LGM-SWAP model (after Tiktak et al.*, 2003).*

2.3 The coupling concept

2.3.1 Basic principles

In the Netherlands, the groundwater level is generally shallow and the drainage system dense. As a result, there is a strong interaction between the regional groundwater system, the local drainage system and the unsaturated zone. The feedback between the unsaturated zone and the saturated zone is particularly strong in the case of shallow groundwater tables. The maximum depth of the groundwater table, where interdependence plays a role, depends primarily on the soil physical properties. For example, the depth reach of interdependence for a coarse-sandy soil is significantly smaller than that for a loamy fine-sandy soil. A numerical experiment investigating the importance of the feedback mechanism is presented by Stoppelenburg *et al.* (2002).

An important point in the current coupling concept is that both SWAP and LGM simulate the interaction with local drainage systems (the topsystem flux). For this reason, there is a vertical overlap between the two models (figure 2.6). This feature of incorporating local drainage fluxes into the SWAP models allows the calculation of residence times of pesticides and nutrients in the uppermost saturated zone.

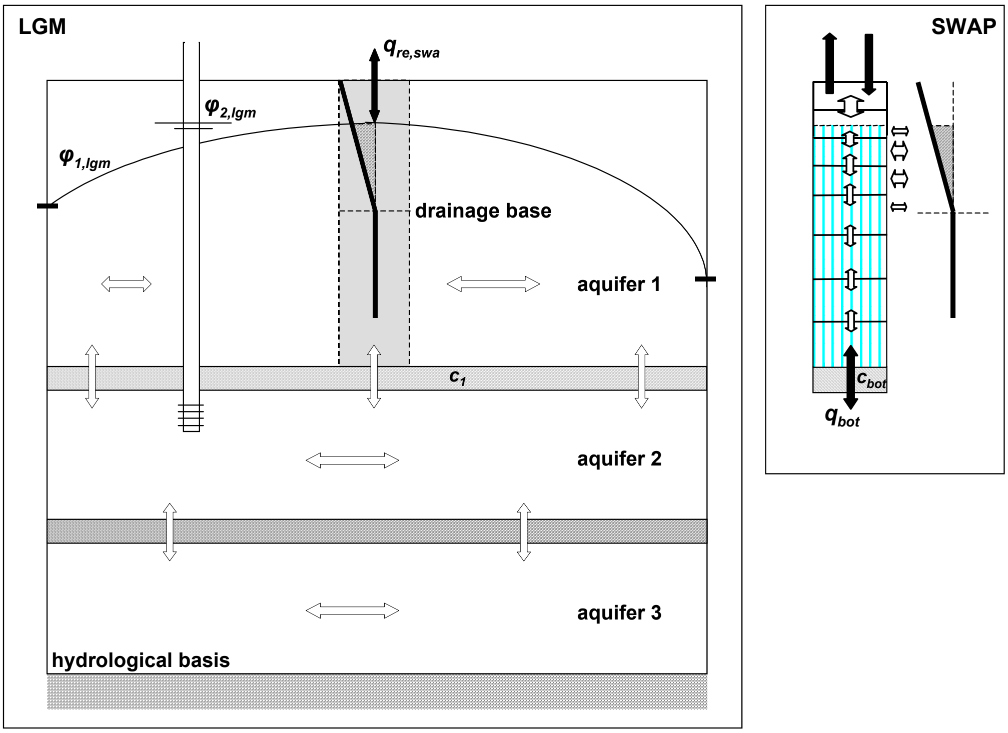


Figure 2.6. Schematic representation of geohydrological system of LGM and SWAP.

Because of the required vertical overlap, the actual link between SWAP and LGM is not carried out at the depth of the groundwater table, but at the depth of the uppermost aquitard (figure 2.6). The two variables that are used for the interaction are the vertical flux and the phreatic storage coefficient. The vertical flux is the bottom boundary condition for SWAP and the upper boundary condition for LGM (section 2.3.2). Because of the higher temporal dynamics in the unsaturated zone, SWAP uses a smaller internal time-step than LGM. For this reason, variables obtained from SWAP are averaged in time before being transferred to LGM (section 2.3.3). In order to get a consistent water balance of the phreatic aquifer in both models, the models should be adjusted in an iterative procedure (section 2.3.4). This iteration procedure must account for the interaction with the local drainage systems, as these systems are part of the (overlapping) phreatic aquifer (section 2.3.5).

2.3.2 Exchange of boundary conditions

Bottom boundary condition of SWAP provided by LGM

Frequently used bottom boundary conditions for unsaturated flow models, that are combined with models for regional groundwater flow, are the Neuman flux condition and the head-dependent Cauchy condition. A Neuman flux as the bottom boundary condition has no real linkage with changing phreatic groundwater heads. In case of an online coupling mechanism (1:1 in time) between a saturated groundwater model and an unsaturated flow model this will not lead to major deviations, as the time-step is small enough to provide for the necessary mutual influence. On the other hand in case of an off-line coupling mechanism, especially when a groundwater model calculates with larger time-steps than the unsaturated flow model, there is no sufficient feedback mechanism to adjust the bottom flux to the phreatic groundwater head and vice visa. This can lead to an under- or overestimation of the infiltration-/seepage flux. As a result a systematic decline or rise of the groundwater table can occur, during the larger simulation time-step of the groundwater model.

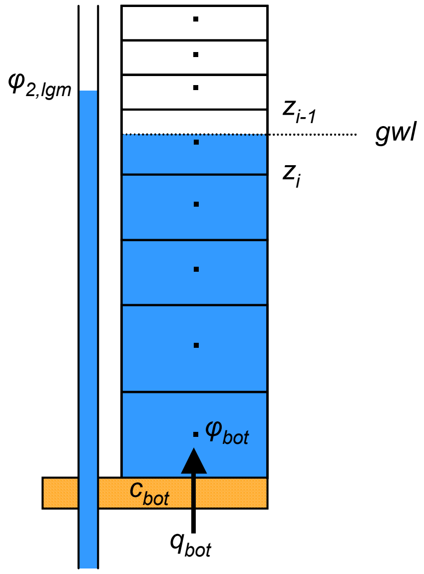
As a Cauchy condition for the bottom boundary of SWAP clearly has a mechanism to adjust the bottom flux to the phreatic groundwater head, it has been selected as most appropriate for the LGM-SWAP coupling. The use of the Cauchy condition provides SWAP with a self-adaptive flux that corresponds with the calculation time-step of the SWAP model itself. The boundary condition at the bottom of the soil column of SWAP, q_{bot} (m d^{-1}) is expressed by (see also figure 2.7):

$$q_{bot} = \frac{\varphi_{2,lgm} - \varphi_{bot}}{c_{bot}} + q_{left,\mathrm{lgm}} \tag{2.3}$$

where $\varphi_{2,lgm}$ (m) is the groundwater head of the second aquifer of LGM, φ_{bot} (m) is the groundwater head of the bottom numerical layer of the soil column of SWAP, c_{bot} (d) is the vertical resistance of the confining layer and $q_{left,lgm}$ (m d^{-1}) is the left-over flux of the phreatic aquifer in LGM, which is explained further on.

Notice that not the phreatic head but the groundwater head of the bottom numerical soil layer is used to define the (regional) bottom flux. In order to produce the same flux across the first aquitard in both models the groundwater head difference should be determined considering the same vertical resistance. Taking the groundwater head at the bottom of the soil column instead of the phreatic head, additional vertical resistance caused by a vertical saturated conductivity in each of the soil compartments will be excluded this way. This is consistent with LGM. The resistance in the groundwater model fully occurs at the flow across the first aquitard (equivalent to the confining layer in SWAP), and no resistance whatsoever takes place for vertical flow in the phreatic aquifer.

At the same time the phreatic head in LGM $\varphi_{1,lgm}$ corresponds in most cases with the phreatic head in SWAP $\varphi_{1,swa}$, on condition that in SWAP the reciprocal of the total vertical saturated conductivity is considerable smaller than the vertical resistance of the confining layer.



$$Cauchy: \; q_{bot} = \frac{\varphi_{2,lgm} - \varphi_{bot}}{c_{bot}}$$

φ_{bot} = groundwater head at bottom numerical layer (m)
$\varphi_{2,lgm}$ = groundwater head of 2nd aquifer of LGM (m)
c_{bot} = resistance of confining layer (day)
q_{bot} = Cauchy bottom boundary flux (m day^{-1})
gwl = groundwater table (m)
z_i & z_{i-1} = z-levels of bottom soil compartments (m)

Figure 2.7. Cauchy bottom boundary condition of SWAP.

The leftover flux $q_{left,lgm}$ (m d^{-1}) is introduced specifically for the coupled LGM-SWAP model. The leftover flux contains a composed flux of hydrological processes within the phreatic aquifer that are considered by the groundwater model LGM, but are not taken into account by the unsaturated flow Modelling with SWAP. The leftover flux $q_{left,lgm}$ is transformed from a volume flux (m^3 d^{-1}) to a spatial distributed flux (m d^{-1}) and can consist of the following three fluxes:

$$q_{left,lgm} = \frac{Q_{riv}}{A_{inf}} + \frac{Q_{well}}{A_{inf}} + \frac{Q_{hor}}{A_{inf}} \qquad (2.4)$$

where Q_{riv} (m^3 d^{-1}) is the volume flux of surface waters incorporated as line-elements in LGM, Q_{well} (m^3 d^{-1}) is the extraction volume rate of wells in the phreatic aquifer of LGM, Q_{hor} (m^3 d^{-1}) is the net horizontal volume flux of a finite element nod to or from its neighbouring nods, and A_{inf} (m^2) is the influence area of a finite element node in LGM.

Important to mention here is that the left-over flux has to be taken into account only in the vicinity of wells and large surface waters, that are incorporated as line-elements. Further away from these hydrological features the left-over flux has very small values.

Upper boundary condition of LGM provided by SWAP

The transient groundwater model LGM requires values of the groundwater recharge *and* the phreatic storage coefficient for its top boundary condition. The groundwater recharge $q_{re,swa}$ (m d^{-1}) is derived from SWAP and is defined as the vertical soil water flow across the groundwater table. A facility is made to assure a smooth transition of the successive daily output values of the groundwater recharge, in case the groundwater table crosses the boundary between two soil compartments during a decade (10 days), the calculation time-step of LGM. The groundwater recharge is actually composed of the vertical fluxes above and below the groundwater table. The proportion between the two vertical soil-water fluxes is determined by their distance toward the groundwater table. The groundwater recharge $q_{re,swa}$ (m d^{-1}) is expressed as follows:

$$q_{re,\,swa} = qv_{i-1}\left(\frac{z_{i-1} - gwl}{z_{i-1} - z_i}\right) + qv_i\left(\frac{gwl - z_i}{z_{i-1} - z_i}\right) \tag{2.5}$$

where qv_{i-1} and qv_i (m d^{-1}) are the vertical soil water fluxes above and below the groundwater table respectively, z_{i-1} and z_i (m) are the bottom boundaries of the soil compartments *i-1* and *i*, and *gwl* (m) is the groundwater level, all negative downwards.

The phreatic storage coefficient μ (m^3 m^{-3}) is determined over the entire unsaturated column and is given by:

$$\mu = \frac{\sum_{i=1}^{n_{gwl}} (\theta_{sat} - \theta_{act})_i \, D_i}{\sum_{i=1}^{n_{gwl}} D_i} \tag{2.6}$$

where θ_{sat} (m^3 m^{-3}) is the volumic saturated soil water content, θ_{act} (m^3 m^{-3}) is the actual volumic soil water content, D_i (m) is the thickness of the soil compartment i and n_{gwl} the number of soil compartments above the groundwater table.

In cases of deep groundwater tables there is a chance that the entire soil column of SWAP becomes unsaturated. In these situations it is not possible to make use of the Cauchy condition as the bottom boundary condition. Therefore, in cases of deep groundwater tables a different kind of lower boundary condition is used to provide LGM with the required groundwater recharge. This so-called free drainage of the soil profile assumes unit gradient at the lower boundary (special case of Neuman condition):

$$\frac{\partial H}{\partial z} = 1 \qquad \Rightarrow \quad q_{re} = -k_{numlay} \qquad \text{if} \quad gwl_{\lg m} < \ \ 6\text{m} \tag{2.7}$$

where k_{numlay} (m d^{-1}) is the unsaturated hydraulic conductivity of the bottom (lowest) compartment of the SWAP column, and gwl_{lgm} is the highest/most shallow groundwater level of the entire simulation period of LGM.

2.3.3 Time-averaging aspects

The coupling is performed with a transient decade-based LGM and a transient day-based SWAP. The output values of both models are exchanged in decades according to the model with the larger time-step, which is the LGM model. The daily output values of SWAP ($q_{re,swa}$ and μ_{swa}) are transformed to decade values according to the following rules of the time-averaging procedure (figure 2.8):

- a year exists of 36 decades;
- the first two decades in a month count 10 days each;
- the third decade includes the number of days to complete the month;
- the leap day has been accounted for.

The LGM model uses smaller internal time-steps to reach convergence, which is usually within a few days (figure 2.8). The output values of LGM($\varphi_{2,lgm}$ and $q_{left,lgm}$) are in decades and used as input for the bottom boundary of the daily-based SWAP model.

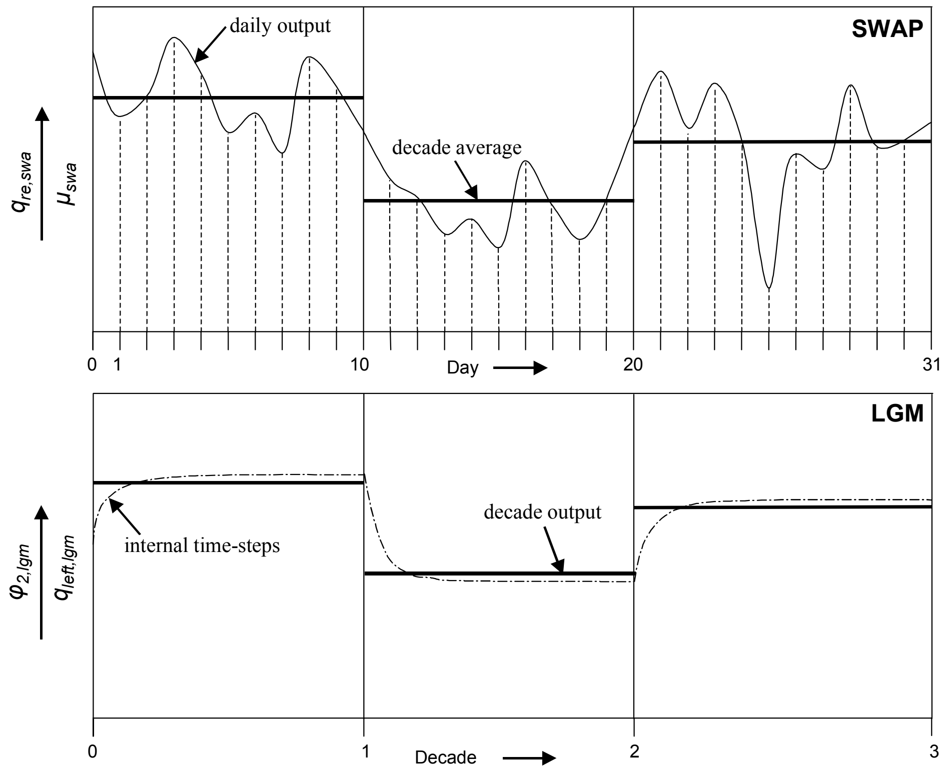


Figure 2.8. Time-averaging aspects of the coupled LGM-SWAP model. Top: Daily output of SWAP averaged to decade values for LGM. Bottom: Internal calculation time-steps of LGM used to produce decade output values, used as input for SWAP.

2.3.4 Convergence procedure

The coupling between LGM and SWAP is based on the following iterative procedure (figure 2.9):

- run LGM with initial input series of the groundwater recharge $q_{re,initial}$ (m d^{-1}) and the phreatic storage coefficient $\mu_{initial}$ (-), both in decades. For $q_{re\ initial}$ (m d^{-1}) a sine wave for a one-year period is used, with an average of 0.8 mm d^{-1} and an amplitude of 0.4 mm d^{-1}, the maximum value is reached at day 90. The $\mu_{initial}$ (-) has a constant value of 0.1 (-) during the first run. The same input series for the groundwater recharge rate and phreatic storage capacity are applied to all finite element nodes as the upper boundary condition of LGM;

- apply the decade values of the LGM-calculated groundwater heads of the second aquifer of LGM $\varphi_{2,lgm}$ (m) and the phreatic leftover flux $q_{left,lgm}$ (m d^{-1}) to the lower boundary condition of SWAP and run the SWAP model;
- proceed to time averaging of the daily output of SWAP to decades values of the groundwater recharge and storage capacity;
- check whether convergence has been reached. The LGM-SWAP convergence has been reached if the groundwater recharge $q_{re,swa}$ (m d^{-1}) no longer show significant changes with the groundwater recharge from the previous iteration.

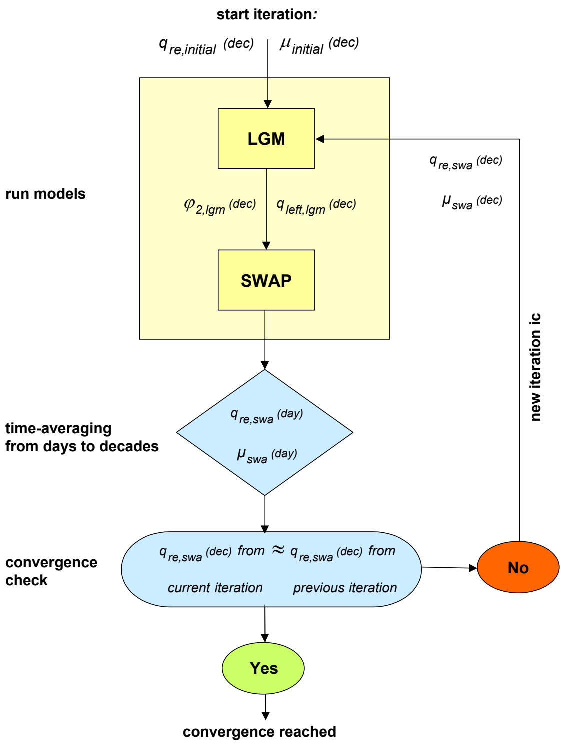


Figure 2.9. Convergence procedure of the coupled LGM-SWAP model.

2.3.5 Surface waters

As the surface waters form an important part of the hydrological functionality in both LGM and SWAP, their parameterisation should be consistent and produce practically the same drainage/infiltration fluxes. Taking in consideration the functionality and limitations of both models leads to the following approach.

Local surface waters

Five different local surface water systems are distinguished, in accordance with the classification in STONE (Kroon *et al.*, 2001). In this concept, three local drainage systems are used for the simulation of discharge into the primary, secondary and tertiary surface water systems (figure 2.10). The definition of these classes was inferred from 1:10.000 Dutch topographical maps. Out of these three systems, only the primary system can simulate infiltration, using an infiltration resistance that may differ from the drainage resistance. Preferable, but not yet possible in the applied 'basic drainage option' of SWAP, is to limit the infiltration rate by defining a groundwater level at which the maximum rate is reached.

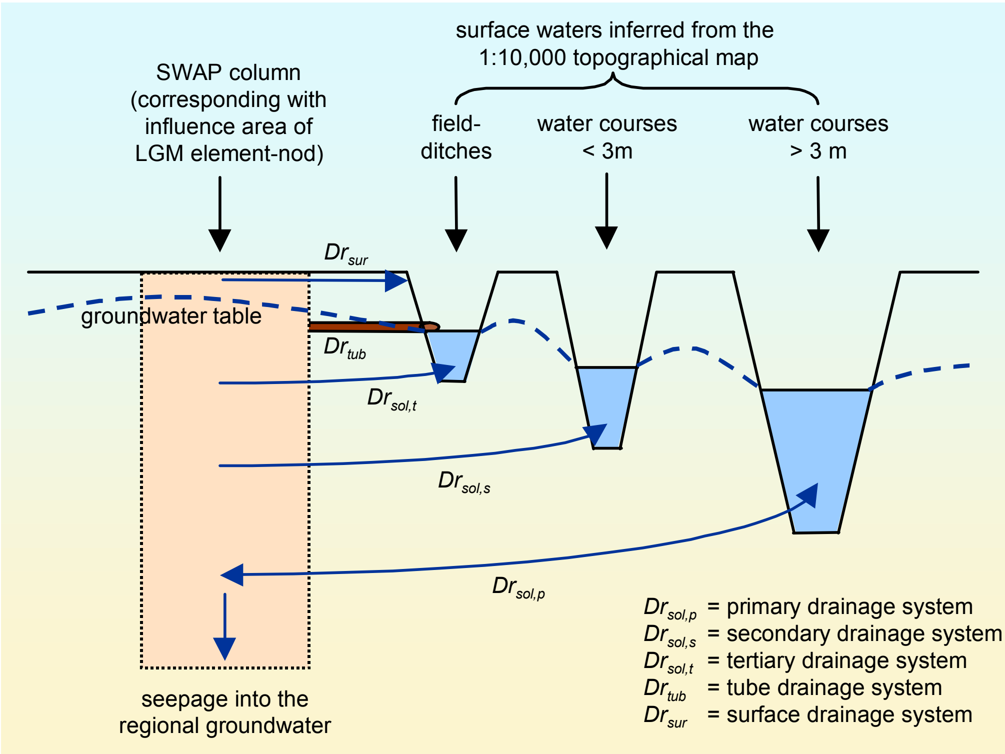


Figure 2.10. The five local drainage systems considered in the coupled LGM-SWAP model (after Tiktak, 2003).

The fourth and fifth drainage systems are used for tube drainage and rapid discharge at the soil surface. This surface drainage occurs when the groundwater table is nearing the soil surface. Due to its irregularities the soil surface will then start to function as a drain. The surface drainage resistance has a constant value of 10 days. The lumped drainage relations of the five local surface water systems, such as they are incorporated in the coupled LGM-SWAP model, are shown in figure 2.11.

Surface runoff

In LGM the simulation of surface runoff is not possible. In SWAP on the other hand, it is a standard functionality which can not be switched off. However the consequence of this inconsistency is limited due to the introduction of the (rapid) surface drainage system, mentioned before. Its low drainage resistance will in most cases prevent the groundwater table from reaching the soil surface.

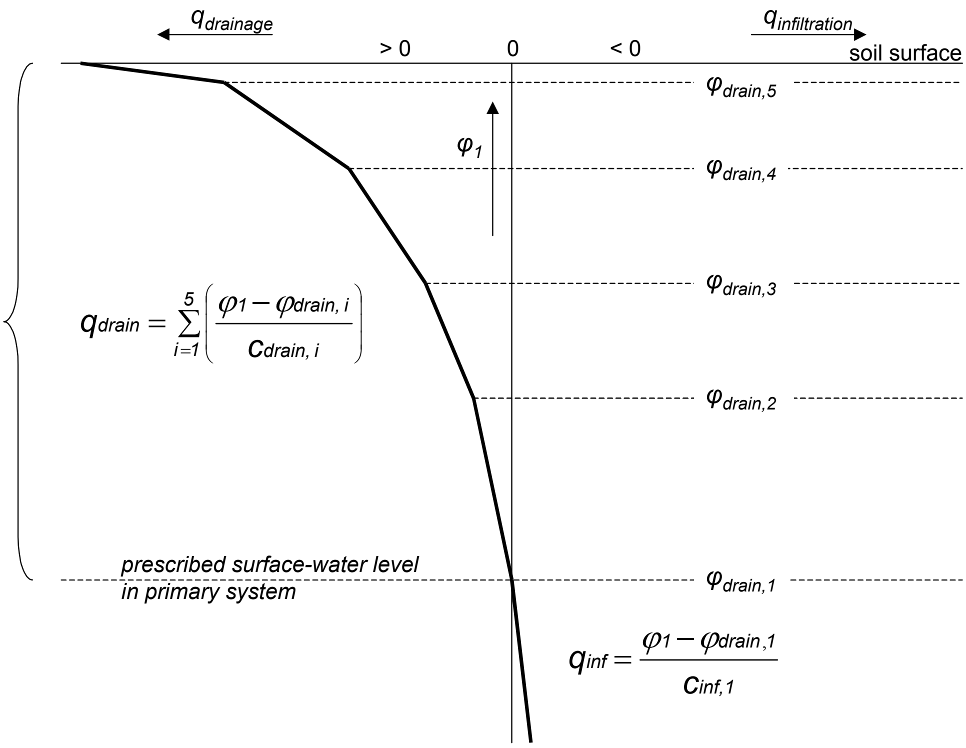


Figure 2.11. Lumped drainage relations of the five surface water systems, as incorporated in the LGM-SWAP model. The drainage-/infiltration flux is a function of the groundwater height (φ_1), drainage base (φ_{drain}) and drainage-/infiltration resistance (c_{drain} and c_{inf}).

3. Derivation of the spatial schematisation and model parameterisation

The coupled model is applicable at both the regional and the national scale, the difference being the size of the modelled area. An example of a regional-scale application is presented in chapter 4 (modelled area 700 km^2, nodal distance 500 m), while a national-scale application is discussed in chapter 5 (modelled area 31600 km^2 with node distance 1250 m, locally downscaled to 250 m). The model output can be generated at any spatial resolution with distances between the model nodes even as small as 25 meters, the latter distance being the most detailed resolution in input data.

3.1 Spatial schematisation

The spatial coupling of LGM and SWAP is realised by using a direct and unique parameterisation linkage between the two models, the so-called one-to-one spatial coupling between LGM and SWAP. In this one-to-one coupling the parameter values for both LGM and SWAP are derived for the same node influence area. Examples of influence areas are shown in figure 2.1. Running the LGM-SWAP model consists of a repeated processing of LGM and SWAP (see section 2.3.4).

The advantage of the one-to-one spatial schematisation is that full consistency is guaranteed between the parameter input values for LGM and SWAP. The drawback of the one-to-one approach is a high execution time of the SWAP model. It is for this reason that –with the currently available computational power– the coupled LGM-SWAP model can be used only for a limited number of nodes. In practice, however, it is often required to zoom in on some areas with a great spatial detail, such as in areas with a high hydraulic gradient, areas with a distinct variability of the groundwater table, or in areas with ecologically valuable water-dependent habitats. When dealing with a large number of model nodes, two ways can be followed:

- decrease the number of SWAP runs by running SWAP only at the limited number of so-called ‘unique combinations of SWAP plots’ (Kroes *et al.*, 2001). Using SWAP plots implies a certain loss of physical relevance and, thus a decrease of accuracy of model outputs. After all, a SWAP plot used at a certain node does not represent the actual parameters uniquely pertaining to that node;
- use the combined one-to-one LGM-SWAP model in combination with a downscaling procedure to generate greater spatial detail.

In this study (chapter 5) we have used the latter two-steps approach: (a) the application of a spatially coarse coupled LGM-SWAP model, with the node distance of 1.25 km and node influence area 1.3 km^2, (b) followed by a single run of a spatially detailed transient LGM model (node distance 250 m) that uses as input the groundwater recharge and storage coefficient downscaled from the coarse coupled model. The detailed transient LGM run is carried out only once, without feedback to SWAP. The feedback is omitted due to high computational time required for running the SWAP model. Therefore its result is an approximation of the output that would have been achieved by applying iteratively the coupled LGM-SWAP model for the detailed 250-m grid. Both LGM models in the two-step approach are identical in terms of model schematisation and parameterisation, such as the type of boundary conditions, layering of aquifers and aquitards, and the topsystem definition.

3.2 Parameterisation of LGM

Model parameterisation is the process resulting in the parameter values at the nodes of the model grid, further referred to as model parameters or model input values. The main type of model parameters concerns the *spatially distributed parameters*, for example aquifer transmissivities and hydraulic resistance of aquitards. The other model parameters are *line-based parameters* (rivers) and *point-based parameters* (wells).

3.2.1 Spatially distributed parameters

The key element for parameterisation of spatially distributed parameters are the influence areas of nodes, denoted as A_{inf} (m^2). The influence areas are used to generate the parameter input values from the basic data in ArcInfo. Three types of basic data (ArcInfo coverage) are used:

- point information like the elevation of ground level;
- line information like thickness of geological layers and hydraulic conductivity of aquifers;
- polygon information like the identification code of geological formations.

An example of a finite element grid for LGM is shown in figure 2.1. An influence area is a polygon. Only if the grid consists of quadrangles, the influence areas will simplify into quadrangles.

The model parameter values at nodes can always be derived by assigning the nodal values from ArcInfo coverage. The procedures are described below in '*Step 1, spatial parameterisation*'. However, this straightforward assignment method may be used only if the parameters do not significantly vary within the space of the model-node influence area A_{inf}. If a parameter varies strongly within an influence area – which in our case is expected to occur for influence areas A_{inf} larger than 250 x 250 m^2 – then an area-weighted spatial averaging within the influence area must be used to account for the parameter variability. The area-weighted spatial averaging for generation of *model parameters* distinguishes four steps:

- first define the parameter values at the nodes of an intermediate grid, which is finer than the model grid. In our case, the intermediate grid consists of a regular mesh of square-shaped elements, with the node distance of 250 m. For basic information defined by ArcInfo coverage for points and lines, the parameter values at the intermediate-grid nodes are defined through the TIN interpolation. For basic interpolation defined by polygons, the parameter values at the intermediate-grid nodes are defined by trivial assignment (*identity* function in ArcInfo);
- second, execute the existing procedures (computer programs and algorithms) to calculate the model parameters at the nodes of the intermediate grid. An example of this is the calculation of aquifer transmissivity as a product of the layer thickness and the hydraulic

conductivity, and the calculation of hydraulic resistance of aquitards as a function of the layer thickness, the layer depth and the type of geological formation (lithology);

– third, generate an overlay of the influence area A_{inf} of the model nodes with the influence area of nodes in the intermediate grid. This intersection of two sets of influence-area polygons produces another –more detailed– image of polygons, intersection polygons;
– finally, as fourth step, use an averaging procedure to calculate the model input values –parameter values at the nodes of the model grid– from parameter values previously defined at the nodes of the intermediate grid. An arithmetic area-weighted average for the intersection polygons is used for all parameters, with the exception of hydraulic resistances. In order to preserve the water balance, the area-weighted averaging cannot be done for hydraulic resistances themselves but has to be done for their inverse value.

In the remainder of this section, the basic data and the procedures are discussed regarding the spatially distributed parameters used in this study. The parameters concerned are the ground level, the boundary conditions, aquifers and aquitards, small-scale surface waters, tube drainage, and surface drainage (in Dutch: 'maaiveldsdrainage').

Ground level
The spatial map of the ground level (meters above mean sea level) is based on the topographic map 1:10,000. The map was digitised to a point-type ArcInfo coverage.

Boundary conditions
LGM requires as input the groundwater heads along the model periphery (constant in time) and the initial groundwater heads within the model area. The latter are the groundwater heads at the onset of the transient calculation. In the application discussed in chapter 5, the time of zero coincides with the beginning of January 1, 1986. The boundary-condition groundwater heads for each of the five aquifers were derived from TNO-NITG groundwater head observations for the year 1988. The annual average for 1988 was spatially interpolated (using the TIN procedure in ArcInfo) to the nodes of the model grid.

Aquifers and aquitards
The groundwater system in the Netherlands can be described as a multi-aquifer system consisting of a sequence of aquifers and aquitards, where the groundwater head in the shallow phreatic top aquifer is strongly influenced by the small-scale surface water system. For the description of the groundwater flow in this system, the Dupuit assumption can be adopted for the flow in the aquifers, while the flow in the aquitards is assumed to be vertical one-dimensional. Five aquifers are distinguished –the phreatic aquifer and four deeper aquifers–, separated by aquitards, and underlain by an impervious base.

Two blocks with basic information are distinguished, namely the data for the phreatic top aquifer, and the data for the aquifer-aquitard system below the phreatic aquifer.

The information required for the phreatic top aquifer is contained in TNO-NITG (2002). That report documents the results of a national-scale study carried out for the topsystem layers in the Netherlands. For this purpose, the 'topsystem' is conceived to be the zone of moderately-to-reasonably permeable deposits occurring (a) between the ground level and the top of the first distinctly permeable layer (to become our model aquifer 1) (b) or, if no aquifer exists within a few metres below ground level (such as in peat-clay polder areas), between the ground level and the bottom of the first-encountered semi-confined layer (aquitard 1, separating the top aquifer and aquifer 2). The national-scale inventory distinguished 25 subareas, each assumed to have a homogeneous geological structure. The inventory was based on shallow borings, and the shallow section of the borings from the DINO archive of TNO-NITG (http://dinoloket.nitg.tno.nl). Using the overall information, the vertical hydraulic resistance and transmissivity of the top aquifer were derived.

For the deeper system, use is made of the geohydrological information already available in the previous version of LGM (Pastoors, 1992). Amongst other items, this database contains:

- the z-level (metres above m.s.l.) of the top and the bottom of each aquifer and aquitard;
- the hydraulic conductivity of aquifers;
- the relationship between the aquitard thickness and the aquitard depth, and the resulting hydraulic resistance of the aquitard. After all, the resistance does not have to be a linear function of the layer thickness. This information is spatially structured through the identification code of geological formations, each formation having its own unique characteristics.

The transmissivity of aquifers at each model node is calculated as the product of the hydraulic conductivity and the aquifer thickness, the latter being the difference of z-levels at aquifer tops and bottoms. The hydraulic resistance of aquitards at model nodes is calculated as a function of the aquitard thickness and the depth of aquitard top below ground level. At places where the aquitard is lacking, the minimum value of hydraulic resistance of 10 days was adopted. More information on the parameterisation is contained in Pastoors (1992).

Small-scale surface waters

Interaction of the top aquifer (phreatic aquifer) with the small-scale surface water system (ditches, drains, brooks) is approximated by a spatially distributed source/sink, where the infiltration or drainage is dependent on the phreatic groundwater head. This flux interaction is handled by means of the so-called topsystem flux relation, as it is described in section 2.1. The other two components of the topsystem flux relation are the tube drainage and the surface drainage.

The small-scale surface waters are split up into three drainage system groups, namely the primary, the secondary, and the tertiary system. This classification is based on the channel width classes used in the Top10-vector database, the topography database containing also the location of all surface waters:

- shallow trenches (small ditches) and gullies that carry water only at very shallow groundwater tables (tertiary system);
- watercourses with width smaller than 3 m (secondary system);
- watercourses with width between 3 and 6 m (primary system);

– watercourses with width larger than 6 m (primary system).

Figures 3.1 and 3.2 illustrate, for a model area in the southern Netherlands, the location and density of the secondary and tertiary drainage systems. The model area shown in the figures is the Brabant-Oost submodel (discussed in chapter 5).

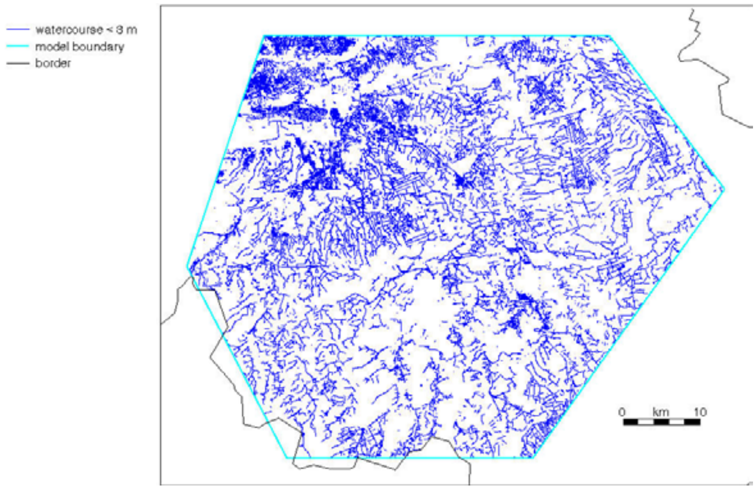


Figure 3.1. Example of location and density of secondary drainage systems, depicted for the Brabant-Oost submodel in southern Netherlands (for location refer to figure 5.1).

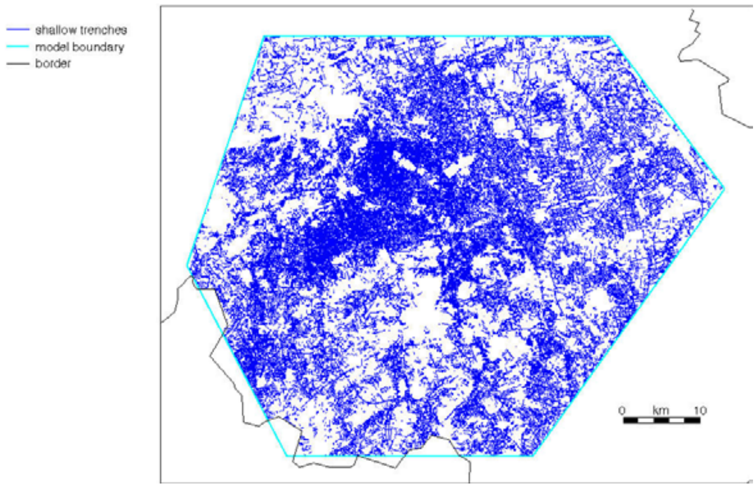


Figure 3.2. Example of location and density of tertiary drainage systems, depicted for the Brabant-Oost submodel in southern Netherlands (for location refer to figure 5.1).

The model parameters required as input for the LGM-SWAP model are (a) the drainage depth (the depth of the drain bottom or surface water below ground level), (b) the hydraulic resistance for the drainage condition, and (c) the hydraulic resistance for the infiltration condition. Obviously, the infiltration from a watercourse into groundwater can occur only if surface water is available and the water level in the watercourse is maintained, as is often the case in polder areas.

For the parameterisation of the drainage depth at each model node, use is made of the so-called 'hydrotype' classification (Massop *et al.*, 2000), based on the 1:600.000 geological map of the Netherlands and geohydrological characteristics of the topsystem. A hydrotype relates to geological characteristics (history) of a region. Separate hydrotypes are defined for, for example, a clay region, a loess region, a river back-swamp region, or a glacial-till region. However, the drainage depth of existing watercourses not only relates to a hydrotype, but also to the groundwater dynamics. The latter expresses the variability of the phreatic groundwater table in time. A convenient way to classify the groundwater dynamics in the Netherlands is the Gt-value, being an identification number for the groundwater depth class (Gt-map 1:50.000). For the parameterisation, we applied the drainage depth as a combined function of hydrotypes and Gt-values (Massop *et al.*, 2000, Appendix 2).

The parameterisation of the drainage resistance and the infiltration resistance at each model node was carried out assuming that the two resistances were equal. For convenience, in the remainder of this section we will use the term ‘drainage resistance’ to denote also the infiltration resistance. The nodal value contribution of the drainage resistance, RD_{iw} (d), due to one watercourse segment, segment *iw*, within a model-node influence area follows from:

$$RD_{iw} = R_{bot,iw} A_{inf} / A_{iw} \tag{3.1}$$

where $R_{bot,iw}$ (d) is the hydraulic resistance of the material at the watercourse bottom, and A_{iw}(m^2) is the surface area of the watercourse segment *iw* within A_{inf}. The segment area A_{iw} is a product of the segment length (m) within A_{inf} and the segment width (m). The segment length within A_{inf} follows directly from the Top10-vector database. However, as the Top10-vector database does not include the information about the watercourse width, a national-average value of the watercourse width was construed and used for each of the three drainage system groups:

- primary system: the mean of the watercourse width assumed 5 m;
- secondary system: the mean of the watercourse width assumed 2 m;
- tertiary system: the mean of the watercourse width assumed 1 m.

$R_{bot,iw}$, the hydraulic resistance of the material at the watercourse bottom is not known for each individual watercourse. For this reason, a national-average value was taken for each of the three drainage system groups:

- primary system: the mean of the bottom resistance assumed 4 days;
- secondary system: the mean of the bottom resistance assumed 2 days;
- tertiary system: the mean of the bottom resistance assumed 1 days.

Tube drainage

A considerable part of the surface area of the Netherlands is drained by tubes and tiles, especially in clayey areas. Little information is available about the location of tubes and tile drains. For the parameterisation, use is made of the tube drainage location map from the STONE project (Massop, 2002). This map was prepared using rules of thumb expressing the probability of tube drainage occurrence at various combinations of land use and the groundwater depth class (Gt-value), supplemented by expert judgement. The drainage resistance of tubes is assumed spatially constant, at the value of 100 days. Also the tube depth is assumed spatially constant, at 1 m below ground level.

Surface drainage

The ground surface is not even, being variable in space (dips and tops, relief on macro- and micro scale). The degree of ground surface deviation from an ideal even (flat) surface increases with the size of the model-node influence area A_{inf} increasing. As the phreatic groundwater level starts approaching the ground surface, the relief in ground surface start collecting surface water and carrying this surface water to drains and ditches. In other words, the ground surface functions as if it were a drain/ditch system. The resistance of the surface drainage is assumed spatially constant, at the value of 10 days. Also the drainage depth is assumed spatially constant, at 0.2 m below ground level.

3.2.2 Rivers and canals

As is considered in section 2.1, LGM features two options for the interaction with surface waters, namely the topsystem-flux relation, to account for the small-scale surface waters, and the so-called rivers. The rivers represent large (wide) river courses such as the Rhine River and its major branches (IJssel River, Waal River, etc.), the Meuse River, and various canals (Amsterdam-Rhine Canal, Twente Canal). The centre line of those large water bodies was incorporated as element sides in the finite element grid (figure 3.3). The parameterisation of rivers/canals was based on the data from the previous version of LGM (Pastoors, 1992). The relevant parameters are the river width, and the drainage and infiltration resistance of the river bottom.

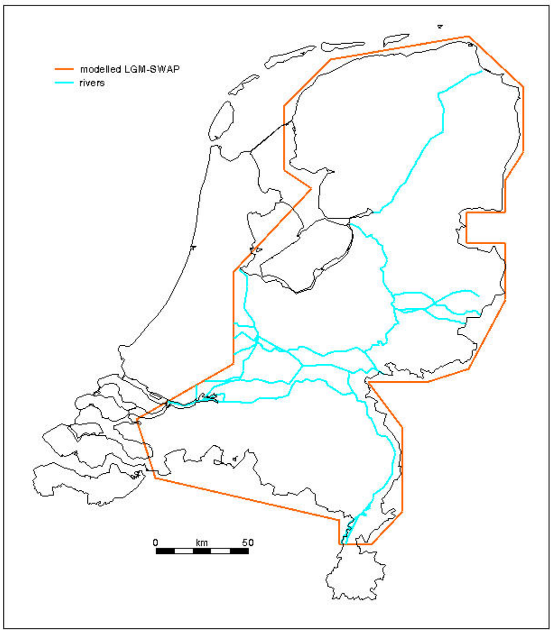


Figure 3.3. Location of rivers and canals incorporated as nodes in finite-element grid for national-scale LGM-SWAP Modelling.

It is worthwhile mentioning here that rivers and canals serve as an internal boundary condition of the Cauchy type. Due to the large portion of surface water area it will not be meaningful to carry out SWAP calculations at those model nodes.

3.2.3 Wells

The groundwater abstractions consist of abstractions for drinking-water supply and abstractions for industrial purposes. The LGM-SWAP calculations were carried out for a single ideal well location for each abstraction site. In reality, the abstraction for drinking-water production takes place in most cases by means of a series of wells spread over a certain area. The well locations, assumed in the ‘ centre of gravity’ of the real well locations, are specified independently of the finite-element grid, i.e. they can be located anywhere inside the grid elements. The program automatically allocates the groundwater abstraction rates to the grid nodes composing the element in which an abstraction site is located. The parameterisation of groundwater abstractions was based on the data from the previous version of LGM (Pastoors, 1992). The well rates from this database represent the amount of groundwater abstracted in 1988.

3.3 Parameterisation of SWAP

To avoid data redundancy, a relational database was set up to assign the parameter values for all SWAP-plots (figure 3.4) This database contains a hierarchy. At the highest level, a distinction is made between spatially constant parameters and spatially distributed parameters. The spatially distributed parameters are given at the plot level. At this level a subdivision is made between spatially distributed parameters that are part of the model parameterisation and those forming a part of the iteration procedure of LGM-SWAP. The latter are parameters altered during each iteration of LGM-SWAP. These parameters mainly concern the time-variable parameters for the Cauchy bottom boundary condition. Prior to each SWAP run it is determined whether the Cauchy condition or the free drainage condition will be applied for the bottom boundary. The free drainage option will be used in case the groundwater remains 6 m below the soil surface, during the entire simulation period of LGM.

A good estimation of the initial groundwater level at the start of a simulation by SWAP will reduce the adjustment period of the calculations considerably. Therefore the initial groundwater level used as input, is the average groundwater level calculated by the previous run of LGM.

Certain spatially distributed parameters that are part of the model parameterisation are valued in accordance with the model parameterisation of LGM. Parameter values for the drainage characteristics and the hydraulic resistance of the bottom boundary layer (the uppermost aquitard) are assigned to each individual plot. The remaining spatially distributed parameters are related to three basic parameters, namely the soil profile number, the weather district and land-use type.

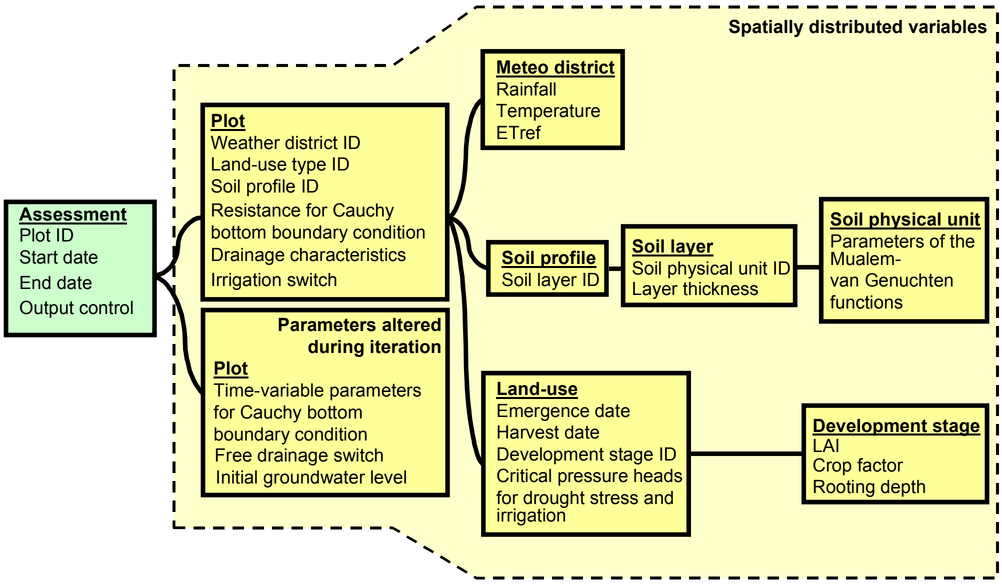


Figure 3.4. Simplified scheme of the GeoPEARL database (only hydrology), used for running multiple SWAP-plots (after Tiktak et al., 2003).

To determine the values of these three basic parameters a map overlay with the finite element grid of LGM has been carried out. The assigned ID's of each of the three parameters is the dominant value within an influence area of a node. By that the influence areas, belonging to the nodes of the finite element grid, are normative for defining the parameter values for SWAP.

Time series of precipitation, temperature and reference evapotranspiration according to Makkink (1957) were available for 15 weather stations. Each station was assumed to be representative for an entire weather district, together covering the total area of the Netherlands. The map is based on an allocation of the weather stations to PAWN-districts, according to Kroes *et al.* (1999). For 14 weather stations only decade values of precipitation, temperature and reference evapotranspiration were available. However daily observations of these meteorological parameters were available for the weather district De Bilt. To obtain daily values for all weather stations the daily variation of the observations of De Bilt has been superimposed on the decade values of the other stations.

Three crop types were distinguished for the simulation of evapotranspiration, namely permanent grassland, maize and other arable land. The areas covered with these three crop types are determined by means of a classification of the land-use map LGN3+ (De Wit *et al.*, 1999). Emergence date, harvest date and development stage dependent crop parameters were derived from simulations with a crop growth model (Hijmans *et al.,* 1994). Critical pressure heads for drought stress (and irrigation) were taken from Van Dam (2000). So far irrigation has been switched off.

There are 21 soil profiles distinguished, which are derived from the soil map 1:50.000 (Klijn, 1997). The applied derivation is based on the classification used to translate the 1:250.000 soil map in soil profiles (Wösten *et al.*, 1988). Each soil profile is composed of soil horizons for which soil physical units are assigned to. Parameter values for the Mualem-Van Genuchten functions to describe the soil physical properties were taken from Wösten *et al*. (1994).

4. Performance of the coupled model at the regional scale

4.1 Introduction

During the development of the combined LGM-SWAP model, a small study area near Lochem (100 km^2) was used for testing. Results of this application were described by Stoppelenburg *et al.* (2002). Following this application, the model was applied to a slightly larger catchment. The objectives of this regional modelling study were:

1) to evaluate the performance of the combined LGM-SWAP model for regional scale studies. An important aspect of the performance of the combined model was the ability of both models to simulate the dynamics of the phreatic aquifer in a consistent way. Therefore, we focussed on the resulting water balances and groundwater dynamics.
2) to compare the performance of the combined LGM-SWAP model with the performance of other models. To achieve this, RIVM participates in the so-called 'Dutch working group on hydrological modelling'. Other partners in this working group were Alterra and RIZA.

The study was carried out in the Beerze-Reusel catchment, which has a surface area of approximately 700 km^2. As a starting point for the study, an existing model of this catchment was used (Van Walsum *et al.*, 2002). To facilitate the comparison between the three models, the schematisation and parameterisation were simplified (see section 4.3). Because of these simplifications, it is not possible to compare the simulated groundwater dynamics with observations; the modelling study was purely performed to test consistency between the models and not to test validity of the final model.

This chapter continues with an introduction to the study area (section 4.2), followed by a short description of the model set-up (section 4.3). In section 4.4, the convergence of the coupled LGM-SWAP model is discussed. The performance is discussed in sections 4.5 and 4.6, respectively on regional level and on plot level. Conclusions are given in section 4.7.

4.2 Description of study region Beerze-Reusel

The study region is located in the Province of Noord-Brabant in the southern part of the Netherlands (figure 4.1). An overview of the Beerze-Reusel catchment itself is depicted in figure 4.2. The description of the study region is partly based on Van Walsum *et al.* (2002).

The subsoil consists mainly of sandy deposits formed in the Pleistocene. The region gently slopes in a north to north-east direction, from an altitude of 45 metres above mean sea level (m above m.s.l.) down to approximately 4 m above m.s.l.. There are several aeolian sand ridges several meters high, orientated in west-east direction. These ridges have a large impact on the geomorphology of the stream valleys, as they are situated transversely to the general slope and drainage pattern of the area. In those areas where the rivers traverse the sand ridges, the valleys narrow, sometimes to no more than a few tens of metres. In the plains between the ridges the valleys are wider. In the valleys, alluvial soils have formed, consisting of rede-posited sand, loam and peat. Because of the intensive agricultural drainage these peat soils are strongly oxidised and have often become very thin.

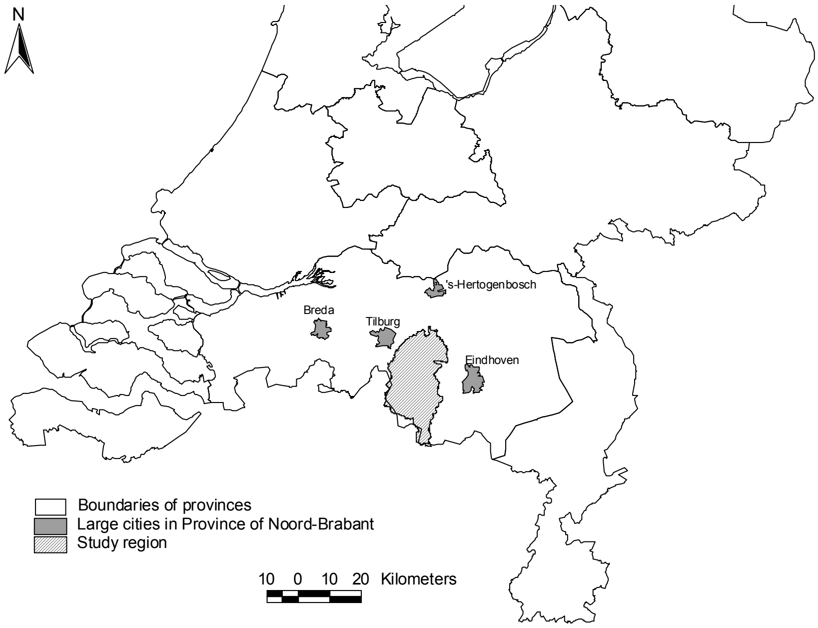


Figure 4.1. Location of the study region in the southern part of the Netherlands (Van Walsum et al., 2002).

Agriculture is the dominant land use in the region. Most of the area is used for grassland and maize. In the region there are a few larger nature conservation areas of more than 1000 ha. These areas are mainly situated on the higher aeolian sand ridges and consist of heathland and pine plantations. The nature conservation areas in the stream valleys are less numerous and are generally much smaller, sometimes not bigger than a few hectares.

4.3 Model set-up

Model set-up follows the generally applicable method as described in detail in chapter 3. However, as described in section 4.1, the existing model (Van Walsum *et al.*, 2002) was simplified for this particular study. The most important simplifications were:

- the number of aquifers was reduced from seven to four;
- the groundwater heads along the model periphery were taken from the NAGROM-model;
- only the three largest groundwater abstractions were input into the model;
- tube drainage was assumed at a constant depth of 90 cm below ground level;
- a constant tube-drainage resistance of 100 days was assumed;
- the entire area was assumed to be covered by grassland;
- the root-zone depth was fixed at 30 cm below ground level;
- the number of weather districts was reduced from five to one (district-number 13 '*Gemert*').

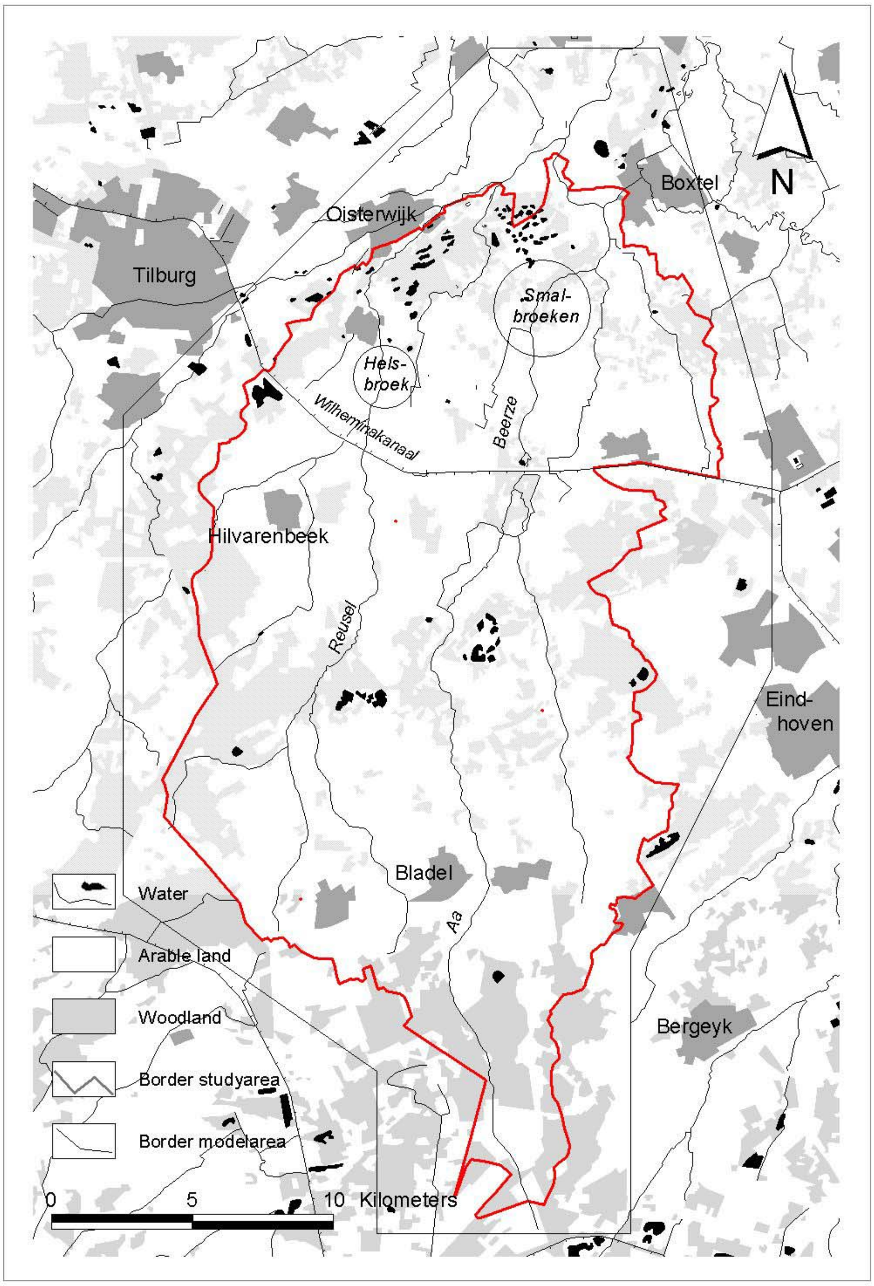


Figure 4.2. Topographic outline of the study region (Van Walsum et al., 2002).

Van Walsum and Massop (2003) reported the effects of these simplifications on the performed modelling exercise. One of the most important findings concerns a reduction of the groundwater dynamics, both spatially and temporarily. This should be kept in mind when evaluating performance of coupled LGM-SWAP model.

Two important hydrological parameters are shown in figures 4.3 and 4.4. Figure 4.3 shows the elevation map and the streams, which are input as line-elements in the groundwater model. Figure 4.4 shows the hydraulic resistance of the uppermost aquitard (denoted in LGM as c_1 and in SWAP as c_{bot}). The interaction between the regional groundwater flow, simulated by LGM, and the local unsaturated-saturated flow, simulated by SWAP, depends largely on the resistance of this layer. The four selected plots, also shown in figure 4.4, will be used in section 4.6, to analyse the time-series of the groundwater table.

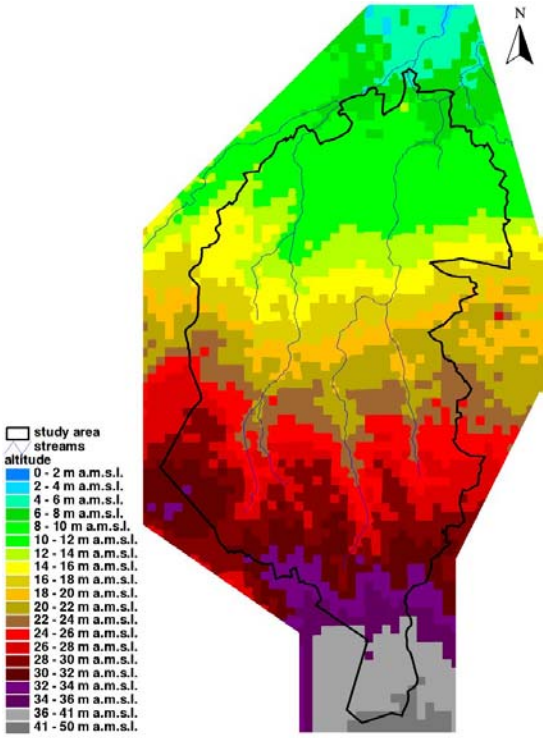


Figure 4.3. Elevation in metres above mean sea level (m a.m.s.l.).

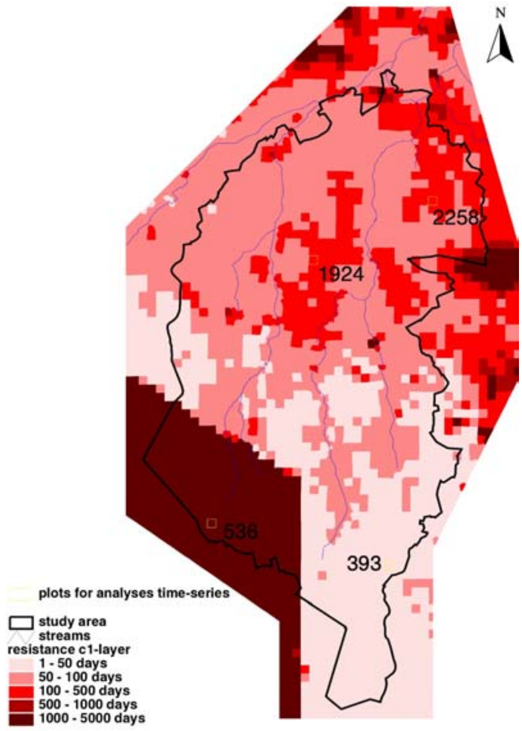


Figure 4.4. Hydraulic resistance c_1 of the uppermost aquitard (d).

The coupled LGM-SWAP model is used to simulate the combined saturated-unsaturated flow over the period 1981-1990. The first four calculation years are considered to be warm-up years, required for the system to adjust from the initial boundary conditions. The remaining six years are used to produce the simulation results.

4.4 Convergence between SWAP and LGM

As described in section 2.3.4., it is assumed that the LGM-SWAP combination has converged if the time-averaged groundwater recharge $q_{re,swa}$ does not show significant differences with the calculated groundwater recharge in the previous iteration (see section 2.3.4 for procedures). In most cases, convergence was reached within three iterations. This can be seen in figure 4.5, which shows that differences between the first and second iteration are already quite small. The actual number of iterations that are needed for convergence depends on the value of the hydraulic resistance c_{bot} of the first (uppermost) confining layer. With higher values of the hydraulic resistance, convergence becomes generally slower. A secondary effect of meeting the convergence criterion is that the simulated phreatic groundwater heads of LGM and SWAP also stabilise at a certain level. However, the phreatic groundwater heads calculated by SWAP do not necessarily stabilise at the same level as the groundwater heads calculated by LGM. These discrepancies will be discussed further in sections 4.5 and 4.6.

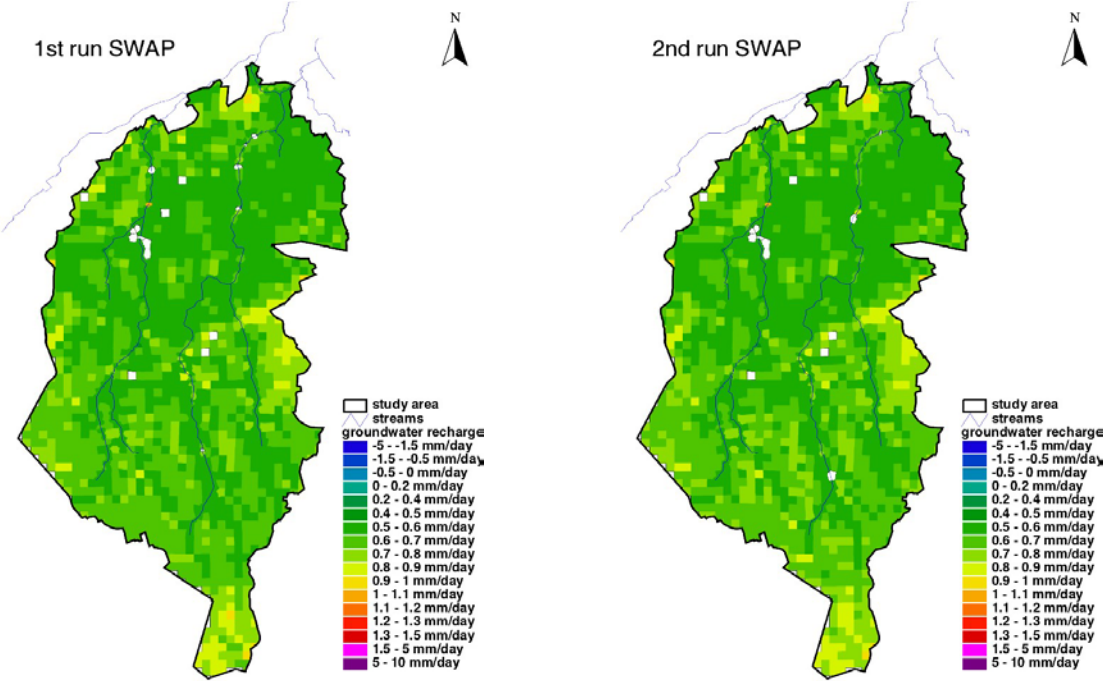


Figure 4.5. Groundwater recharge (mm d^{-1}) as a six years average (1985-1990) after the first iteration (left) and the second iteration (right).

4.5 Performance of the coupling procedure

4.5.1 Spatial patterns of the simulated groundwater depths

LGM and SWAP produce an almost similar spatial pattern of the six-years average of the depth of the groundwater table (figure 4.6). In view of the hydrological features in the catchment, the predicted spatial patterns appear to be plausible as well. The shallowest groundwater tables are found in the stream valleys. The sandy-soil ridges sloping between the valleys show somewhat deeper groundwater tables, which are more profound in the southern part of the study area. Deeper groundwater tables, caused by the well at the eastern border of the study area, are clearly visible as well.

Deviations between the groundwater tables simulated by LGM and SWAP occur as well, but these deviations are limited to individual nodes that are spread randomly throughout the study area. Larger deviations occur in a region adjacent to the Reusel river, where LGM simulates deeper groundwater tables than SWAP. The first confining layer (just below the phreatic aquifer) in this part of the Beerze-Reusel catchment has a relatively high resistance (figure 4.4), so there is relatively little feedback between the two models. In these cases more iterations between SWAP and LGM are needed. Notice that slow convergence between LGM and SWAP is not a problem in the stream valley itself. In the valley, the local drainage systems determine the depth of the groundwater table and not the groundwater recharge.

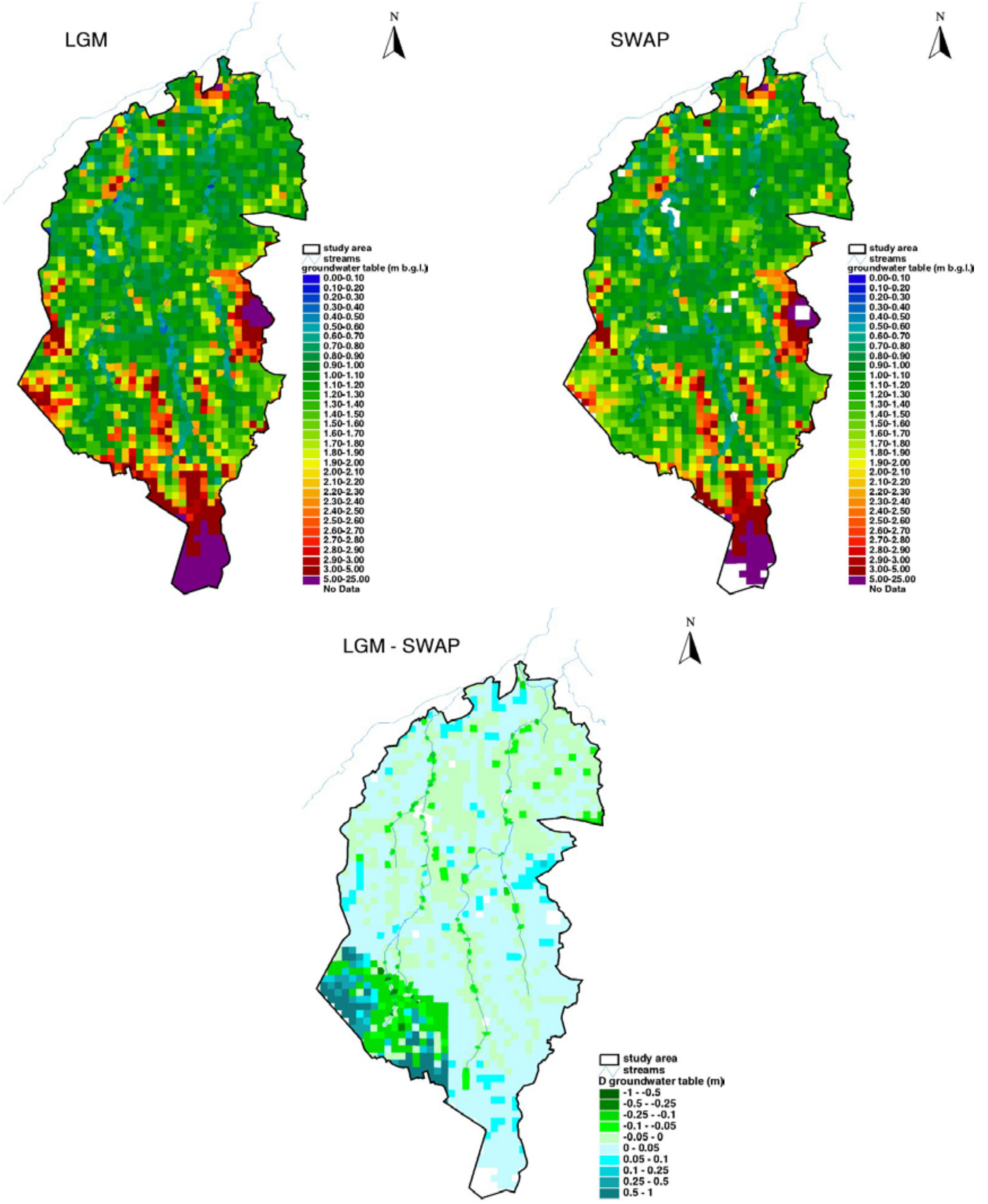


Figure 4.6. Six-years average (1985-1990) of the groundwater table in metres below ground level (m b.g.l.) simulated with LGM and SWAP. Also shown is the difference between LGM and SWAP (lower figure). Values are positive if SWAP calculates deeper groundwater tables than LGM.

4.5.2 Regional-scale water balances

Table 4.1 shows the water balance of the phreatic aquifer as simulated with SWAP and LGM. Notice that there is a small difference between the groundwater recharge simulated with SWAP and LGM. This is due to the fact that LGM uses the groundwater recharge from the previous iteration; LGM lags one iteration behind. The left-over flux $Q_{left,lgm}$, which is the net flux composed of the river-flux, the extraction well rates and the horizontal flux (see section 2.3.2), has the same value in both water balances, as it is transferred directly from LGM to SWAP. The total drainage flux of the five local surface-water systems is also similar. On the other hand, a significant discrepancy has evolved concerning the simulated seepage flux Q_{bot} across the uppermost aquitard c_1. Figure 4.7 shows the differences between the simulated seepage fluxes. These values are averages over the entire simulation period (1985-1990). To find an explanation with respect to these differences, we investigated the simulated time-series (section 4.5.3).

Table 4.1 Six-years average (1985-1990) water balance for the study area Beerze-Reusel (mm a^{-1}).

h	*P-ET*	Q_{re}	Q_{left}	Q_{drain}	Q_{bot}	S_{swa}	S_{lgm}
SWAP	236.5	246.7	19.8	-240.3	-23.1	-7.1	---
LGM	---	245	19.8	-246	-42.3	---	-23.5

P is precipitation, *ET* is evapotranspiration, Q_{re} is groundwater recharge, Q_{ll} is the left-over flux (net flux of river-flux, extraction well rates and horizontal flux, all exchanging with the phreatic aquifer), Q_{drain} is total discharge by five orders of local surface-water systems, Q_{bot} is seepage-/infiltration flux, S_{swa} is net storage of the entire unsaturated-saturated SWAP column and S_{lgm} is storage of the phreatic aquifer of LGM. Positive values refer to net inward flow.

4.5.3 Time-series of the simulated groundwater depths

Time-series of the simulated groundwater depths were examined using results from four plots with different properties (refer to figure 4.4 for locations). Figure 4.8 shows the simulated groundwater dynamics. The simulated water balances are shown in table 4.2.

Case 1: System not converged

Node 393 represents the southern part of the study area, where deeper groundwater tables occur in combination with a confining layer c_1 of low resistance, separating the phreatic aquifer from the second aquifer. Because of this low resistance, the predicted groundwater heads of the first two aquifers in LGM will only slightly deviate. The groundwater head of the second aquifer of LGM also imposes its variation upon the dynamics of the phreatic head of SWAP. With no local surface waters active, the groundwater recharge Q_{re} is of the same order of magnitude as the infiltration flux Q_{bot} across the first confining layer (table 4.2). These fluxes, however, differ in magnitude between the two models, because convergence has not yet been reached. In this particular situation, the averaging of the groundwater recharge during the iteration procedure, slows down the convergence unnecessarily. If enough iterations would have been carried out, it can be expected that LGM results will approximate the water balances generated by SWAP.

Case 2: Effect of underestimation of the phreatic storage coefficient

Node 536 represents an infiltration situation across the first confining layer c_1, with a high hydraulic resistance of 3000 d. In this situation, the local drainage systems is active during part of the simulation period. Figure 4.8 shows that the temporal dynamics of the groundwater table is considerably higher in SWAP as compared to LGM. These difference can be attributed to the methodology for the derivation of the phreatic storage coefficient from SWAP results. As shown in section 2.3.2, this parameter was calculated over the entire unsaturated column of SWAP. This yielded an overestimation of the phreatic storage coefficient. The consequence is an underestimation of the groundwater dynamics by LGM. This also results in a larger groundwater head difference in LGM, which leads to overestimation of the infiltration flux by LGM.

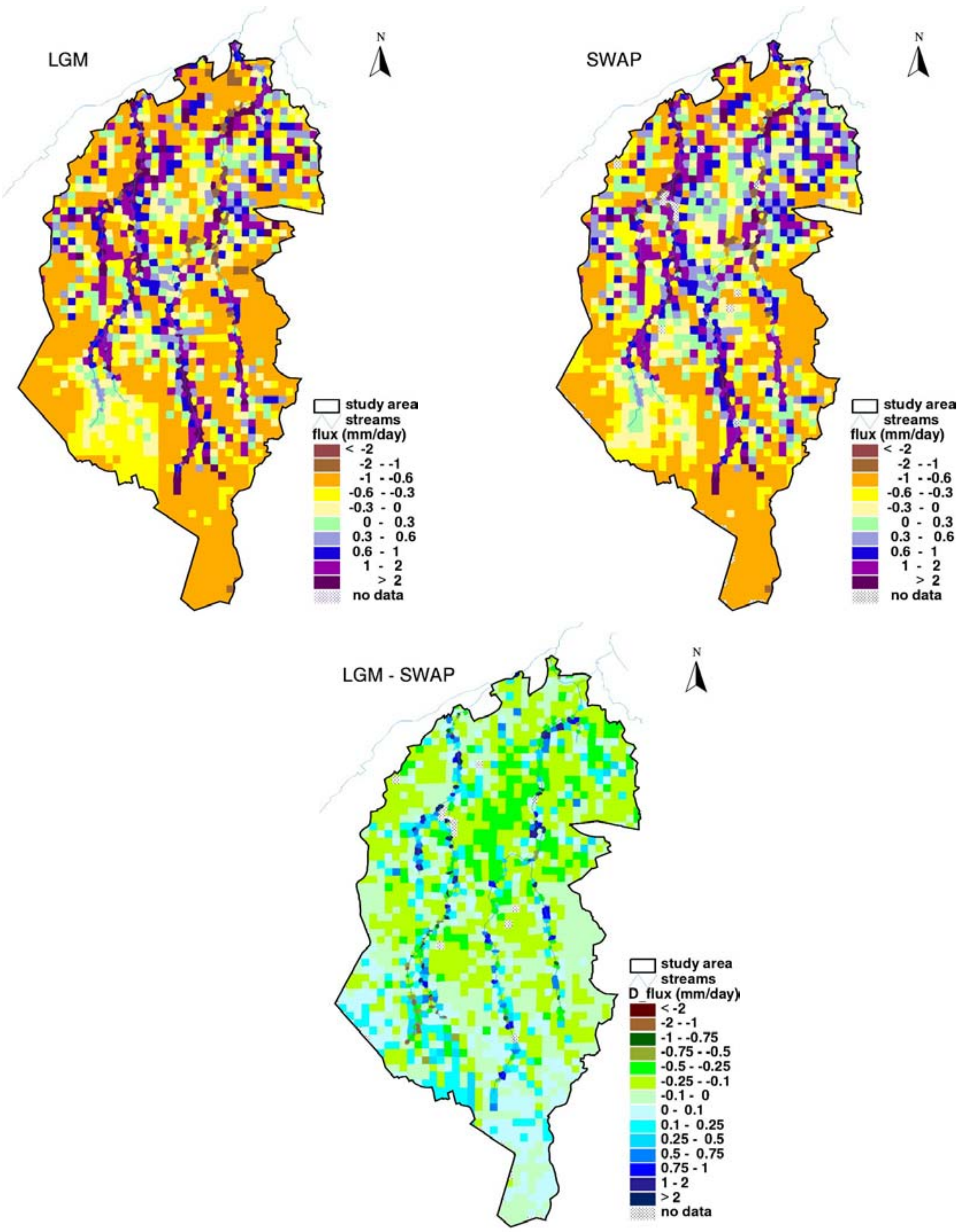


Figure 4.7. Six-years average (1985-1990) of the seepage-/infiltration flux Q_{bot} (mm d^{-1}) across the first confining layer c_1, simulated with LGM and SWAP respectively (positive is seepage or upward flow). Also shown is the difference between LGM and SWAP (mm d^{-1}). Values are positive if LGM generated higher seepage fluxes than SWAP or if SWAP generated larger infiltration fluxes than LGM.

Case 3: Strong interconnectivity leads to acceptable results

Node 1924 is characterised by seepage across the uppermost confining layer, during most of the simulation period. Comparable to the previous case, the predicted groundwater dynamics are slightly higher in SWAP than in LGM. With intermediate hydraulic resistance c_1 of approximately 200 days, a stronger interconnectivity result in more similar groundwater dynamics between LGM and SWAP. The corresponding water balance shows in this case a stronger seepage flux Q_{bot} and a larger drainage flux Q_{drain} to local surface water systems by SWAP, in comparison to LGM.

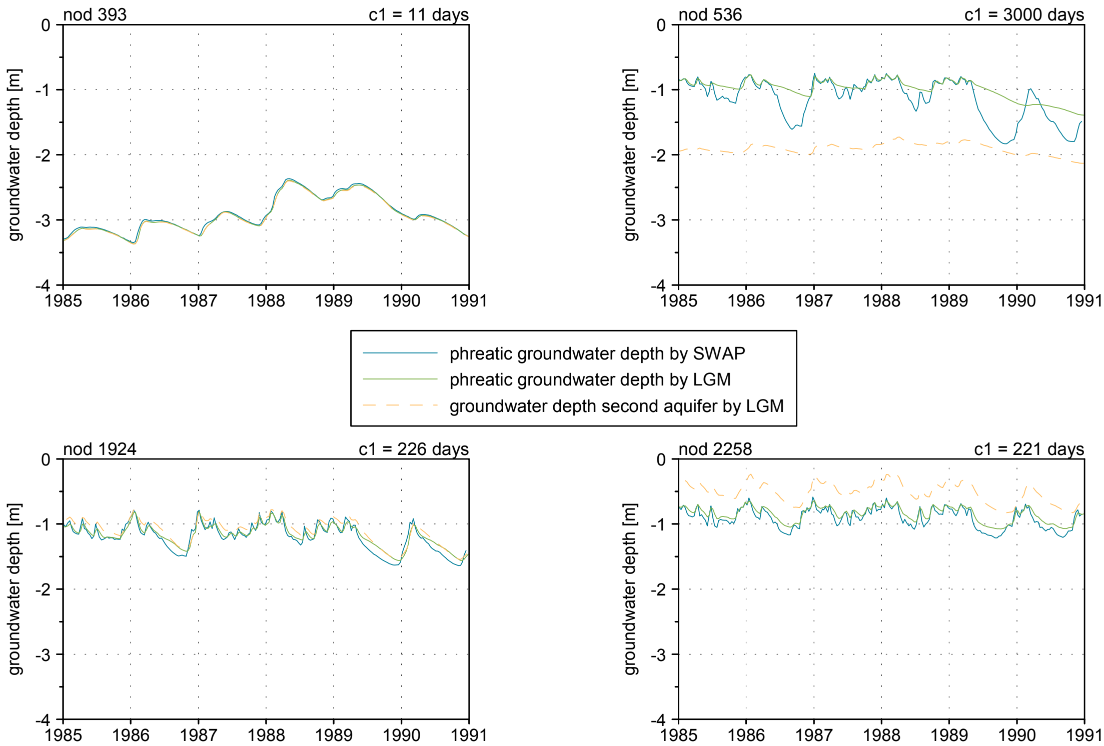


Figure 4.8. Groundwater dynamics for four selected plots/nodes within the study area Beerze-Reusel. All results are averaged over decades. c_1 is the hydraulic resistance of the uppermost confining layer.

Case 4: Effect of the left-over flux

Node 2258 represents a similar situation as the previously discussed node 1924. However, a considerable groundwater-head difference is responsible for a more extreme seepage flux, with values around 2.5 mm d^{-1}. This plot is situated in a stream valley of one of the branches of the Beerze. In a catchment area like Beerze-Reusel the highest seepage fluxes occur in these stream valleys. Notice that, unlike the streams Beerze and Reusel, their branches are not implemented as line-elements, but as spatially distributed drainage relations (figure 4.4). As was the case at node 1924, the groundwater dynamics show almost a same level of comparability between LGM and SWAP. However the water balance of node 2258 shows considerable discrepancies between the models. Given the groundwater-head differences, one would expect the seepage flux Q_{bot} by SWAP to exceed the seepage flux by LGM, and not the other way around (see figure 4.8 and table 4.2). A possible explanation could be found in the interaction of the left-over flux $Q_{left,lgm}$ with the Cauchy boundary condition at the bottom of the SWAP column (see section 2.3.2). It seems that in case of a considerable $Q_{left,lgm}$ flux, the mixed lower boundary condition, as we have implemented does not work properly. Further examination is necessary to come up with a satisfactory solution.

Table 4.2 Six-year average water balance (1985-1990) for four selected plots within the study area Beerze-Reusel (mm year^{-1}). Results from the 2nd coupling cycle with LGM-SWAP.

		P-ET	Q_{re}	Q_{ll}	Q_{drain}	Q_{bot}	S_{swa}	S_{lgm}
plot 393	SWAP	256.5	269.7	-7.3	0	-261.7	-12.5	---
	LGM	---	244.6	-7.3	0	-248.2	---	-10.9
plot 536	SWAP	223.7	235.1	14.6	-168.1	-80.7	-10.5	---
	LGM	---	233.6	14.6	-157	-113.2	---	-22
plot 1924	SWAP	224.7	225.6	3.7	-392.4	167.5	3.5	---
	LGM	---	222.7	3.7	-368.7	113.2	---	-29.1
plot 2258	SWAP	219.3	226.6	29.2	-712.3	466.8	3	---
	LGM	---	219	29.2	-814	551.2	---	-14.7

P is precipitation, *ET* is evapotranspiration, Q_{re} is groundwater recharge, Q_{ll} is the left-over flux (net flux of river-flux, extraction well rates and horizontal flux, all exchanging with the phreatic aquifer), Q_{drain} is summed discharge by five orders of local surface water systems, Q_{bot} is seepage-/infiltration flux, S_{swa} is net storage of the entire unsaturated-saturated SWAP column and S_{lgm} is storage of the phreatic aquifer of LGM. Positive values refer to net inward flow.

4.6 Discussion and conclusions

The current coupling procedure does not guarantee that the simulated water balances and the simulated groundwater levels are equivalent in both models. There are a number of reasons for this, the most important ones discussed below:

1) In some cases, particularly in cases with deep groundwater levels or in cases with a high resistance of the first confining layer, convergence between LGM and SWAP proceeds slowly. Convergence is slowed down by the fact that average values between the two iterations are used (a half-implicit method). This feature was implemented to avoid oscillations between the iterations. The offspin, however, is reduced convergence speed. Currently, the best solution is to use more iterations. With the implementation of grid-computing technology, this is no longer a real problem.
2) The temporal resolution of the boundary conditions of LGM and SWAP are different. LGM uses 10-days average values for the boundary conditions, whereas SWAP uses daily values for rainfall, evapotranspiration, etc. As a result, results from LGM are smoothed when compared to SWAP results. This problem can be solved by choosing a shorter time step for the boundary conditions in LGM, for example one day. This would, however, substantially increase the amount of data to be transferred between the models. We therefore consider the current coupling time-step of ten days an appropriate compromise for regional-scale studies.

3) The procedure, which was used to derive the phreatic storage coefficient from SWAP results (section 2.3.2), yielded only a rough approximation of the actual variation of the 'real' phreatic storage coefficient, required by LGM. Correct estimation of the storage coefficient is extremely important to simulate correctly the groundwater dynamics with LGM, so we decided to implement an improved method for the storage coefficient calculation (see appendix 1). Results from this improved coupling mechanism were not available when this report was created, but will be reported in a scientific article.
4) There are conceptual differences between LGM and SWAP with respect to the implementation of the larger rivers. In LGM, these larger systems are represented by line elements (see section 2.1). The flux to and from these rivers is described in LGM with a head dependent relationship, which is different from the relationship for the primary drainage system in SWAP. For this reason, we switched off the primary drainage system and used the left-over flux instead. Notice that this problem does not pertain to the representation of smaller rivers, brooks and drains. These systems are represented in LGM as spatially distributed source/sink relationships, which follow exactly the same definitions as the local drainage systems in SWAP.
5) The procedure described in this report does not guarantee that the water balance of SWAP and LGM are the same. In a newly developed coupling procedure, this problem has been resolved. This new procedure is outlined in Appendix 1.

In conclusion it can be stated that the performance of the coupling procedure is sufficient for regional-scale model applications. However, in the currently documented procedure, the groundwater dynamics tend to be underestimated by LGM due to overestimation of the phreatic storage coefficient. Also, the water balance is not closed. In particular cases there are larger deviations between LGM and SWAP. These deviations occur in those situations where there is little interaction between the two models (deep groundwater systems, high resistance of the confining aquifer) and in situations with large left-over fluxes (rivers and groundwater extractions). A new coupling procedure, which guarantees a closed water balance and a better calculation of the phreatic storage coefficient is now operational. This new procedure will be described in a scientific paper.

5. Application on a national scale

The study was carried out within the framework of an RIVM-MNP (Netherlands Environmental Assessment Agency) project aimed to assess the state of desiccation in the Netherlands (RIVM, 2003a). This chapter discusses the application of the coupled LGM-SWAP model for an area covering about two-thirds of the Netherlands, with focus on the sandy-soil areas. Subsequently, using output from this national-scale model, four spatially detailed submodels were developed by using a downscaling method for groundwater recharge and phreatic storage coefficient. The modelling approach and the results are discussed in sections 5.1 and 5.2, respectively. Specifically, the results of the detailed submodel are presented for the 'Brabant-Oost' area located in southern part of the country.

The depth of the phreatic groundwater table below ground surface, and its variability in time, is an important factor influencing the diversity and richness of vegetation in terrestrial ecosystems. This is especially relevant in wetland conditions, where groundwater depth measures a few metres below ground level as in most parts of the Netherlands. The shallowest levels (0-1 m below ground surface) exist in the clay-peat areas with controlled surface-water systems (polders). Another typical region contains sandy soil areas in eastern and southern parts of the Netherlands. In these areas, with their sparse surface-water systems (brooks, ditches), typical groundwater levels are found up to 4 m below ground surface, and the range of seasonal variability is about 1 m. It is especially in the valleys of small rivers and brooks where valuable vegetation occurs, conditioned by the availability of shallow phreatic water-table and seepage-induced groundwater with low nutrient content.

The sandy soil areas are particularly vulnerable to environmental stresses (desiccation by lowering of groundwater tables, acidification, etcetera) associated with intensive agriculture, industrial activity and groundwater abstractions. Especially the lowering of the groundwater tables is a major threat to terrestrial ecosystems in the Netherlands. For example, during the last century, particularly since the 1950s, a distinct long-term trend of decreasing groundwater levels can be observed. The trend is caused by land reclamation combined with intensified land drainage and by increasing groundwater abstractions.

Policy measures on national level have been proposed, aimed at restoration of historical moist conditions (shallower groundwater tables), in areas with ecologically valuable water-dependent habitats. The results of the modelling study presented are essential (a) to assess the state of desiccation in the Netherlands, (b) for creating proper management conditions for plant growth and environmental protection, and (c) for the evaluation of effectiveness of the policy measures. The coupled LGM-SWAP model was used to simulate the combined saturated-unsaturated flow over the 1986-2000 period, a 15 years period. Subsequently, transient groundwater levels were simulated in a few detailed submodels over the 13-year period 1988-2000. Those levels were used to derive four indicators for characterisation of the groundwater dynamics. These indicators are the Mean Highest Groundwater-table (GHG), the Mean Lowest Groundwater table (GLG), the Groundwater Depth Class (Gt), and the Mean Spring Groundwater table (GVG).

5.1 Two-step modelling approach

In the national study described here, we followed a two-step approach:
- Step 1, coarse-grid national-scale coupled LGM-SWAP model;
- Step 2, downscaling for spatially detailed submodels (fine grid).

This two-step approach will be explained in this section.

5.1.1 Coarse-grid national-scale coupled LGM-SWAP model

The coupled LGM-SWAP model was developed and executed for an area covering about two-thirds of the Netherlands, further referred to as 'national scale'. The boundary of this model is depicted as a red line in figure 5.1. The grid is relatively coarse, the distance between nodes being about 2.5 km (node influence area about 6.25 km^2). However, at a number of locations, not necessarily at the location of the four submodels, this 2.5-km grid was condensed to a finer grid, with the nodal distance of about 1.25 km (node influence area of about 1.3 km^2).

The number of nodes in the finite element grid for saturated groundwater flow calculations in LGM was 11337. The transient calculation was carried out for the time period 1986-2000 (15 years, 540 decades). It was not necessary to carry out the SWAP calculations in all 11337 nodes of the grid. The SWAP simulations were done in only about 5400 nodes, the remaining nodes being:
- The nodes along the model periphery, with the groundwater level constant in time along the model boundary;
- The nodes located along the large river courses that were incorporated as element sides in the finite element grid (section 3.2.2, figure 3.3). This regards, for example, the Rhine River and its major branches (IJssel River, Waal River, etc.), the Meuse River, and various canals (Amsterdam-Rhine Canal, Twente Canal). At these nodes, the node influence area contains only or mainly the surface water (unsaturated zone is non-existent);
- The nodes located at lakes, the sea and the estuaries (unsaturated zone non-existent);
- The nodes located at polder areas where the groundwater level is, to a great extent, controlled by surface-water level in ditches. The groundwater levels show only small variability in time, the depth of groundwater being in the range of a few decimetres to one metre. Due to the high hydraulic resistance of the clay-peat layer (between ground level and the uppermost sandy aquifer), the regional geohydrological system in those areas only weakly interacts with the shallow unsaturated-saturated system. In other words, though the SWAP simulation could be performed, its outcome would be trivial, namely a more or less constant shallow groundwater table, and would thus hardly contribute to the simulation of the regional saturated groundwater system.

At those nodes of LGM where SWAP calculations were not performed, we have used as input for LGM the average values of the groundwater recharge and the phreatic storage coefficient from the nodes (about 5400) at which the SWAP simulations were carried out. It is recommended to use in the future a physically more realistic procedure for the assignment of values to these nodes. An improved procedure would be, for example, to base the assignment only on the SWAP-generated values in a limited number of nodes in the immediate vicinity of the non-SWAP node, instead –as it was done now– on values in all SWAP nodes. This would yield the values of the groundwater recharge and the phreatic storage coefficient in the non-SWAP nodes better reflecting the local conditions in non-SWAP nodes, such as the groundwater depth and soil physical properties.

The cycle of the LGM-SWAP convergence procedure (see section 2.3.4) was repeated three times. The results from the third iteration run of LGM were used as starting point for simulation in detailed submodels by means of a downscaling procedure (next section).

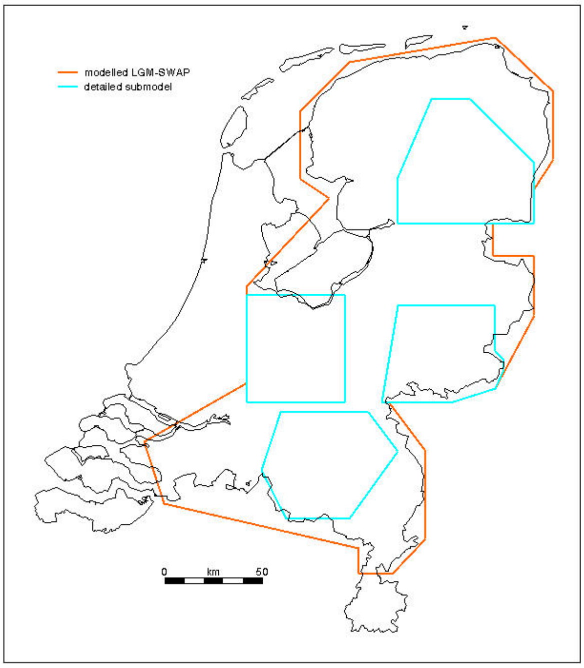


Figure 5.1. Model boundaries for two-step modelling approach: (a) coarse-grid national-scale coupled LGM-SWAP model, and (b) four spatially detailed (fine grid) submodels for sandy-soil areas.

5.1.2 Downscaling for spatially detailed submodels (fine grid)

The spatial resolution (node distance 1.25 to 2.5 km) of the model at the first step is too coarse for applicability in ecology-related issues. While dealing with ecologically valuable water-dependent habitats, one has to consider the variability of soil moisture (or groundwater level) at the scale of hundreds of metres, sometimes in the immediate vicinity of brooks even tens of metres. An obvious manner to achieve a greater spatial detail would be to run iteratively the coupled LGM-SWAP model for a detailed grid in an area of interest, for example using the node distance 250 m. Though this procedure would be practicable for a solitary small-size model, one could not follow this approach to model the entire area of the Netherlands. This is because with the computational power currently available running the coupled LGM-SWAP model at so many nodes would require too much execution time. Hence, it was decided to employ an approximate method for the simulation at a fine-grid scale. The principle feature of the method is that only one transient fine-grid LGM run is carried out using as input the time varying values of (a) the groundwater recharge rate, Q_{re}, and (b) the phreatic storage coefficient, μ. The latter two input parameters for the single LGM run were spatially downscaled from the last-iteration output of the coupled coarse-grid LGM-SWAP model. However, the parameter variability in time in the downscaled model is the same as that in the coarse model. The spatial-downscaling method was rather simple:

- It is assumed that the parameters Q_{re} and μ are constant values within the influence area $A_{inf,coarse}$ of a node in the coarse-grid model;
- The influence area $A_{inf,coarse}$ of one node in the coarse-grid model corresponds to many smaller influence areas $A_{inf,fine}$ in a spatially detailed model;
- The value of $Q_{re,fine}$ and μ_{fine} at the fine-grid node $A_{inf,fine}$, as a time series over 540 decades (1986-2000), is created by assigning Q_{re} and μ from that node in the coarse-grid model in whose influence area $A_{inf,coarse}$ the fine-grid influence area $A_{inf,fine}$ is located.

We consider the downscaling method used here as a first-order approximation of reality. Better downscaling results would have been achieved by taking into account the dependence of Q_{re} and μ on soil type, land use and groundwater table depth. Needless to stress that the downscaling is an approximation of reality as it would have been simulated by running the coupled LGM-SWAP model for the fine-grid area of interest.

Four detailed submodels were developed by using the downscaling method. The models (figure 5.1) are located in sandy-soil areas of the Netherlands:

- Submodel Drenthe;
- Submodel Achterhoek;
- Submodel Utrecht;
- Submodel Brabant-Oost.

The distance between nodes was about 250 m (node influence area about 0.0625 km^2), the detailed grid being 5 to 10 times finer than the coarse grid used in the first step.

Analogous to the coarse-grid model, the transient run of LGM for each of the four downscaled submodels was also carried out for the time period 1986-2000 (15 years, 540 decades). The first two calculation years, 1986 and 1987, are considered to be a tune-up period, required for the system to adjust from the initial boundary conditions. The remaining 13 years, 1988-2000 (468 decades), were used to produce simulation results. For brevity, the simulation results will be presented only for the detailed submodel Brabant-Oost, in southern part of the country (figure 5.1).

5.2 Results

In the geohydrological practice in the Netherlands, four parameters are commonly used to characterise the variability of groundwater table in time. These parameters are:

- the Mean Highest Groundwater table *(GHG)*;
- the Mean Lowest Groundwater table *(GLG)*;
- the Groundwater Depth Class *(Gt)*;
- the Mean Spring Groundwater table *(GVG)*.

The parameters represent the depth of groundwater table below ground level. Obviously, the *GHG* value is smaller than the *GLG* value, in other words *GHG* is shallower than *GLG*.

5.2.1 *Mean Highest and Lowest Groundwater level*

The definition of the Mean Highest Groundwater table *(GHG)* is, expressed in terms of gauged (observed) groundwater tables (Van Walsum *et al.*, 2002):

- From a series of gauged groundwater tables on the 14th and 28th day of each month, the three highest (shallowest) levels are selected for each of the gauging years;
- For each year, the average of the three selected levels is taken, yielding the so-called HG3-levels for each of the available years;
- The HG3-levels are averaged over the years, yielding the value of the Mean Highest Groundwater table *(GHG)*.

The procedure to derive the Mean Lowest Groundwater table *(GLG)* is analogous to the one for *GHG*, using the lowest (deepest) groundwater levels instead.

Though the original procedure for calculation of the *GHG* and *GLG* values assumes an observed series of groundwater levels, the coupled LGM-SWAP model calculates *GHG* and *GLG* from the simulated groundwater levels.

The *GHG* and *GLG*-values for the coupled LGM-SWAP model are derived by using a procedure slightly different than the procedure mentioned before. The *HG3* is calculated from a series of LGM-simulated decadal groundwater heads $\varphi_{1,lgm}$, the three highest (shallowest) decadal values $\varphi_{1,lgm}$ being selected for each of the gauging years in the 13-year period (1988-2000). Those three decades can be any of the 36 decades composing a year. After all, because of the decadal nature of the LGM output we do not calculate the daily values of $\varphi_{1,lgm}$, and hence cannot use the values on the 14th and 28th day of each month to calculate *GHG*. A sensitivity analysis was carried out of the GHG as a function of the number of decadal values of $\varphi_{1,lgm}$ within each year. Specifically, we examined the possibility to use only one highest (shallowest) decadal value of $\varphi_{1,lgm}$ per year, *HG1*. The difference between the *GHG* derived from *HG3*, and the *GHG* derived from *HG1* was only a few centimetres, which indicates that the three values used for creating *HG3* are more or less the same.

Though *GHG* and *GLG* were calculated (using the two-step approach explained before) they are not presented here. The two parameters were used to generate the Groundwater Depth Class (*Gt*).

5.2.2 *Groundwater Step Group*

The map of the Groundwater Depth Class (*Gt*), shown in figure 5.2, was derived from a classification of *GHG* and *GLG* (table 5.1). A value of *Gt* is assumed constant within a model-node influence area. An increasing value of *Gt* indicates a deeper groundwater-level range.

Table 5.1 Groundwater Depth Class (Gt) as function of Mean Highest Groundwater table (GHG) and Mean Lowest Groundwater table (GLG). GHG and GLG are in metres below ground level (m b.g.l.).

Groundwater Depth Class (*Gt*)	*GHG* (m b.g.l.)	*GLG* (m b.g.l.)
I	—	< 0.50
II	—	0.50-0.80
III	< 0.40	0.80-1.20
IV	> 0.40	0.80-1.20
V	< 0.40	> 1.20
VI	0.40-0.80	> 1.20
VII	> 0.80	> 1.20

Please note that table 5.1 contains a simplified version of the classification used in the Netherlands. For simplicity, we lumped the *Gt*-subclasses II*, III* and VII* with class II, III and VII, respectively.

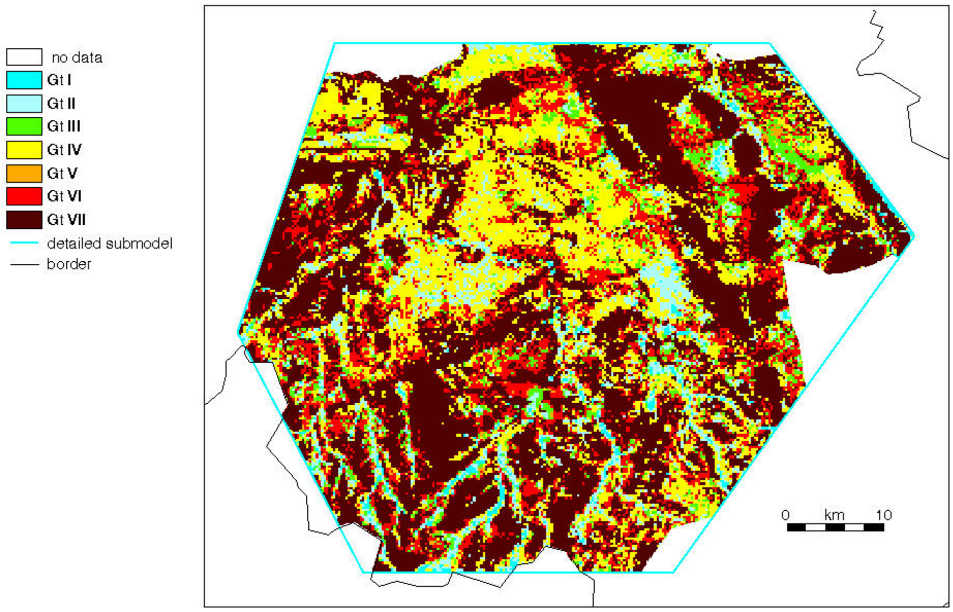


Figure 5.2. Groundwater Depth Class (Gt) derived from GHG and GLG, for detailed-scale Brabant-Oost submodel. GHG and GLG calculated by downscaling results of coupled LGM-SWAP model for the 1988-2000 period.

5.2.3 *Mean spring groundwater level*

Another parameter produced by the coupled LGM-SWAP model (referring to the two-step approach explained before) is the Mean Spring Groundwater *(GVG)*. The value of *GVG* is defined as an average depth of the groundwater table occurring at 14 April each year, for each year within the considered multiple-year time period. In our case, we have used the LGM output of groundwater heads $\varphi_{1,lgm}$ at the end of 14 April during 1988-2000 (13 years). The *GVG* value, expressed in metres below ground level, is an indicator for the amount of soil water available for plants at the onset of the growing season. In other words, the larger the *GVG* value, the deeper the groundwater level and, hence the drier the top section of the soil profile. *GVG* is often used to express the degree of desiccation, for the evaluation of policy measures.

Figure 5.3 depicts the Mean Spring Groundwater table (GVG) simulated by the coarse-grid national-scale coupled LGM-SWAP model, as explained in step 1 in section 5.1. The groundwater table can be taken either from the LGM output or from the SWAP output. Note that the influence area at the river nodes (where SWAP runs were not performed) are omitted. Subsequently, in the modelling step 2, the GVG was simulated at four detailed-scale sandy soil areas. The results for the four submodels are shown in figure 5.4.

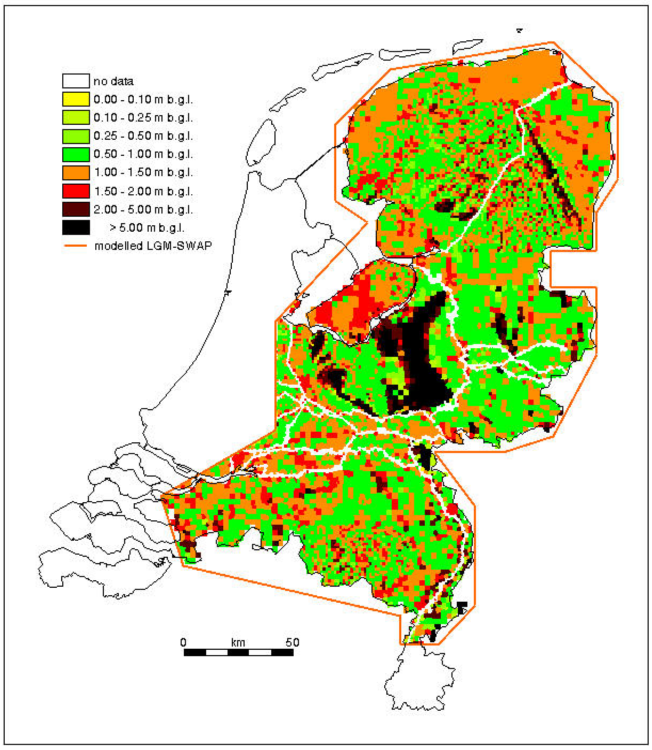


Figure 5.3. Mean Spring Groundwater table (GVG, m below ground level) for national-scale coarse schematisation of coupled LGM-SWAP model (iteration 3) for 1988-2000 period.

Since the actual value of the Mean Spring Groundwater table (*GVG*) for the Brabant-Oost submodel is available from a recent field survey combined with geostatistical processing (figure 5.5), one can compare this field-observed value with the simulated *GVG*. The field-survey generated data were received from the Province of Noord-Brabant (RIVM, 2003b). The differences between the between calculated *GVG* values (figure 5.4) and the field-surveyed *GVG* values (figure 5.5) are presented in figure 5.6. Based on this, three remarks can be made:

- At 40% of the locations, the differences are greater than 25 cm; these locations are, however, generally characterised by deep groundwater tables (> 1.5 m; see figure 5.5);
- Areas with deviations larger than 0.25 m and smaller than -0.25 m form spatial clusters;
- The LGM-SWAP output as an average over the entire modelled area, does systematically under- or overestimating the field-surveyed values.

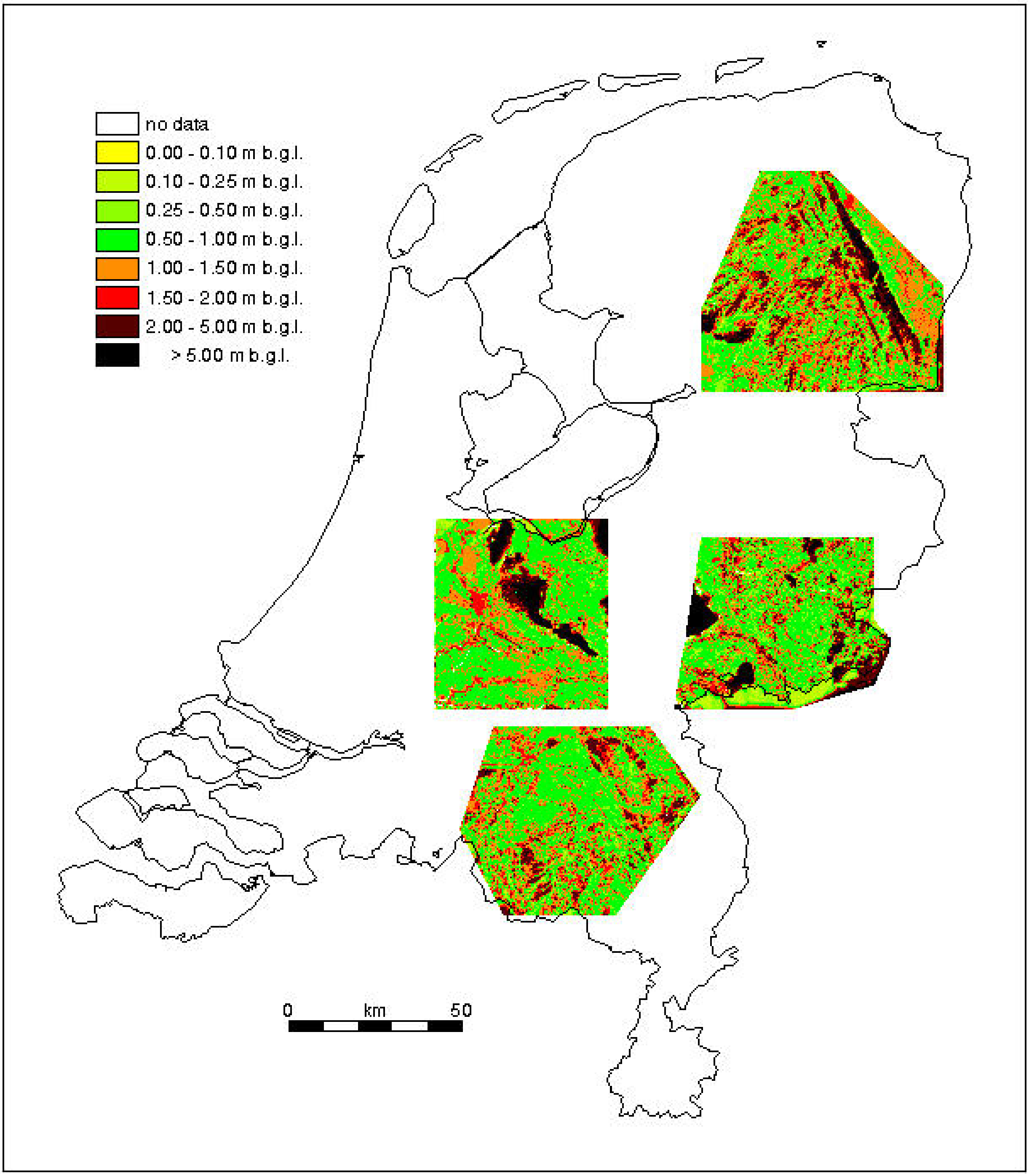


Figure 5.4. Mean Spring Groundwater table (GVG, m below ground level) for detailed-scale schematisation of LGM at four selected submodels, calculated by downscaling results of coupled LGM-SWAP model (figure 5.3) for 1988-2000 period. Most southern located is the Brabant-Oost submodel.

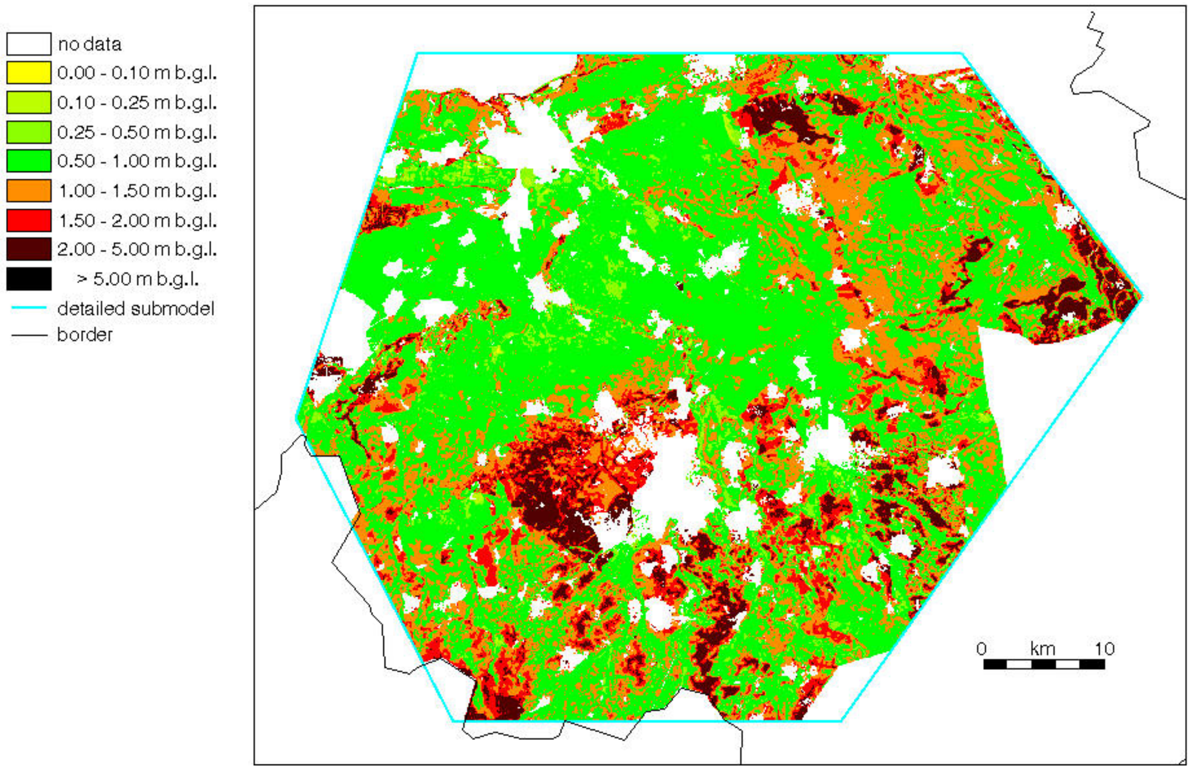


Figure 5.5. Mean Spring Groundwater table (GVG, m below ground level) assessed by field survey (RIVM, 2003b), shown for the region of the Brabant-Oost submodel. White regions represent urban areas (no field survey).

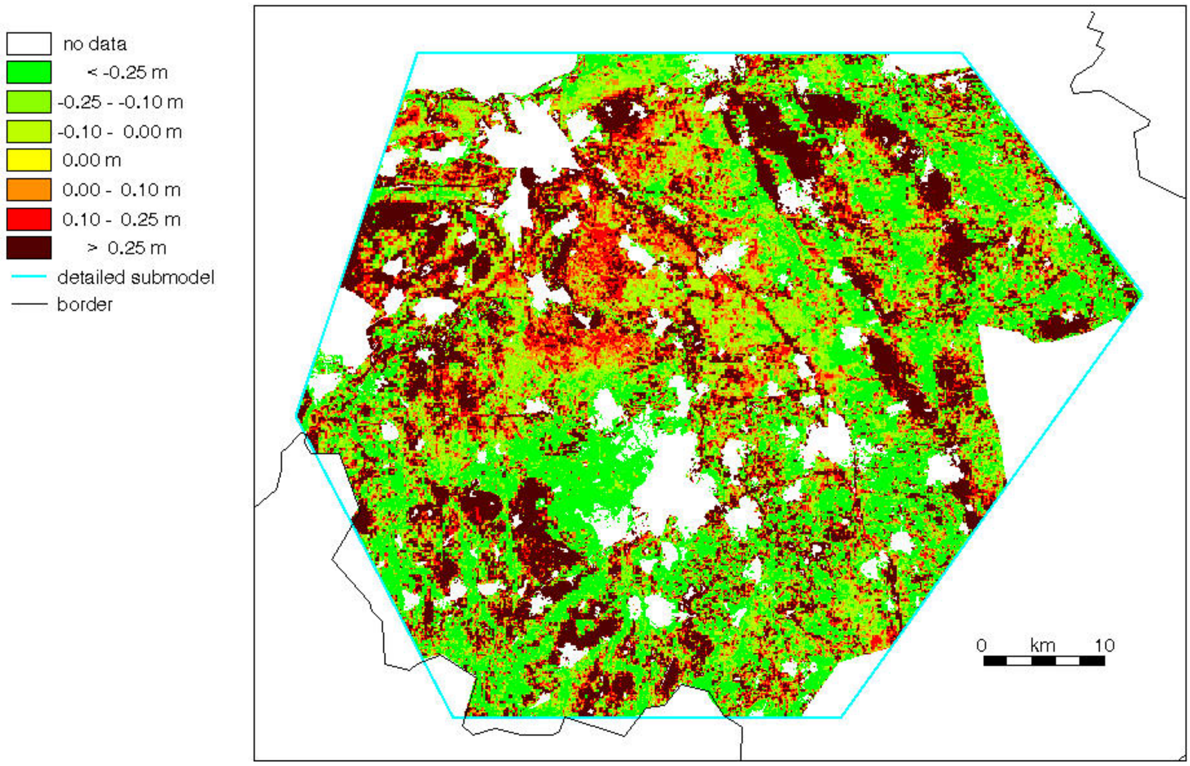


Figure 5.6. Difference (m) in Mean Spring Groundwater table (GVG), as difference between calculated GVG values and field-surveyed GVG values. White regions represent urban areas.

5.3 Summary and conclusions

The following summarising remarks are relevant with regard to the applicability and limitations of the modelling approach developed here for simulating the dynamics of the phreatic groundwater table:

1) **Spatial aspects.** The coupled LGM-SWAP model for saturated-unsaturated flow was developed and applied for an area covering about two-thirds of the Netherlands. The distance between nodes in this so-called 'coarse grid' varied between 1.25 and 2.5 km. In a subsequent modelling step, by way of zooming in into the coarse model, four separate spatially detailed (fine grid) submodels were developed in sandy soil areas (see remark 3 below).
2) **Temporal aspects.** The transient calculation by the coupled LGM-SWAP was carried out for the time period 1986-2000 (15 years, 540 decades). The first two calculation years, 1986 and 1987, are considered to be a tune-up period, required for the system to adjust from the initial boundary conditions. The remaining 13 years, 1988-2000 (468 decades), were used to produce simulation results. An integral part of the data flow between LGM and SWAP are the groundwater recharge rate and the phreatic storage coefficient, both variable in time within the 540 decades.
3) **Calculation in four detailed submodels.** The 1.25-2.5 km node distance of the coupled LGM-SWAP model (see remark 1 above) is too big for applicability in ecology-related issues, where a spatial resolution of hundreds of metres –sometimes even tens of metres– is required. Since running the coupled LGM-SWAP model at this detail for the entire country would lead to high computational requirements, an approximate method was used for the simulation at a fine-grid scale. Four detailed submodels (node distance about 250 m) were developed in sandy-soil areas by using a downscaling method: submodel Drenthe, submodel Achterhoek, submodel Utrecht, and submodel Brabant-Oost. The principle feature of the method is that only one transient LGM run –without feedback to SWAP– is carried out for the detailed model using as input the time varying values of the groundwater recharge rate and the phreatic storage coefficient. The latter two parameters were spatially downscaled –using a rather simple data assignment method– from the last-iteration output of the coupled coarse-grid LGM-SWAP model.
4) **Model output to characterise dynamics of groundwater table.** The aim of this study was to calculate four parameters commonly used to characterise the dynamics of the phreatic groundwater table, the parameters being: the Mean Highest Groundwater-table (GHG), the Mean Lowest Groundwater-table (GLG), the Groundwater Depth Class (Gt), and the Mean Spring Groundwater-table (GVG). Those parameters are derived from the simulation results of 13 years (1988-2000).
5) **Database with basic data covers most of the Netherlands.** The basic data is stored in a database covering most of the area of the Netherlands (sections 3.2 and 3.3). This basic data is used by various procedures (computer programs, GIS algorithms, etcetera) for generation of input data for LGM and SWAP, at each of the nodes of the finite element grid (chapter 3). As compared to the database for the previous LGM version, LGM3 – for

example used by Kovar *et al.* (1998)– the current database contains data different in two respects:

a) Data for geohydrology of the first (phreatic) aquifer. The LGM-SWAP coupling approach used here requires that the first aquifer is phreatic, while this was not required in LGM3. As compared to LGM3, the phreatic aquifer in the current study is considerably thinner, with transmissivities ranging between 1 and 250 m^2 d^{-1};
b) Data for the topsystem (small-scale surface waters). While the topsystem in LGM3 consisted of two drainage levels at maximum, the current topsystem is a combination of five components, those being the primary, secondary and tertiary drainage system, the tube drainage and the surface drainage (maaiveldsdrainage).

6) **Database with basic data contains data of different spatial detail and different quality.** The ultimate goal of this study is to carry out modelling for the entire area of the Netherlands. The information contained in our database was compiled using different sources. Primarily, use is made of existing national databases. For locations where no data was available, the model database was filled up by extrapolation of other data. Although most of the information is based on observations of the reality (borehole logs, groundwater head observations, weather data, etc.), use is also made of expert-judgement information. In other words, we are using data of different quality (reliability). The data collection and processing were guided by the principle purpose of the data, namely their application on <u>national</u> scale. The national-scale nature implies that the data do not have the presumption to represent the information on a spatially detailed scale. Therefore the database also contains data relevant on the scale of 1 km and even larger. On the other hand, as the opposite extreme, the database also contains data collected with a much higher resolution, even as small as 20 m. Here follows, by way of example, a description of three typical types of basic data included in the database:
   a) Examples of the data available at small spatial scale are soil use (25×25 m), soil type (20×20 m) and the location of watercourses in the Top10 vector database (detail of a few metres);
   b) Examples of the data available at large spatial scale are the depth and the thickness of aquitards, and the hydraulic conductivity of aquifers (spatial detail in the range of a few hundred metres);
   c) A special kind of basic data known only at large spatial scale is the information based on expert judgement. An example of this are the maps of the drain-tube occurrence (location in the field) and the depth of drain-tubes below ground level. Another example of expert-judgement-based information are maps with the depth and width of secondary and tertiary watercourses.
7) **Derivation of model input from information in database, for different model grid densities.** The simulations can be carried out using finite-element grid of any required density. In our case, the grid densities were 1.25-2.5 km in the coarse grid, and 250 m in the detailed grid. The model input data is derived on the basis of node influence areas, which are polygons around the grid node locations. Hence, the finer the grid, the smaller the node influence areas, and thus increasingly more spatial detail can be included into the model input. However, whether the model input data actually contains a significant

spatial detail depends on the relation between the spatial detail of the basic data and the spatial detail of the grid. Two situations can occur:

a) The basic data is spatially more detailed than the grid. An example of this is the 20×20 m polygon-based map of soil type, used for the simulation grids 1.25-2.5 km and 250 m. In such cases, the basic data has to be upscaled. In practice, the upscaling is done, for example, by generating an area-weighted averaged parameter value or a dominant parameter value in the node influence area. The dominant value is the parameter value –for example the code number of soil type– most frequently occurring in the node influence area. If the basic data is available as points or lines, this data is spatially interpolated to the node locations.
b) The basic data is spatially less detailed than the grid. An example of this are the maps of the drain-tube location and the depth of drain-tubes below ground level –often available as constant values within a region of many square kilometres– used for the grids 1.25 km and 250 m. In such cases, the basic data has to be downscaled. The downscaling is done by using the same data processing (GIS) techniques as upscaling.

The reader is once again reminded of the fact that we have used the same database as starting point for preparation of model input for any of the grid densities used in this study, including the detailed models (250 m). Specifically, one should note that though elsewhere more detailed information is available (for example in provincial databases), this detailed information was not used in our models.

8) **Procedure for downscaling of groundwater recharge and storage coefficient from coarse- to detailed-grid model.** The coupled LGM-SWAP model –by its nature– takes into account the interaction between soil-water flow in the unsaturated zone (SWAP) and the saturated groundwater flow (LGM). The feedback mechanism is caused by the dependence of groundwater recharge rate (and phreatic storage coefficient) on the depth of groundwater table, and *vice versa*. In addition, the depth of groundwater table is also a resultant of regional 3-D saturated groundwater flow (modelled by LGM). The interdependence between the unsaturated and saturated flow can be ignored only for the groundwater table deeper than a few metres, in most cases deeper than 3-4 metres. In addition to the groundwater table depth, the other factors composing the feedback mechanism most strongly are soil physical properties and land use (via the root zone). In a first modelling step, the groundwater recharge rate and the phreatic storage coefficient were calculated by means of the coupled LGM-SWAP models. Subsequently, as part of the second modelling step, we have used a simple procedure to downscale QRE and POR from the coarse-grid model to the input for the four detailed submodels. The procedure consists of straightforward copying QRE and POR from a coarse-grid node to all nodes in the detailed grid that are in the vicinity of that coarse-grid node. As a first approximation, this method is suitable. More realistic downscaling results would be achieved by taking into account the dependence of QRE and POR on –in either case– the soil type, the land use and the groundwater table depth.

6. Conclusions and recommendations

An offline coupling was established between the regional groundwater flow model LGM and a one-dimensional model of soil water flow, SWAP. With this combined model, it is possible to calculate fluxes and residence times of chemicals (particularly nutrients and pesticides) in both the unsaturated zone and the phreatic aquifer. Because the model interacts with local surface-water systems, the model provides a solid base for calculating the fluxes of these chemicals into surface waters as well. Another possible application of the model is the simulation of the seasonal dynamics of the groundwater table, which is particularly important in ecohydrological studies where the depth of the groundwater table at the start of the growing season is an important indicator of water availability. Procedures have been implemented to make the final results available at a very high spatial resolution. The combined model provides an important knowledge base for many policy evaluation studies as carried out by the Netherlands Environmental Assessment Agency. The following characteristics of the combined model are of importance for these policy oriented applications:

- both the regional groundwater flow model and the soil water flow model interact with surface water systems. For this reason, there is a vertical overlap between the two models. Because of the required vertical overlap, the actual link between SWAP and LGM is not carried out at the depth of the groundwater table, but at the depth of the uppermost aquitard. The two variables that are used for the interaction are the vertical flux at the depth of the uppermost aquitard and the phreatic storage coefficient. In order to get a consistent water balance of the phreatic aquifer in both models, the two models are tuned in an iterative procedure. This feature is important to calculate fluxes of nutrients and pesticides into surface water systems;
- both LGM and SWAP are run in transient mode, with a coupling time-step of 10-days. The dependence of the groundwater recharge rate and the phreatic storage coefficient on the variability of soil moisture in depth and time is taken into account. Correct description of these two parameters is extremely important for correctly describing the seasonal fluctuations of the groundwater table as required for ecohydrological studies;
- the simulations can be carried out at different spatial scales, using finite-element grids of any required spatial resolution. Regardless the grid size, GIS procedures convert the basic model parameters available in the LGM database into effective model input parameters. This feature is used to make the final results available at a very high spatial resolution. In a first step, the combined model was applied to a coarse grid. Once the system converged, LGM was applied at a fine grid using downscaled model parameters obtained from the final iteration with the combined model.

The performance of the combined model was tested in a regional-scale model application. Performance of the model is partly governed by the speed of convergence between LGM and SWAP. Based on the applications so far, the number of the LGM-SWAP iteration cycles required to reach convergence was 3 to 5, which is a manageable number. After convergence was reached, there was generally a good agreement between the mean depth of the groundwater table simulated by SWAP and the mean groundwater depth simulated by LGM. Also, as expected, due to the use of the Cauchy boundary condition at the bottom of the SWAP column, the long-term trend of the groundwater table did not show a trend in time. Despite all this, the current coupling procedure suffers from a number of drawbacks. First, the groundwater dynamics tended to be underestimated by LGM due to overestimation of the phreatic storage coefficient. Also, the water balance, when comparing LGM and SWAP, was not closed. In particular cases there were large deviations between LGM and SWAP. These deviations occurred in those situations where there is little interaction between the two models (deep groundwater systems, high resistance of the confining aquitard) and in situations with large left-over fluxes (rivers and groundwater extractions). A new coupling procedure, which guarantees a closed water balance and a better calculation of the phreatic storage coefficient is now operational and tested. This new procedure is described shortly in appendix 1 and will be further described in a scientific paper.

Summarising it can be stated that the combined model provides a solid knowledge base and valuable tool for future policy evaluation studies. Due to the generic nature of the model, the model can provide the hydrological inputs required by different studies, such as the evaluation of nutrient abatement plans and ecohydrological studies. Moreover, after the implementation of a grid-computing system at RIVM, the processing time has decreased dramatically.

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Appendix 1 Improved method for coupling of LGM and SWAP

The LGM-SWAP coupling method discussed in this report was applied on a national scale (chapter 5). As explained in section 4.6 (item 3), the procedure, which was used to derive the phreatic storage coefficient from SWAP results yielded only a rough approximation of the actual variation of the 'real' phreatic storage coefficient, required by LGM. Correct estimation of the storage coefficient is extremely important to simulate correctly the groundwater dynamics with LGM, so we decided to implement an improved method for the storage coefficient calculation (Pastoors *et al.*, 2004). The improved coupling method was developed in the framework of a Dutch national project aiming at the comparison of various techniques for the coupling of saturated and unsaturated groundwater models, applied for the pilot study area Beerze-Reusel ('consensus working group hydrology').

Adaptation of coupling approach

The major difference between the former coupling approach and the newly developed approach pertains to the derivation of the phreatic storage coefficient. As described at page 23, the phreatic storage coefficient was calculated over the entire unsaturated column (equation 2.6). In the newly developed approach, the storage coefficient is calculated from the water balance of the saturated zone in SWAP (see also figure A1.1):

$$S(t)\Delta\varphi(t) = (q_{bot}(t) + q_{re}(t) - q_{dra}(t))\Delta t \qquad \text{(A1.1)}$$

where S ($m^3\ m^{-3}$) is the phreatic storage coefficient, φ (m) is the phreatic groundwater table, q_{bot} ($m\ d^{-1}$) is the bottom boundary flux for SWAP, q_{re} is ($m\ d^{-1}$) is the groundwater recharge flux and q_{dra} ($m\ d^{-1}$) is the local drainage flux. The disadvantage of this procedure is that the phreatic storage coefficient can become extremely small in the case of small changes of the groundwater table (risk of dividing by zero). In these cases, convergence between SWAP and LGM will become extremely slowly. It was therefore decided to regularise the phreatic storage coefficient. The actual time-dependent phreatic storage coefficient was replaced by a constant phreatic storage coefficient equal to the storage at full saturation of the soil column, θ_{sat} ($m^3\ m^{-3}$). Notice that due to this adaptation a water balance error is created, which is equal to $\Delta t(\theta_{sat}-S(t))$. To assure that the water balance remains closed, the actual groundwater recharge rate in equation A1.1 is therefore replaced by a modified groundwater recharge rate. This modified groundwater recharge rate can be calculated from the simplified water balance of the saturated zone:

$$\theta_{sat}\Delta\varphi(t) = (q_{bot}(t) + q_{\mathrm{mod}}(t) - q_{dra}(t))\Delta t \qquad \text{(A1.2)}$$

where q_{mod} ($m\ d^{-1}$) is the modified groundwater recharge rate. The modified groundwater recharge rate and the regularised phreatic storage coefficient are both used as input for LGM. The most important advantages of using these modified variables are:

- the water balance is calculated in a consistent way in both SWAP and LGM, assuring that the water balance of the entire coupled model is closed;
- q_{mod} shows less variability in time than q_{re}. This assures faster convergence of the coupling procedure.

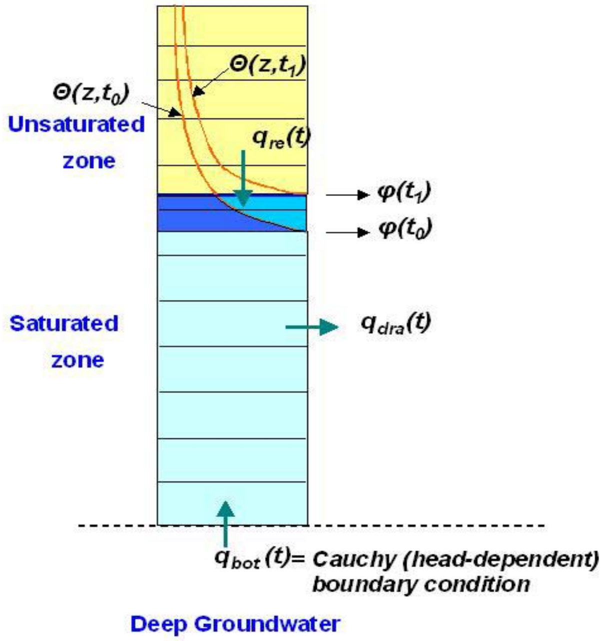

Figure A1.1. Water balance of the saturated zone in SWAP.

Summary of results for the Beerze Reusel study area

Within the framework of the above mentioned project of the consensus working group, LGM-SWAP was applied to the Beerze Reusel catchment (see chapter 4 for a description of the study area). The application will be described in a separate report, here a brief summary of the most important results are given.

Figure A1.2 shows how the system converges. The figure shows that six iteration cycles were needed to obtain full convergence between SWAP and LGM. Figure A1.3. shows the phreatic groundwater table after six iteration cycles. It can be seen that there is a good agreement between the water table simulated by SWAP and the water table simulated by LGM, both with respect to the long-term trends as with respect to the seasonal dynamics.

We have also compared various water-balance terms of LGM and SWAP. Also here, we found a good agreement. We compared the following two fluxes:

– the topsystem flux, which is the flux between the phreatic aquifer and the local drainage systems (section 2.1). The values, as spatial averages for the entire model area, are 203 mm a^{-1} from LGM, and 201 mm a^{-1} from SWAP;
– the flux across the aquitard separating the first and second aquifers in LGM, which is equivalent to the flux across the bottom of the SWAP column. The values, as spatial averages for the entire model area, are 50 mm a^{-1} from LGM, and 52 mm a^{-1} from SWAP.

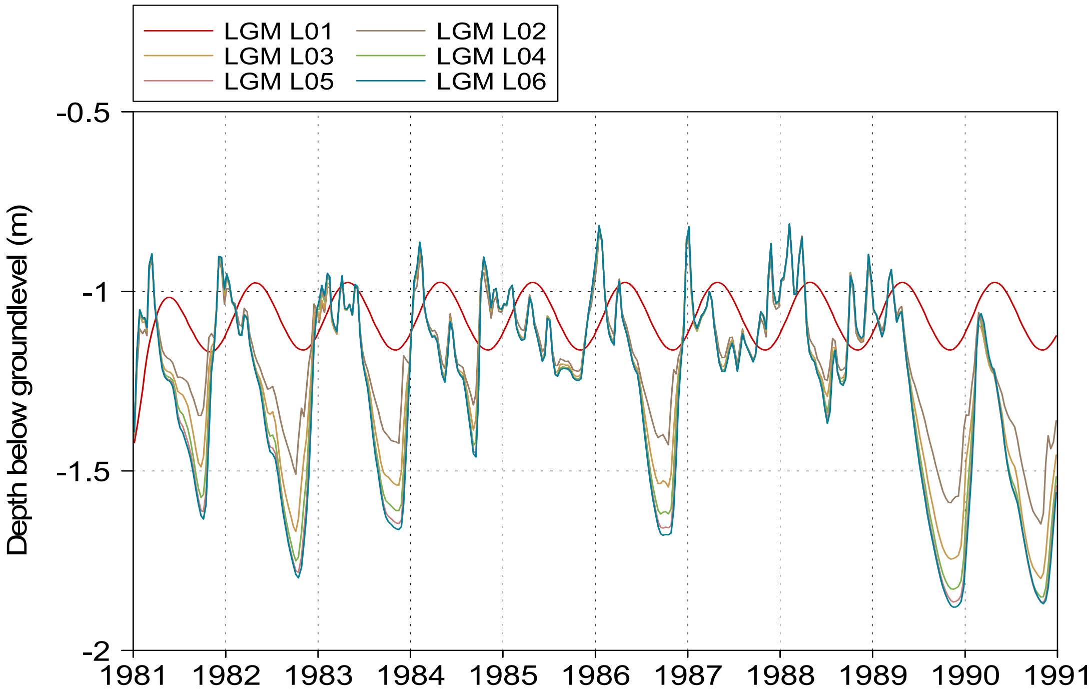

Figure A1.2. Change of phreatic water table (10-days average) at a selected during LGM-SWAP convergence (6 iterations cycles nuber L01 through L06).

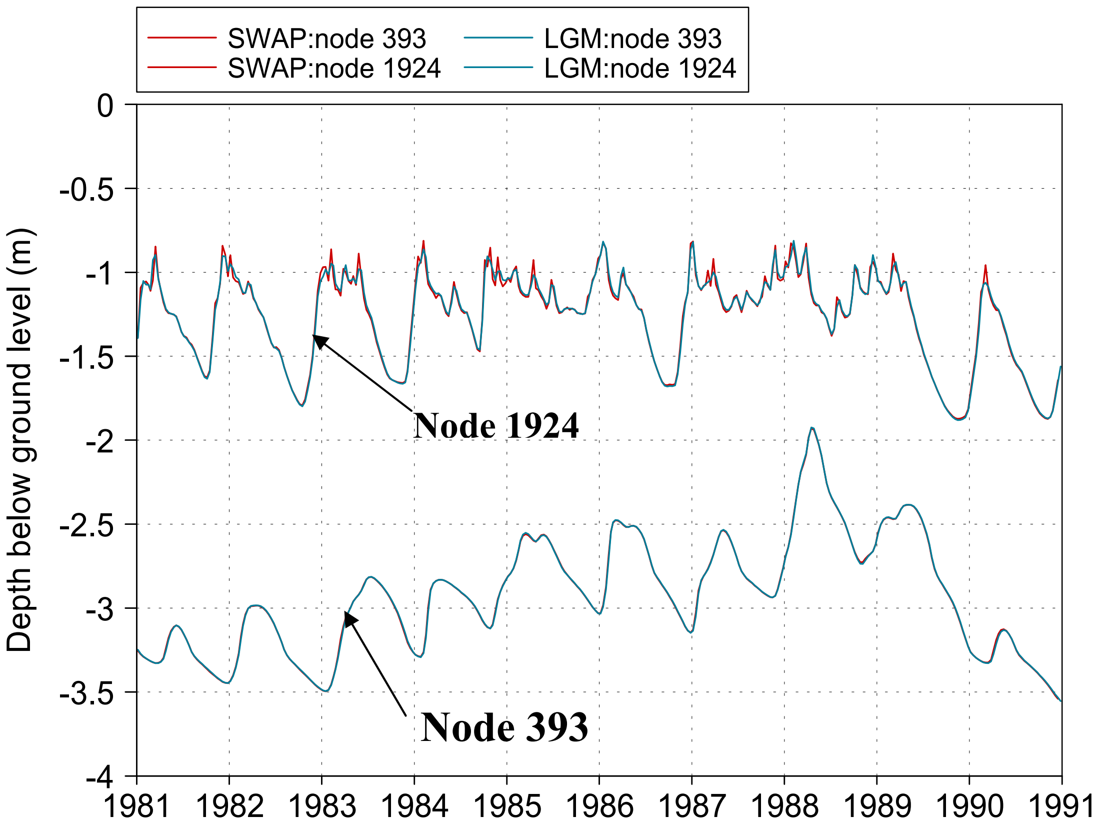

Figure A1.3. Phreatic water table simulated by SWAP and LGM at two selected nodes within the Beerze Reusel study area. Notice that the lines for node 393 appear as one line.

Conclusions

The new coupling procedure guarantees a closed water balance between SWAP and LGM and a better calculation of the phreatic storage coefficient. The most important improvement is that there is now a good agreement between the water table simulated by SWAP and the water table simulated by LGM, both with respect to the long-term trends as with respect to the seasonal dynamics. As a final conclusion, it can be stated that a tool is now operational for providing the hydrological base for both ecohydrological studies and water quality assessments.

Reference

Pastoors, M.J.H., Kovar, K., Stoppelenburg, F.J., Tiktak, A., Leijnse, A. 2004. Interaction between transient saturated and unsaturated groundwater flow: Off-line iterative coupling of LGM and SWAP. Poster presented at the Int. Conf. FEM_MODFLOW held 13-16 September 2004 in Karlovy Vary, Czech Republic.