Deltares

Combined groundwater – surface water modeling with a lumped hydrological model

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Abstract

The Lowland Groundwater-Surface water Interaction model (LGSI-model) is a lumped model concept which describes changes in storage via changes in the average groundwater depth and spatial variation in groundwater depth. These characteristics of the groundwater depth are used to calculate discharge. The spatial distribution of groundwater depths are described by means of a normal distribution that is related to the average groundwater depth within the catchment. The LGSI-model was first tested by Van der Velde et al. (2009) in the Hupsel brook catchment ($6km^2$) and showed very promising results. The goal of the study described in this report is to apply the theory and model concepts developed by Van der Velde et al. (2009) to a larger catchment with a more complex geomorphology. For this purpose the Drentsche Aa catchment was selected.

To build the lumped LGSI-model, the relations between groundwater depth distributions and fluxes can be calculated based on a spatially distributed groundwater. In this case, the spatially distributed model MIPWA, that includes the Drentsche Aa catchment, was used. Based on the MIPWA model results on a daily basis for the period 1989-2001, relations between storage above the surface (negative groundwater depths) and water fluxes between groundwater and surface water (e.g. stream discharge, tube drain discharge, saturated overland flow, evapotranspiration) could be formulated. These relations formed the basis of the LGSI-model of the Drentsche Aa Catchment. To improve the representation of the discharge generating processes within the catchment, the LGSI-model of the Drentsche Aa catchment was calibrated to a measured discharge series of the period 1989-2001 using the GLUE analysis.

Due to the variations in the geomorphology of the catchment, the Drentsche Aa catchment had to be divided into two different areas. One low area with shallow groundwater tables reaching up to the surface and high, very dry areas where the groundwater tables never reach the surface. These two area types, or reservoirs, could be described by different statistical distributions: in the low areas, a normal distribution was valid, while in the high areas groundwater depth distributions were described by a gamma distribution. Both areas were coupled using a Darcy based equation which was a modification to the original model concept of Van der Velde et al. (2009).

Results of the LGSI-model of the Drentsche Aa catchment were very promising and the Nash-Sutcliffe model efficiency for discharge and groundwater depth simulation for both low and high areas were respectively 0.76 (discharge), 0.78 (groundwater depth low area) and 0.87 (groundwater depth high area) over the calibration period 1989-2001 (all at a daily time steps). Peak discharges were slightly underestimated by the model, which is the result of inaccurate simulation of the groundwater depth, whereas recessions and periods with small discharge were modelled with high accuracy. A detailed analysis of the model stability was performed, by extending the model simulation of discharge to the period 1980-2010 (Nash-Sutcliffe discharge 0.64). The LGSI-model was also tested on a hourly time step to determine if the model could have a good model performance on a smaller timescale (Nash-Sutcliffe discharge 0.75).

The results of the fast calibration using the GLUE analysis can be useful for evaluation of model parameters of the spatially distributed groundwater model. Since this type of calibration cannot be done for spatially calibrated models without very long calculation times, the LGSI-

model could be used as a tool for calibration of these models. Another interesting feature of the LGSI-model concept is that it divides the total discharge of the catchment into its separate components (groundwater exfiltration in rivers, saturated overland flow, drainage). This offers the possibility to analyse the composition of peak discharge or determine the relative contributions of the discharge components throughout the year.

It was concluded that the LGSI-model generated very good simulations of discharge and groundwater depths in the Drentsche Aa catchment. Due to these simultaneous and rapid model simulations of groundwater depth, storage and discharge, the LGSI-model concept provides additional insight in the discharge behaviour for a variety of groundwater depth distributions and parameter values. Moreover, the LGSI-model shows that knowledge of the groundwater system and the groundwater-surface water interaction processes that occur in a catchment is very useful, if not crucial, for good simulation and prediction of stream discharge of a catchment.

Table of contents

Appendices

1 Introduction

1.1 Background

Groundwater discharge into surface waters in lowland catchments is driven by local gradients of the groundwater table. Many processes affect these gradients, such as precipitation, evapotranspiration, and ditches and drains which run dry (De Vries, 1994; Tiemeyer et al., 2007; Wriedt et al., 2007). In addition, Seibert et al. (2003) showed that the interaction between saturated and unsaturated zone amplifies the precipitation signal towards the groundwater and hence is also a key process in the interaction between groundwater and surface water.

It has been suggested that an accurate simulation of saturated and unsaturated zone is required in order to have an accurate simulation of discharge (Seibert et al., 2003). Seibert and McDonnell (2002) also state that it is more important to capture all processes in a catchment accurately than focussing on only one discharge of groundwater. However, the interaction between groundwater and surface water is often a very difficult process to capture in models, due to time delay affect of the unsaturated zone to the recharge of the saturated zone (Brunner et al., 2010; Jolly and Rassam, 2009). The high temporal and spatial variability in surface waters also increase the complexity of modelling of surface and groundwater interaction (Westhoff et al., 2007). In groundwater modelling, the outflow to the surface water is determined by boundary conditions like a prescribed ditch level, while in surface water modelling groundwater heads are set as fixed heads. When groundwater is modelled, this is a reasonable choice, but when outflow from the catchment is modelled, the interaction between groundwater and surface water will have a very large influence on the modelled discharge, e.g. precipitation response of the discharge and width of contributing streams (Becker et al., 2004; Binley, 2005; Jolly and Rassam, 2009; Smits and Hemker, 2004). Since the discharge is highly related to the total storage in the catchment, the assumption of fixed heads of the groundwater table will give no accurate simulations of the discharge and different solutions are required.

Groundwater models like MODFLOW (Harbaugh et al., 2000) are in some situations very poor in simulating surface water discharge, since they are not developed for modelling this type of fluxes (Brunner et al., 2010). Lumped conceptual models on the other hand are not designed to simulate the complex spatial behaviour of groundwater and will calculate only one groundwater head for the entire catchment (Beven, 2001). The spatial patterns of groundwater heads get lost in a lumped hydrological model, which is simplified into a limited number of reservoirs. Van der Velde et al. (2009) proposed a lumped hydrological model that uses a distribution of groundwater heads for the simulation of discharge. The distribution of groundwater heads is used to preserve part of the spatial information from the catchment in the lumped model, instead of only one average groundwater head. In their study, the authors investigated which statistical distribution of groundwater heads would give the best representation of the actual groundwater heads in a particular catchment. As study area, they used the Hupsel brook catchment situated in the Netherlands, in the province of Gelderland near the border of Germany. The Hupsel brook catchment is a very small catchment of six km^2 and boundary flow over the borders of the catchment is absent. The authors showed that a normal distribution with a standard deviation related to the mean groundwater depth was the best option to simulate the distribution of groundwater heads. They also showed that the discharge of the Hupsel brook catchment could be modelled with this new lumped hydrological model, with high model efficiencies for both discharge and groundwater heads.

Although this was a very promising result, it remained uncertain if this model approach could also be used in larger catchments with more complex catchment structures and catchment response to precipitation events.

In this study, the conceptual lumped hydrological model of Van der Velde et al. (2009) was tested for a catchment with a very different physical catchment structure. For this purpose, the Drentsche Aa catchment was selected which is situated in the Northern part of the Netherlands in the province of Drenthe. The Drentsche Aa catchment is approximately 40 times the size of the Hupsel brook catchment and has a more hilly surface, consisting of ice-pushed ridges and valleys with peat. For this area a detailed groundwater model is available and calculations from this model are validated by groundwater level observations (Hoogewoud, 2009). The focus was to find relations which could describe the reaction of discharge through ditches, drains and overland flow as a function of the spatial patterns of groundwater depth. The second goal of the research was to see if these relations could be used to simulate the groundwater levels and discharge in this catchment.

1.2 Objectives

The main objective of this study is to examine if the conceptual hydrological model developed by Van der Velde et al. (2009) could be used to model groundwater and surface water in a large catchment with complex geomorphology. This leads to the following research questions:

- Which statistical distribution is best suited to describe the groundwater depths of the Drentsche Aa catchment?
- Is it possible to capture the complex dynamic behaviour and spatial patterns of the distribution of groundwater depths for a catchment with one mathematical equation?
- Is it possible to simulate the discharge and groundwater depths of the Drentsche Aa using these relations between average groundwater depth of the catchment and different components of the discharge (e.g. groundwater exfiltration in streams, drainage discharge and overland flow)?
- What is the sensitivity of the model to changes in parameters and time series of precipitation, evaporation and discharge?
- Is it possible to use the conceptual hydrological model in scenario studies, discharge forecasting or coupling with spatially distributed surface water model or use the output as input for other studies (e.g. water quality)?

1.3 Approach

The approach of this study is given by a schematic overview in Figure 1.1. Section numbers in Figure 1.1 indicate the sections in which a more detailed explanation about the data or procedure is given.

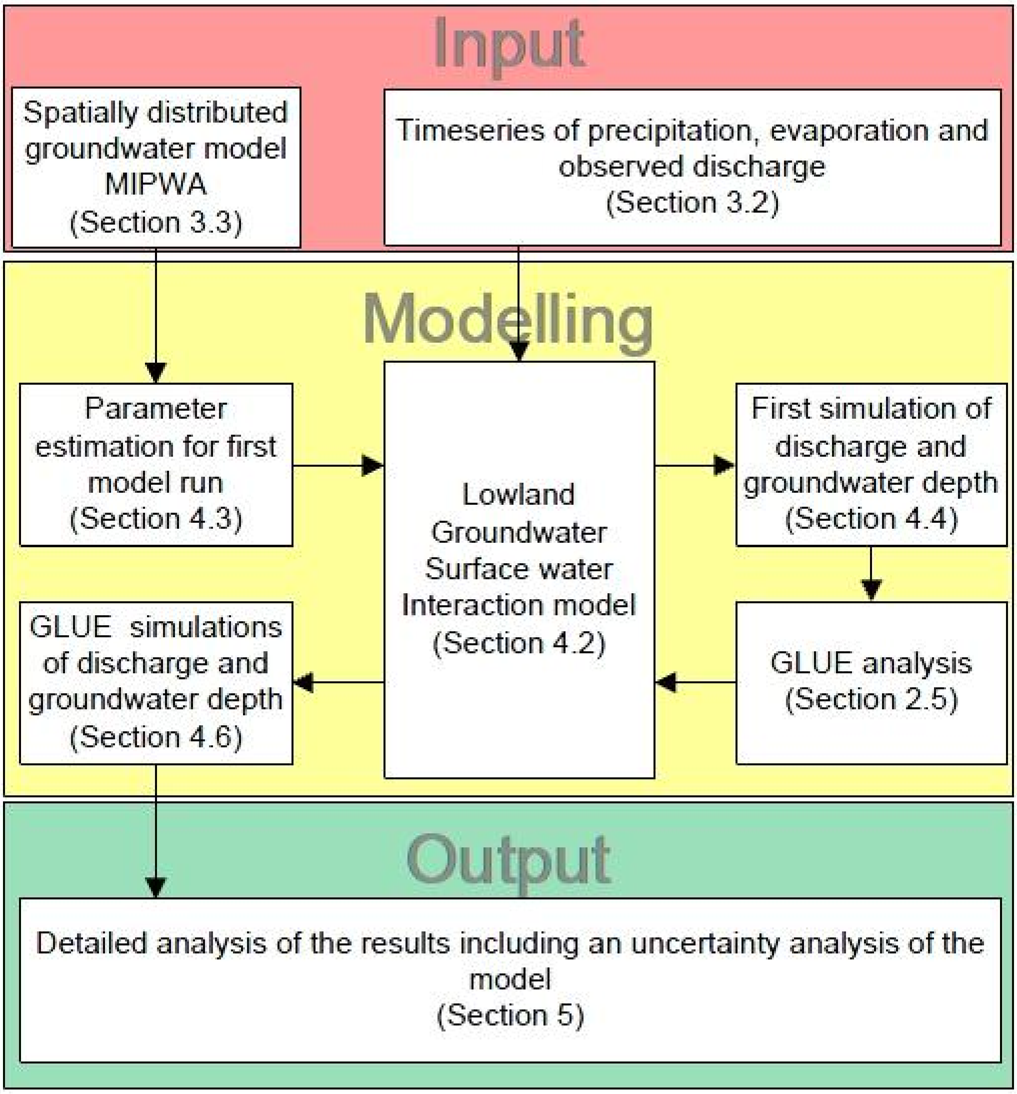

Figure 1.1 Schematic overview of the research approach of this study. Section numbers in each block indicate which section of this report describes the action or data given in that block.

1.4 Outline

In Chapter 2 the theory of this study is explained. In this, the focus lies on the conceptual model of Van der Velde et al. (2009) and the relations used in the model. A description of the study area and forcing data is given in Chapter 3. The results are presented in Chapter 4, followed by detailed analysis including a sensitivity analysis in Chapter 5. A discussion on the performance of the LGSI-model is presented in Chapter 6. In Chapter 7 the conclusions is given and in Chapter 8 recommendations of this study are listed. Acknowledgements and references can be found in respectively Chapter 9 and Chapter 10, followed by the Annexes.

2 Theory

In this chapter, the general theory of the Lowland Groundwater Surface water Interaction model (LGSI-model) is discussed. First a summery of the conceptual hydrological model developed by Van der Velde et al. 2009 and Van der Velde et al. (2010) is given. For a full description of this model concept including all equations we refer to Van der Velde et al. (2009). Additionally, the techniques to determine the model efficiency and sensitivity analyses are also explained in this chapter.

Section 2.1 gives an introduction to statistical distributions to describe the groundwater heads of a catchment. The setup of the conceptual hydrological model is described in Section 1.1 and the equations of the model are given in Section 2.3. The efficiency of the model was evaluated with 3 different criteria which are described in Section 2.4. Calibration of the LGSI-model was done with a GLUE analysis (Section 2.5) as well as a sensitivity analysis of the model to changes in parameters or input variables.

2.1 The Lowland Groundwater-Surface water Interaction model

The Lowland Groundwater-Surface water Interaction model (LGSI-model) was developed by Van der Velde et al. (2009) to describe the discharge of the Hupsel brook catchment. The LGSI-model is a conceptual hydrological model which describes the entire catchment by means of a single reservoir. The model was developed to give a better simulation of discharge based on groundwater depths which are determined by relations derived between groundwater depths and discharge. To keep the spatial information of a spatially distributed hydrological model, the groundwater depth is not given by one single average value, but by a distribution of groundwater depths dependent on the average groundwater depth.

The LGSI-model is based upon the water balance where the total change in storage is related to changes in groundwater depth distribution. The statistical distribution of groundwater depths is determined by the average groundwater depth which has an unique relation with the standard deviation. This distribution is used to define the storage for the three compartments of the LGSI-model. The three compartments are: storage in the saturated zone, unsaturated zone and on the surface. Discharge can only occur in the model if there is storage on the surface, which means that the groundwater must be above the soil surface to become discharge. This can happen in ditches where water is above the soil surface or as overland flow. The discharge from the surface is composed of overland and groundwater flow and direct runoff from precipitation which falls in ditches or ponds. Another type of outflow from the catchment is discharge through drains. This type of discharge will come from storage in the saturated zone only since drains are situated below the surface. When the groundwater depth is below the drain depth, the drain discharge will become zero.

2.2 Statistical distributions of groundwater depth

Van der Velde et al. (2009) assumed that within a catchment each stored volume of water corresponds to a unique spatial distribution of groundwater depths. This relation between storage and the distribution of groundwater depth was quantified by a unique relation between the average groundwater depth and the standard deviation of the groundwater depth.

Van der Velde et al. (2009) used the groundwater depth (u) in meters relative to the surface to ensure that regional trends in surface elevation do less affect the shape of the distribution describing the groundwater table and to ensure a direct relation between surface elevation and the groundwater table. The standard deviation of u depends on the wetness conditions of the catchment. Under extremely wet conditions, the groundwater level has the tendency to follow the deviation of the soil surface and therefore the standard deviation of groundwater depths (σ_u) was very small. under dry conditions, the groundwater level also followed the soil surface because evapotranspiration reduction occurred for deep groundwater tables and consequently σ_u was decreased. In the intermediate situation the groundwater table was strongly affected by ditches and tube drains and thus only partly followed the soil surface. This led to an elevated standard deviation. Thus σ_u can be given as function of the average groundwater depth $\langle u(t)\rangle$, Van der Velde et al. (2009) proposed the following relation:

$$\sigma_u = (\sigma_{\max} - \sigma_{\min}) \cdot e^{-\left(\frac{\langle u(t)\rangle - u_{sd\max}}{b}\right)^2} + \sigma_{\min} \tag{3.1}$$

where $\sigma_{\max}$ and $\sigma_{\min}$ respectively are the maximum and minimum standard deviation of u, $u_{sd\max}$ is the groundwater depth at $\sigma_{\max}$ and b is the shape parameter of the function.
With Equation (3.1) the distribution of u is calculated for any given moment in time with:

$$f_u(t) = f(\langle u(t)\rangle, \sigma_u(t)) \tag{3.2}$$

where $f_u(t)$ is the normal distribution of u as a function of $\langle u(t)\rangle$ and $\sigma_u(t)$. A normal distribution was assumed by Van der Velde et al. (2009), based on the assumption that when a large number of separate fields (all with their own distribution) is regarded the distribution of all fields would become a normal distribution (central limit theory, Rice, (1995)). This normal distribution of groundwater depths can be used to determine relations between processes (e.g. discharge or overland flow) and average groundwater depth.

2.3 Storage and flux expressions of the hydrological model

In Section 2.1, Equation (3.1) was derived to calculate the distribution of groundwater depths ($f_u(t)$) at any given t. In the Lowland Groundwater Surface water Interaction model (LGSI-model), this distribution was used to determine the amount of storage and the fluxes which depend on the storage. In general the change in storage of the LGSI-model is given by:

$$\frac{d}{dt}S_{sat} + \frac{d}{dt}S_{unsat} + \frac{d}{dt}S_{surf} = P(t) - E(t) - Q(t) \tag{3.3}$$

where $\frac{d}{dt}S_{sat}$, $\frac{d}{dt}S_{unsat}$ and $\frac{d}{dt}S_{surf}$ are respectively the change in storage of the saturated zone, unsaturated zone and surface water. $P(t)$ is the precipitation and $E(t)$ is the actual evapotranspiration at time t. $Q(t)$ is the outflow of water out of the catchment, which is composed of drainage, overland and groundwater flow to the ditches at time t.

Storage in all three compartments of the LGSI-model can be calculated via the function that describes the behaviour of the groundwater depth distribution (Equation (3.2)). The change in the storage of the saturated zone is given by:

$$\frac{d}{dt}S_{sat}(t) = -\theta_s \frac{d}{dt}\left(\int_0^{-\infty} f_u(t) \cdot u\,du\right) \tag{3.4}$$

where θ_s is the average porosity of the soil. To calculate the change in storage all groundwater depths from the surface to an infinite depth are used. The change in the unsaturated zone is given by:

$$\frac{d}{dt}S_{unsat}(t) = \theta_s \frac{d}{dt}\left(\int_0^{\infty} f_u(t) \int_0^{u} \left[1 + (\alpha h)^n \right]^{\frac{1}{n}-1} dh du \right) \quad (3.5)$$

where α and n are the Van Genuchten parameters Van Genuchten (1980). These parameters are correlated to the soil type and the capacity of this soil to retain water. From Equation (3.4) and (3.5) it can be derived that a positive change in $S_{sat}(t)$ will result in a negative change in $S_{unsat}(t)$. When the groundwater depth is above the soil surface, $S_{unsat}(t)$ will become zero since the integral from 0 to u will become zero. In these situations, there will be storage above the surface of which the change is given by:

$$\frac{d}{dt}S_{surf}(t) = -m \frac{d}{dt}\left(\int_{-\infty}^{0} f_u(t) u du \right) \quad (3.6)$$

where m is the fraction water of the total volume of negative groundwater depths stored in ditches and ponds. Storage on the surface (S_{surf}) for a particular location will only occur when there is no unsaturated zone in this location, since the groundwater depth must be negative for surface storage and therefore have a saturated zone up to the surface. This also means that perched water table are not included in the model concept, as well as ponding on the surface due to low infiltration capacities of the topsoil.

At any given t, there is a distribution of groundwater depths depending on the average groundwater depth ($\langle u(t) \rangle$) by equation (3.2). Therefore, it is possible to have both storage in S_{surf} and S_{unsat} in the catchment at any given t but never at the same location.
At any given t, the total discharge from the catchment is given by:

$$Q_{tot}(t) = Q_{dr}(t) + Q_{ov}(t) + Q_{gr}(t) + P_q(t) \quad (3.7)$$

where $Q_{dr}(t)$ is the drainage flow, $Q_{ov}(t)$ is the overland flow and $Q_{gr}(t)$ is the groundwater flow. Every different flux depends on the distribution of groundwater depths ($f_u(t)$). In the LGSI-model, the drainage flow is given by:

$$Q_{dr}(t) = \frac{A_{dr}}{r_{dr} A_{tot}} \int_{F_u^{-1}\left(A_s / A_{tot} \right)}^{D_{dr}} f_u(t) \cdot (D_{dr} - u) du \quad (3.8)$$

where A_{tot} is the total catchment size and A_{dr} is the area of the catchment with drains. The average drain depth is denoted by D_{dr} and r_{dr} is the average drain resistance $F_u^{-1}\left(A_s / A_{tot} \right)$ is the fraction of the area which is wet, but does not have any drains (e.g ditches and ponds).
Discharges by overland flow and groundwater flow are both driven by negative values of u and can therefore occur at the same time and same location. The combined discharge of overland and groundwater flow is given by:

$$Q_{ov}(t) + Q_{gr}(t) = \frac{m-1}{R_{tot}} \int_{-\infty}^{0} f_u(t) u du \quad (3.9)$$

where, m is the fraction of the total catchment which has ditches and ponds and R_{tot} is the total resistance of overland and groundwater flow. Because in this study, it will be important that the total discharge can be split up in different components, we decided to divide the flow via overland and groundwater in two different fluxes. Hereby, it will be easier to determine the fraction of overland flow of the total discharge and when, for example, the water quality of the catchment is modelled, all different discharge components could have their own nutrient concentrations. This will result in a better simulation of the water quality since every type of discharge has a different nutrient load. The equation for the overland flow is now given by:

$$Q_{ov}(t) = \frac{\mathrm{m}-1}{\mathrm{R_{ov}}} \int_{\min(F_u^{-1}\left(\mathrm{A_s}/\mathrm{A_{tot}}\right),0)}^{0} f_u(t)u\,du \tag{3.10}$$

where, R_{ov} is the resistance of the overland flow and $\min(F_u^{-1}\left(\mathrm{A_s}/\mathrm{A_{tot}}\right),0)$ is the term which divides the negative part of u in a fraction with groundwater flow and a fraction with overland flow. Therefore, the groundwater flow is given by:

$$Q_{gr}(t) = \frac{\mathrm{m}-1}{\mathrm{R_{ex}}} \int_{-\infty}^{\min(F_u^{-1}\left(\mathrm{A_s}/\mathrm{A_{tot}}\right),0)} f_u(t)u\,du \tag{3.11}$$

where, R_{ex} is the resistance of the catchment to groundwater flow.

The last two terms which determine the changes in storage, are the changes generated by the precipitation and evaporation. The precipitation which leads to recharge is given by:

$$P_r(t) = P_{tot}(t)\int_{0}^{\infty} f_u(t)du \tag{3.12}$$

where, $P_{tot}(t)$ is the total precipitation on time t. The rest of the precipitation will fall on areas with ditches and ponds and is given by:

$$P_q(t) = P_{tot}(t)\int_{-\infty}^{0} f_u(t)du \tag{3.13}$$

This precipitation will be added to the discharge and will not lead to recharge of the catchment. The potential evaporation will only be reduced when u is below a certain threshold and is given by:

$$E_{act}(t) = E_{pot}(t)\int_{0}^{\mathrm{E_m}} f_u(t)du \tag{3.14}$$

where E_m is the threshold value in meters below the surface.

2.4 Calculation of the model efficiency

The R^2 (Steel and Torrie, 1960) and the Nash-Sutcliffe (Nash and Sutcliffe, 1970) model efficiency are commonly used to indicate the model performance for hydrology models (Torfs, 2006). Another parameter to calculate model efficiency was developed in this research and will be explained in detail in this Section. The R^2 is very commonly used and widely accepted method to estimate model efficiency. The R^2 is given by:

$$R^2 = \left(\frac{n\sum Q_{obs}Q_{sim} - \sum Q_{obs}\sum Q_{sim}}{\sqrt{\left[n\sum Q_{obs}{}^2 - \left(\sum Q_{obs}\right)^2\right]\left[n\sum Q_{sim}{}^2 - \left(\sum Q_{sim}\right)^2\right]}} \right)^2 \tag{3.15}$$

Where Q_{obs} is the observed discharge, Q_{sim} is the modelled discharge and n is the number of observations. The R^2 only gives an indication of the goodness of fit of the fluctuations in the modelled discharge. When the simulated discharge is biased the R^2 can still be very high, but may not have the exact values of the observed discharge since R^2 only account for the fluctuations. The values of R^2 have a range between -1 and 1, where -1 indicates a negative correlation and 1 a positive correlation.

The Nash-Sutcliffe model efficiency (NS_{eff}) also accounts for the bias in the simulated discharge. The Nash-Sutcliffe model efficiency is given by:

$$NS_{eff} = 1 - \frac{\sum_{t=1}^{n}\left(Q_{obs}(t) - Q_{sim}(t)\right)^2}{\sum_{t=1}^{n}\left(Q_{obs}(t) - \overline{Q_{obs}}\right)^2} \tag{3.16}$$

where n is the number of observations and $\overline{Q_{obs}}$ is the average observed discharge. The NS_{eff} has a range from -∞ to 1, where 1 is a excellent fit and any value below 0 is worse than using the mean observed discharge as model.
The last parameter to estimate the model efficiency is developed for this study. The parameter is based upon the equation for the NS_{eff}, but modified to use with a possible time lag of x time steps. The formula for this parameter is given by:

$$NS_{lag} = 1 - \frac{\sum_{t=1+x}^{n-x}\min\left(\sum_{t-x}^{t+x}\left[Q_{obs}(t) - Q_{sim}(t)\right]\right)^2}{\sum_{t=1+x}^{n-x}\left(Q_{obs}(t) - \overline{Q_{obs}}\right)^2} \tag{3.17}$$

where x can be any value between 0 and $n/2 - 1$. This new parameter is developed to account for problems with the NS_{eff} when daily data is fitted. Because the exact timing of a precipitation event is unknown and could vary within 24 hours, the corresponding discharge peak could vary the same 24 hours. The model however, will simulate the discharge in the same time step as the precipitation event took place, while in reality this does not always happen. For example, when a precipitation event takes place late in the evening, the corresponding discharge peak will be the next day. Due to the fact that the peak is modelled incorrect by one day the NS_{eff} will decrease, while in reality the model may have a good performance but a time offset of x days. When simulations are done on a daily basis, a value of x equals 1 is a good estimate for possible time lags in discharge simulation caused by the model.

2.5 The GLUE analysis

The GLUE analysis was developed by Beven and Freer (2001) and was based upon the work of Spear et al. (1994). Since the GLUE analysis has recently been applied successfully in a number of hydrological studies (e.g. De Louw et al., 2011; Hassana et al., 2008; Van Huissteden et al., 2009) it is used in this study for the calibration of parameters and sensitivity analysis of the LGSI-model. The method is based upon the theory that there is no unique combination of model parameters that leads to a good model simulation. Each possible set of feasible parameter combinations gives more insight in the possible behaviour and performance of the model, than in a situation when only one optimal combination is used. The possible parameter combinations are found by calculating the model performance for random sets of parameters. These random sets are drawn from a uniform distribution with a predefined minimum and maximum value of each parameter, which are based on expert knowledge of the local catchment conditions. The parameter combinations for which the model performance exceeds a certain minimum performance are dubbed “behavioural”. These behavioural sets of parameters all result in models with good model performance. If a sufficient number of parameter sets are found the spread within possible results (bandwidth) can be determined. When the bandwidth is small and observed values are (nearly) always within the bandwidth the GLUE analysis is very successful. On the other hand when the bandwidth is very large this often is the result of a low model performance. The bandwidth generated with the GLUE analysis can be seen as the model uncertainty due to parameter equifinality. The median of all possible model solutions can be used as an indicator of the observed values.

3 Material and methods

In this chapter, all the input for the research is described. The Drentsche Aa catchment, study area of this research, will be described in Section 3.1. The properties of the forcing data (precipitation and evaporation) are given in Section 3.2, as well as the characteristics of the observed discharge within the catchment. Finally, the MIPWA groundwater model and its components are described in Section 3.3.

3.1 Description of study area, the Drentsche Aa catchment

The Drentsche Aa catchment is situated in the Northern part of the Netherlands (Figure 3.1) in the province of Drenthe. The city of Assen is situated at the western boundary of the catchment; only a small part of the city is within the catchment. The total size of the catchment is 228 km^2 and elevation ranges between 0 and 27 meter above sea level. The Drentsche Aa catchment is a pleistoceen groundwater system of which the streams are fed by rainwater and seepage originating from the ice-pushed ridges on the boundaries of the catchment (Hoogewoud, 2009). A large part of the streams is still in the original meandering state and only a small part has been canalized. In the catchment only one water sluice is present which is situated at Loon in the southwest of the catchment, where water can be divided to the Drentsche Aa or the Noord-Willems kanaal. Only in case of extreme precipitation events the water will flow to the Noord-Willems kanaal to prevent flooding of a small part of the Drentsche Aa catchment. Forty percent of the catchment is artificially drained by ditches or tube drainage; most of this area is situated in the low areas and the urban areas. Land use mainly consists of nature (wetlands, forest and heath) and agriculture (maize). The Drentsche Aa catchment has a semi-humid sea climate with an annual precipitation which ranges from 535 up to 1088 mm with an average of 824 mm. Reference potential evaporation can vary between 477 and 615 mm (average 542 mm), where the total annual discharge of the Drentsche Aa catchment ranges between 118 and 435 mm with an average of 264 mm. Photographs of the various parts of the catchment have been taken on 19-01-2011 and are included in Annex 10A.

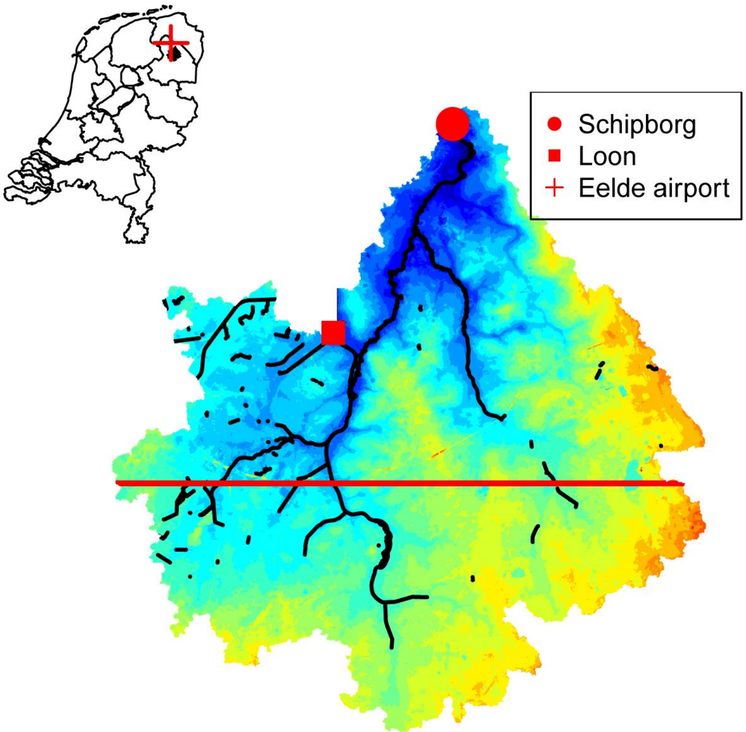

Figure 3.1 Location of the Drentsche Aa catchment including a digital elevation map of the catchment in meters. The red plus indicates the meteorological station (Eelde), the red point indicates the weir (Schipborg) where the observed discharge is measured and the weir at Loon is indicated by a red square.

3.2 Available meteorological and hydrological data

In the Drentsche Aa catchment, discharge is measured at six locations. Time series of daily measured discharge over the period from 1981 to 2010 were placed at our disposal by the water board Hunze and Aa's. To calculate the model performance, simulated discharge is validated with the observed discharge from the Schipborg weir. This weir uses the stage discharge method (Mulder et al., 2009) which provides to give a measurements of the total discharge of the catchment. Daily precipitation and reference evaporation for the catchment are measured at Eelde airport meteorological station of the KNMI (Royal Dutch Meteorological Institute) for the period from 1965 to 2010. Precipitation values are also available with an hourly time step for the period 1965 tot 2010.

3.3 Description of spatially distributed groundwater model MIPWA

Groundwater modelling in this study was done with the use of the spatially distributed groundwater model MIPWA model that was developed at TNO Groundwater (Snepvangers and Berendrecht, 2007). A small Section of the entire MIPWA model had been used to simulate the Drentsche Aa catchment. In this study, the suggested adjustments to the MIPWA model of Hoogewoud (2009) were included to have the most accurate simulation of the groundwater depths in the catchment (MIPWA 2.0). MIPWA model consist of two parts, namely SIMGRO (Querner, 1997; Van Walsum et al., 2006) for the simulation of the unsaturated zone and MODFLOW (Harbaugh et al., 2000) for the simulations in the saturated zone, both modules are coupled in the MIPWA model. The MIPWA model uses input from maps of TNO (2007) which are used for the simulation of groundwater depths of the Drentsche Aa. The MIPWA model uses seven separate layers to simulate the groundwater in the catchment. In this study only the results of the top layer were analyzed for the dynamics in spatial patterns of groundwater depth.

In order to make distributions of groundwater depths for the entire catchment of the Drentsche Aa, a sufficient number of groundwater depths has to be available in order to calculate a valid statistical distribution. These groundwater depths can be either measurements or modelled groundwater depths (Section 2.1). Groundwater is measured on 768 locations, which do not have an random spatial distribution (Figure) and also a low temporal resolution it was not possible to calculate a valid statistical distribution from these observed data. In order to be able validate modelled groundwater depths the modelled MIPWA groundwater depths were used for validation of the model results. Since MIPWA is extensively calibrated with groundwater measurement from different piezometers in and around the catchment groundwater depths in MIPWA are accurate enough to use them for model validation.

The MIPWA-results were available for the period 1989 -2001 with a temporal resolution of one day and a spatial resolution of 25 x 25m, which resulted in 365000 modelled groundwater depths in total. This groundwater depths were the result of the MODFLOW module of MIPWA and only the top layer was used, to have an accurate simulation of the groundwater depth in the phreatic aquifer. In addition, maps with the minimum, average and maximum groundwater depths for the entire catchment are given in Figure 10.2 – Figure 10.4 of Annex C.

4 Results

In this chapter, the results of this study are discussed. In Section 4.1, the first two research questions of Section 1.2 are answered with an inspection of the MIPWA results (Section 3.3). In Section 4.2, the set-up of the LGSI-model of the Drentsche Aa catchment is described. In Section 4.3 relations between average groundwater depth and all fluxes and storages as described in Section 2.3 are shown. These original relations and the estimated parameters values from these relations are used to do a first run of the model and compare the results of this model run with observed discharge and modelled discharge and groundwater depths from MIPWA (Section 4.4).

4.1 First analysis of statistical distribution of groundwater depths

The data from the spatially distributed groundwater model MIPWA (Section 3.3), showed that the behaviour of the groundwater in the high ice-pushed ridge was different from the surrounding low areas near the Drentsche Aa stream. In the low areas, the shape of groundwater table was affected by draining ditches, tube drains and depressions, while in the high areas the groundwater table was affected by the shape of the ice-pushed ridges: i.e. large scale features in the surface elevation. The behaviour of the groundwater table is also different for wet and dry situations as shown in Figure 4.1, where a cross-section of the catchment in shown. To determine the most suitable statistical distribution to describe the groundwater depths, a histogram of the distribution of groundwater depths is calculated for each day of the period 1989-2001. The distribution of groundwater depth for both days is also shown in Figure 4.1, where the two histograms respectively describe the groundwater depths of a dry and a wet day. It should be noted that the top of the distributions is not situated in the centre of the distribution. In wet conditions the groundwater table will have the tendency to follow the surface level and especially the ditches and streams present on the surface. In dry conditions, this effect is absent and groundwater tables will be more flatten. Bottom graphs indicate histograms of groundwater depths for the dry and wet day, where the black line indicates the normal distribution of these groundwater depths. From Figure 4.1, it was concluded that a normal distribution, that suited the Hupsel Brook catchment really well, was not able to describe the distribution of groundwater depths in the Drentsche Aa, since the overall is distribution was not described in an accurate way.

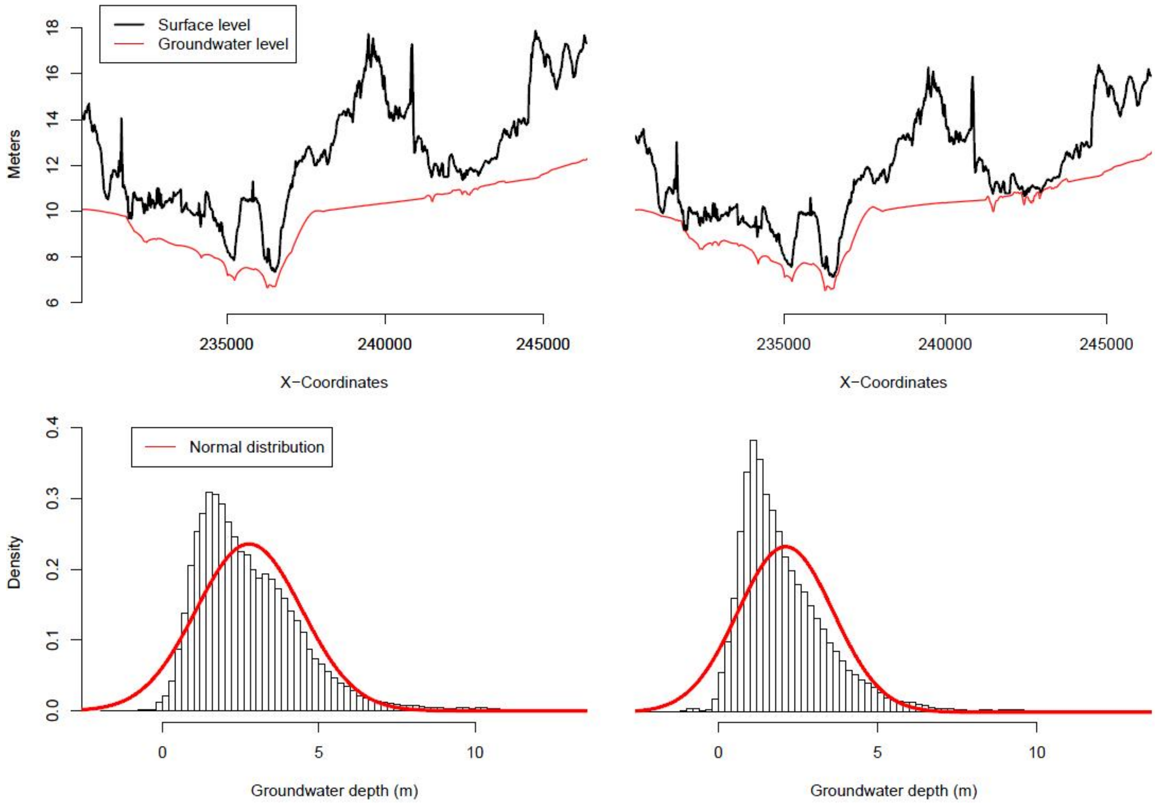

Figure 4.1 The upper graphs show a cross-section of the Drentsche Aa catchment (Figure 3.1) for a dry day (05-11-1991) and a wet day(17-12-1991) respectively. The groundwater table is indicated in red and surface level is indicated by the solid black line.

The average groundwater depth and the corresponding standard deviation of the groundwater depth were calculated for the entire catchment and are illustrated by Figure 4.2. In this figure there are two processes present, the general trend is the increase of the standard deviation of the groundwater with an increasing average groundwater depth as. Another less significant trend is the slow increase of the average groundwater depth without significant changes in the standard deviation. A more detailed study into the second observed pattern showed that this behaviour of groundwater depths was caused by long periods without precipitation and slow drainage of the catchment by discharge and evapotranspiration. In these periods the catchment would drain itself with an increasing groundwater depth as a result of these processes. In the ice-pushed ridges this processes did not result in an changes of the standard deviation while a in the lowland areas a small increase of the standard deviation was present. However, a very large part of the catchment is situated in the ice-pushed ridges and therefore the total standard deviation did not change significantly.

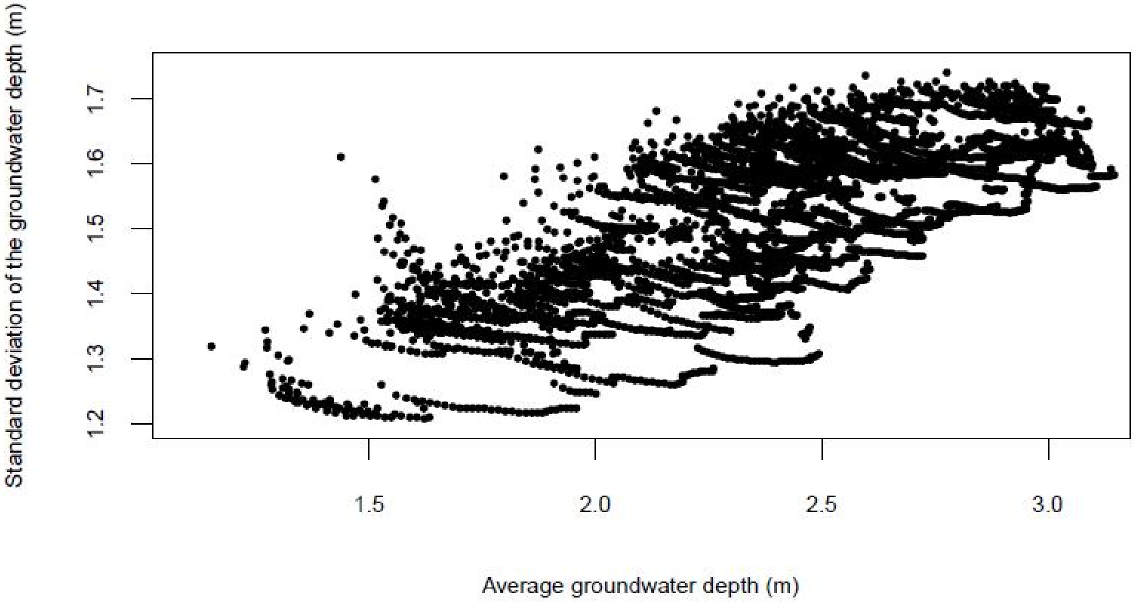

Figure 4.2 Average groundwater depth (in meters from the surface level) plotted versus the standard deviation of the groundwater depth (in meters) for the entire Drentsche Aa catchment

The concept of the Lowland Groundwater Surface water Interaction model (LGSI-model) is based on the assumption that every average groundwater depth corresponds to one standard deviation of the groundwater depth and that the negative part of the groundwater depth distribution represents the contact interface between groundwater and surface water. To reduce the spread in the relation between average groundwater depth and the standard deviation of groundwater depth (Figure 4.2) and to better capture the negative part of the distribution and skewed distribution (Figure 4.1) it was decided to divide the catchment into two parts. One part in which the groundwater depth is low (wet areas) and another part in which water will never reach the surface level (high and dry areas). In the low areas the groundwater will directly contribute to discharge because they are situated next to streams or in surrounding areas (groundwater exfiltration). The high areas consist mainly of the ice-pushed ridges and higher areas around the streams, which only indirectly control the discharge via groundwater flow towards the low areas. One exception is a drain flow, which is sometimes present at some parts of the higher areas and located under urban development and agriculture. The water from the high areas will go to the low areas via groundwater flow and will only exfiltrate to the surface when it is in the low areas. The divide between the two parts was made based on the minimum groundwater depth of every cell in the catchment over the entire modelled period (1989-2001) of the spatially distributed groundwater model. When groundwater depth is negative at a certain location somewhere within this period, this particular cell is located in the low area. Surrounding cells of such a location were also classified as low area because they might contribute to the discharge in other periods of time outside the period 1989 -2001. This division in low and high areas resulted in the Figure 10.5 which can be found in Annex B. The low and high areas respectively represent 27% and 73% of the total catchment size.

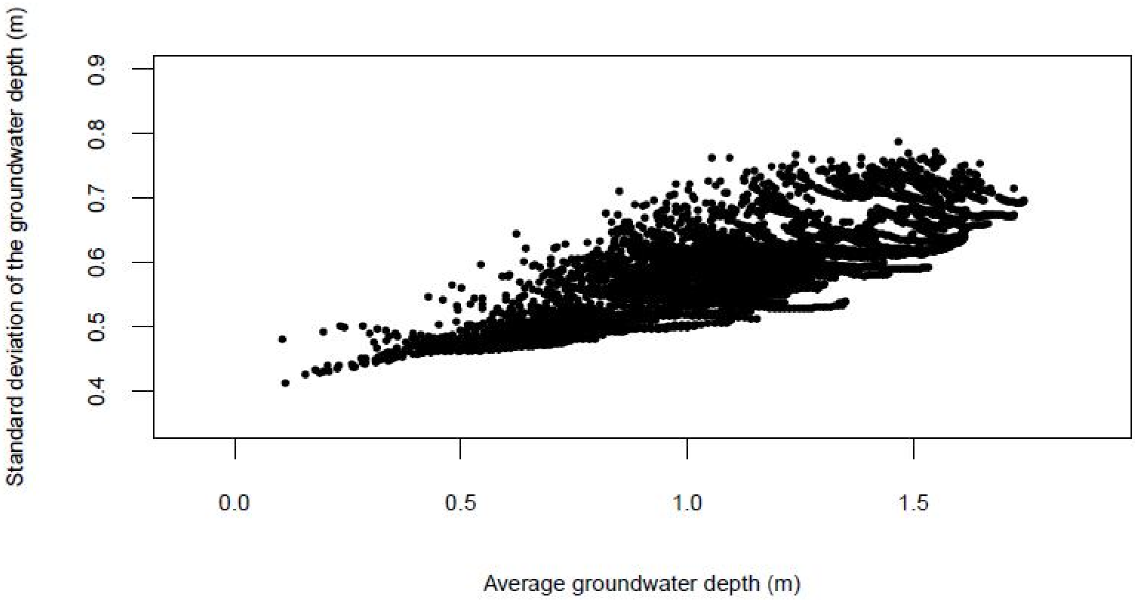

Figure 4.3 Average groundwater depth (in meters from the surface level) plotted versus the standard deviation of the groundwater depth (in meters) for the low areas (figure Annex B) of the Drentsche Aa catchment.

Figure 4.3 (low areas) and Figure 4.4 (high areas) give the average and standard deviation in the distribution of groundwater depths of the two new sub catchments. From the histograms of groundwater depths it was concluded that the low areas are best modelled with a normal distribution, while the distribution of the groundwater depths in high areas is better represented by a gamma distribution. This gamma distribution can be obtained from the mean and standard deviation of the groundwater depth and is therefore easy to simulate. The use of a gamma distribution to describe the groundwater depths of the high areas is also supported by expert knowledge of hydrological principles. When the Hooghoudt equation (Hooghoudt, 1940) is applied to one field with a ditch on either side, the distribution of the groundwater depths in this field could be represented by a gamma distribution (personal communication: Van der Velde (2011). The high areas of this catchment are the large ice-pushed ridges which have streams on either sides and therefore will have a groundwater depth distribution which is very similar to a field with ditches as described by Hooghoudt (1940). This behaviour is also illustrated in Figure 4.5, where the distribution of all groundwater depths is well described by a combination of the normal and gamma distribution as presented in Figure 4.6.

For both parts of the catchment, new relations between average and standard deviation of the groundwater depth had to be found. Figure 4.4 shows the relation between average and standard deviation of the groundwater depths for the low areas; the scatter within this relation is smaller than the scatter present in Figure 4.2 where the catchment was not divided. The new relation gives a better estimate of the standard deviation as a function of the average groundwater depth in comparison as well as a much better estimate of the negative fraction of the groundwater depth distribution. For the high areas, this relation did not improve significantly (Figure 4.4). However, when the groundwater depth of the high area is plotted as shape and scale parameter of the gamma distribution, the scatter within this relation reduces significantly (Figure 4.7). Because this results in a unique relation between the parameter of the gamma distribution, the new division of the Drentsche Aa into two separate area can be used to model the catchment.

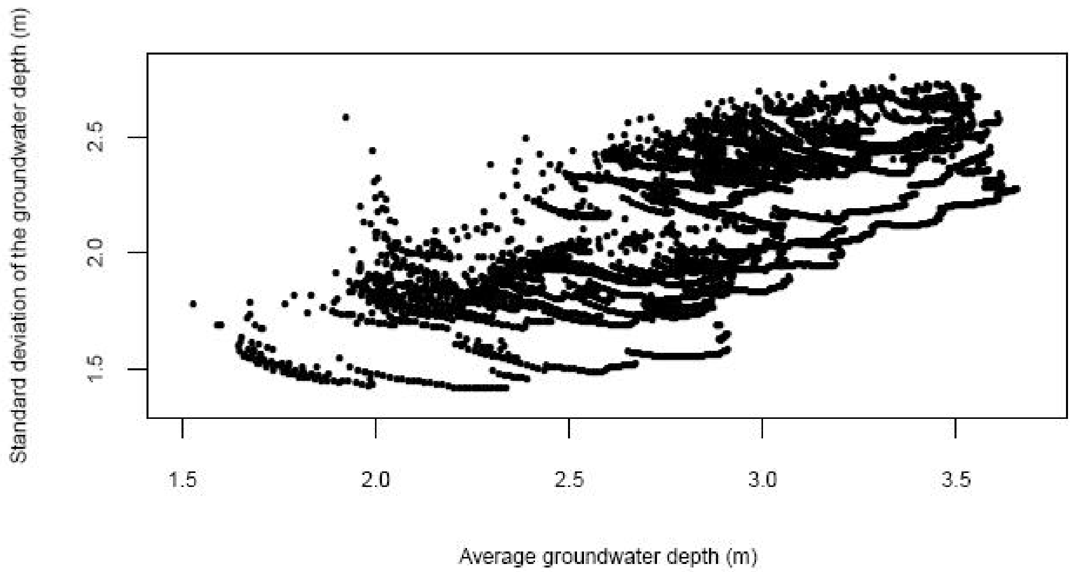

Figure 4.4 Average groundwater depth (in meters from the surface level) plotted versus the standard deviation of the groundwater depth (in meters) for the high areas (figure Annex B) of the Drentsche Aa catchment.

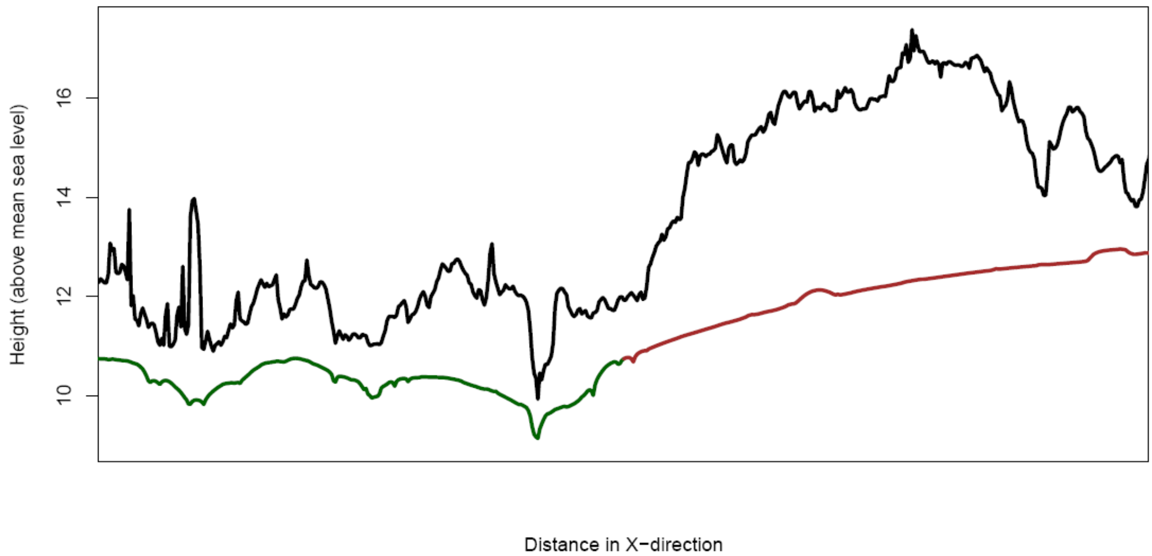

Figure 4.5 Groundwater depths for cross-section of the Drentsche Aa catchment (Figure 3.1). On the left side the groundwater depths of the low areas are described (green line) which can be described by a normal distribution. The right side shows the groundwater depths for the high areas (red line) which can be described with a gamma distribution.

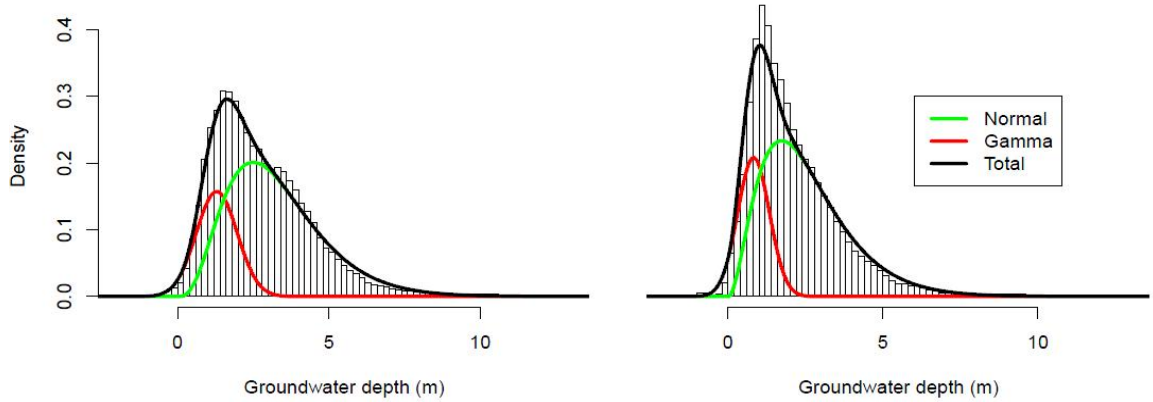

Figure 4.6 Histogram of groundwater depths for a dry day (17-12-1991) and a very wet day (05-11-1993), with lines indicating the fitted distribution for the low and high reservoir and the combined distribution.

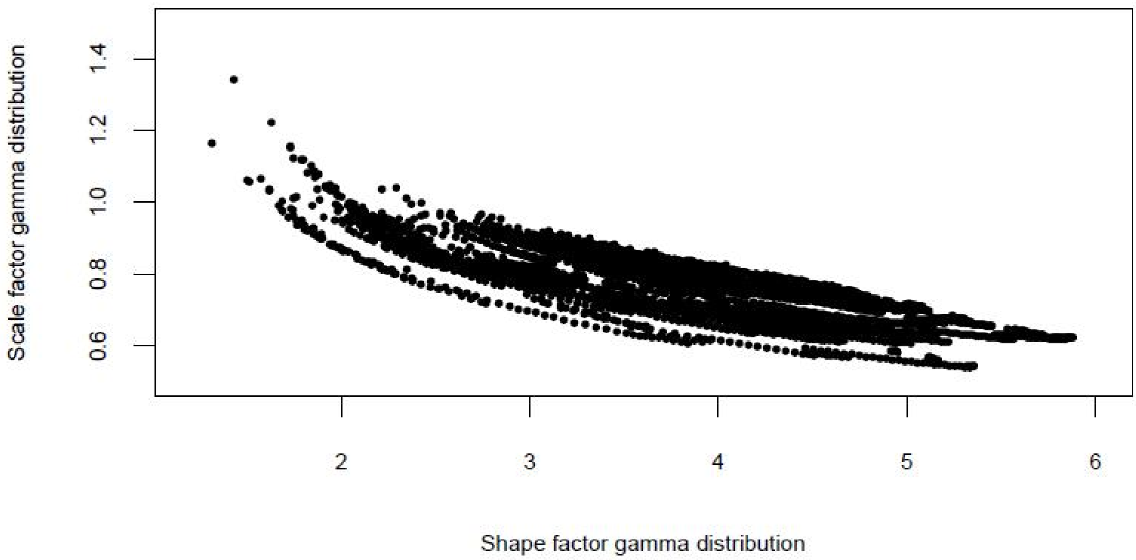

Figure 4.7 Shape factor of the gamma distribution plotted versus the scale factor of this distribution, for the high areas (figure Annex B) of the Drentsche Aa catchment.

4.2 The set-up of the Lowland Groundwater Surface water Interaction model

The Lowland Groundwater Surface water Interaction model (LGSI-model) described in Section 1.1 was used to simulate the groundwater levels and discharge of the Drentsche Aa catchment. In this catchment, two modules of the LGSI-model were used, one reservoir to simulate the lowland areas of the catchment and another reservoir to simulate the behaviour of the higher parts of the catchment. The catchment was divided into two reservoirs because the behaviour of the deep slowly responding groundwater was different from the more quickly responding shallow groundwater levels in the low areas (see Section 4.1). The models are coupled because deep groundwater in the ice-pushed ridges of the catchment will influence the base flow of the Drentsche Aa. However, this reservoir that represents the high areas will have no or a very small influence on the response of the discharge to heavy precipitation events, because no groundwater exfiltration occurs and drain flow is limited to small areas. The coupling between both models is accomplished through a Darcy based approach (Darcy, 1856) where the flow between the models is characterized by:

$$Q_{\text{int}} = \frac{1}{c}(h_{dif} - u_{dif}) \tag{5.1}$$

where c is the resistance (in days) between the high and the low area which can be related to the soil type, soil permeability and distance between the reservoirs, h_{dif} is the height difference of the average surface level between both reservoirs (in m) and u_{dif} is the difference in groundwater depths between the reservoirs (in m).

The standard deviation of the normal distribution of the groundwater depths in the deep reservoir did not follow Equation (3.1) as described by Van der Velde et al. (2009). This is related to the fact that ditches and drains did not influence the groundwater depth of the high areas because they are absent or very rare. Therefore, a linear relation for the standard deviation of the high areas is proposed based upon the groundwater depth distributions of the MIPWA model for the Drentsche Aa catchment of which the parameter of the gamma distribution can be used. The standard deviation of the groundwater depth for the high areas was hence calculated by:

$$\sigma_{uH} = a \cdot \langle u_H \rangle + off \tag{5.2}$$

Where a is the increase in standard deviation when the average groundwater depth of the high areas ($\langle u_H \rangle$) increases and off is the standard deviation for $\langle u_H \rangle$ equals 0 meter.

The last modification to the original LGSI-model is an additional outflow from the high reservoir. This outflow is generated by leakage to deeper groundwater and subsequent region groundwater flow leaving the Drentsche Aa catchment and drinking water extractions in the ice-pushed ridges of the Drentsche Aa catchment. This outflow is assumed constant over time and independent of the groundwater depth of which the initial value is described in Table
.

Figure 4.8 gives a schematic overview of the set-up of the LGSI-model for the Drentsche Aa catchment with all fluxes and interactions. The parameters of the LGSI-model were estimated with the use MIPWA results and input maps (e.g topography, soil type) (Snepvangers and Berendrecht, 2007). Initial values and ranges of all parameters are given in Table which can be found in the Annex 10E.

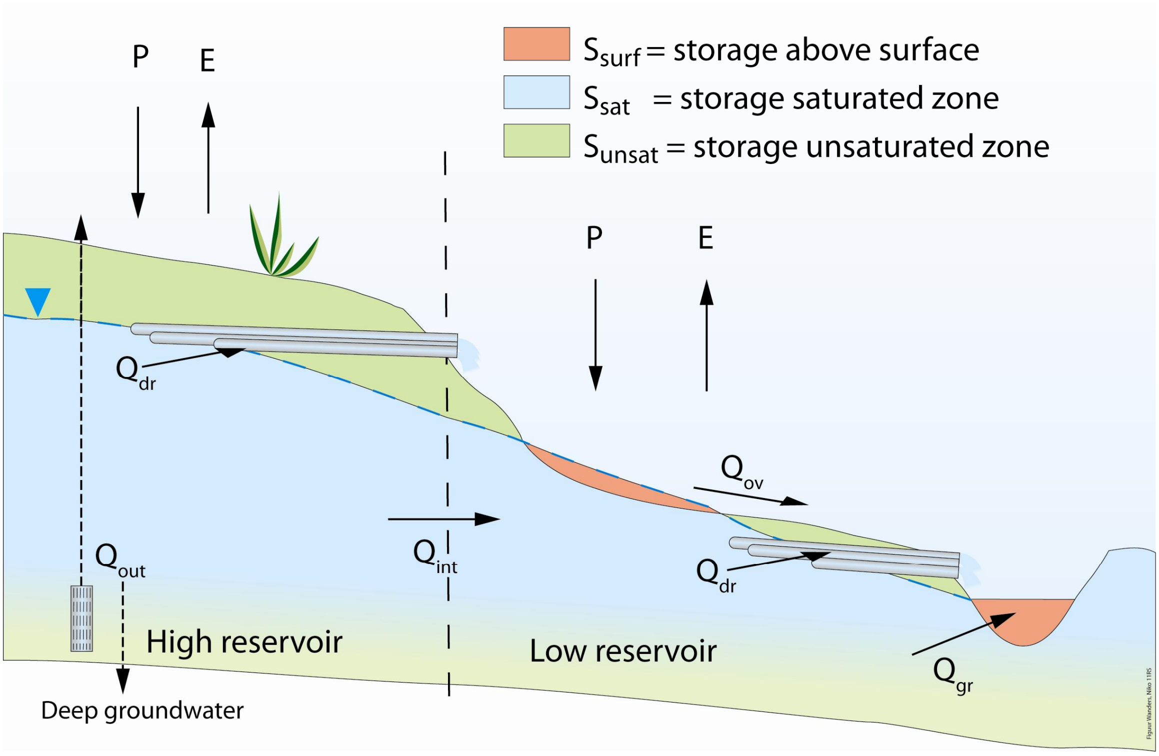

Figure 4.8 Schematic overview of the Lowland Groundwater Surface water Interaction model, fluxes are given by arrows.

4.3 Relations between average groundwater depth and fluxes

For both the low and high areas (Figure 10.5, Annex B) of the Drentsche Aa catchment, relations between the average groundwater depth and different types of fluxes had to be determined (Section 2.3). The data from the MIPWA model (Section 3.3) and equations suggested in Section 2.3 were used to find suitable relations to describe both reservoirs of the model. The parameters were determined with least square regression based on the groundwater and discharge data from the MIPWA model. For the low reservoir, three different types of fluxes (Equation (3.7)) were identified. However, for the high reservoir the number of fluxes is reduced to three, namely a drain flux, a groundwater flux to the low reservoir (Equation (5.1)) and an outflux out due to losses by regional groundwater and drinking water extractions. In figure 4.6 the relations for relevant fluxes and storages are plotted as a function of the average groundwater depth (in m) of the reservoir, related parameters are given in Table . The flow between the high and low area, which is dependent on the groundwater depths in both reservoirs is not plotted the parameters of all relations are given in table Annex 10E. The most right plot indicates the reduction of precipitation or evaporation as a function of groundwater depth. The relations which are depicted in Figure 4.10, are a result from the MIPWA data of the Drentsche Aa, the reduction in evaporation was derived from the results from the SIMGRO module for the unsaturated zone, all other relations were composed from the MODFLOW output.

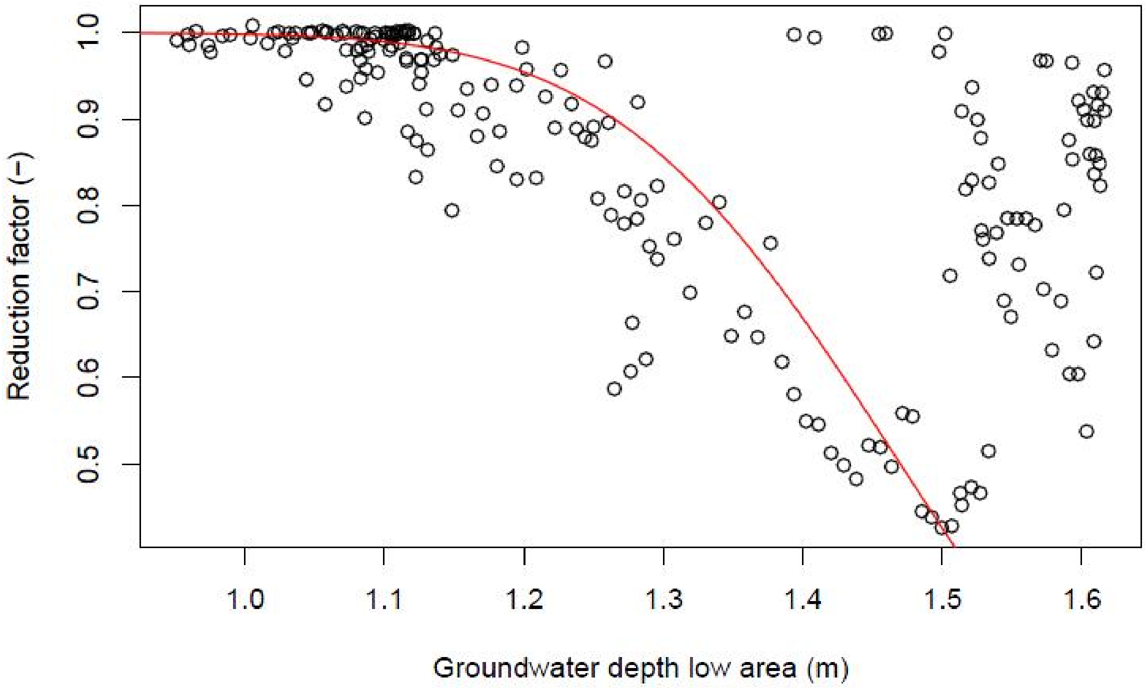

Figure 4.9 Reduction factor of potential evapotranspiration as a function of the groundwater depth in the low areas. Black dots indicate values derived from the SIMGRO module of MIPWA, the red line is the best of this relation.

The potential evaporation is reduced by a normal distribution, which is the result of a mean (average rooting depth) and standard deviation (deviation in average rooting depth). The mean and standard deviation of the reduction function are derived from the SIMGRO output (Figure 4.9). The original equation for the actual evapotranspiration (Section 2.3) is now rewritten as:

$$E_{act}(t) = E_{pot}(t) \cdot f_e\left[f_u(t), \mathrm{E_m}, \sigma_{\mathrm{E_m}} \right] \tag{5.3}$$

Where f_e is the normal distribution of the reduction of $E_{pot}(t)$ as a function of the groundwater depth, $\mathrm{E_m}$ and $\sigma_{\mathrm{E_m}}$ are respectively the mean (average rooting depth) and standard deviation (deviation in average rooting depth) of this normal distribution.

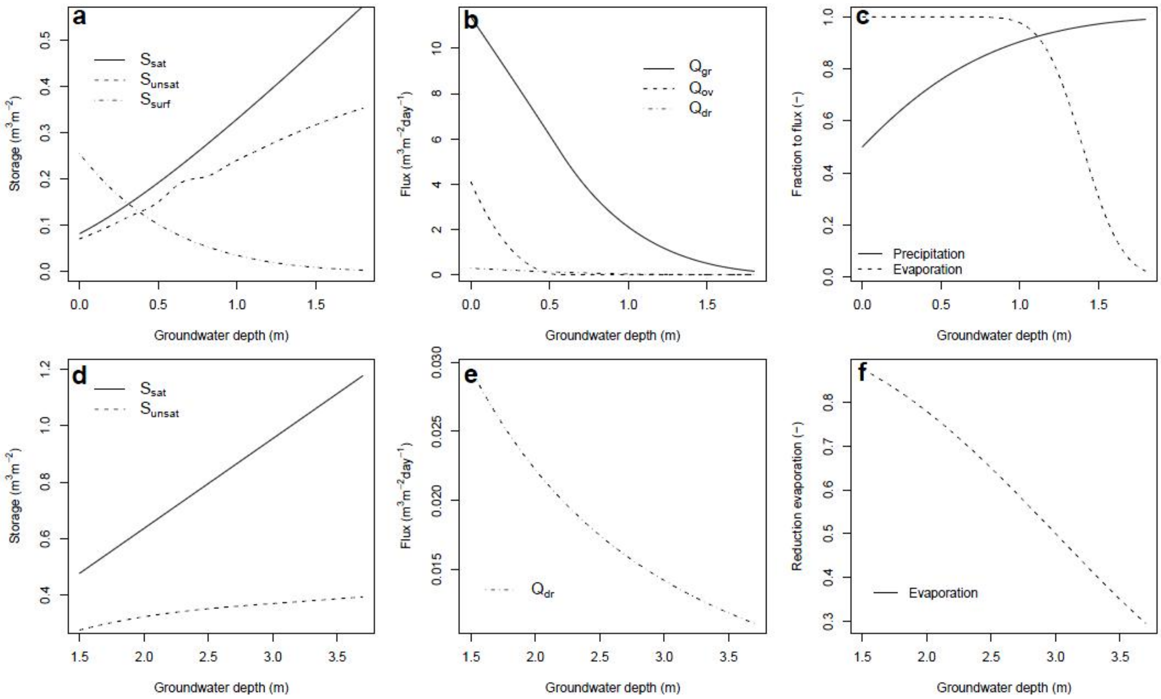

Figure 4.10 Fluxes and storage expressions of the LGSI-model of the Drentsche Aa based on the initial values described by Table . The upper graphs (a-c) indicate the relations between average groundwater depth (in meters) and all fluxes and storages of the low reservoirs. The lower graphs (d-f) indicate the same relations as function of groundwater depth for the high reservoir.

4.4 First simulations of groundwater depth and discharge

The relations based on the MIPWA model that were described in Section 4.3 are subsequently used in order to execute a first simulation of the groundwater levels and discharge of the Drentsche Aa catchment. The initial parameter values of these relations can be found in Annex 10E. The first result of the LGSI-model was compared with observed discharge data and model output from MIPWA (discharge and groundwater depths) and model performance was calculated in three different ways (Section 2.4).

The first simulation of discharge and groundwater depths for the period 1989-2001 is shown in Figure 4.11 together with the simulation of MIPWA for both outputs and observations of discharge. It can be concluded that simulated discharge values of the LGSI-model are higher than the measured discharge, while the simulated discharge values of MIPWA are biased to lower values. Overall the LGSI-model gives a better representation of the observed discharge at Schipborg than the discharge calculated by the groundwater model MIPWA (Table 4.1). However, the overall fluctuations are better represented by the groundwater model, which is indicated by a higher R^2 (Table 4.1). The groundwater levels could only be verified with the modelled groundwater level originating from MIPWA, because there are not enough piezometers in the catchment to give an accurate representation of the distribution of groundwater depths. Since MIPWA is extensively calibrated with groundwater measurement groundwater depths are use from MIPWA (Section 3.3). Since groundwater is a very slow responding component in the model, values of the Nash-Sutcliffe model efficiency with a one day lag (NS_{lag}) (Section 2.4) are not different from the Nash-Sutcliffe (NS_{eff}) model efficiency and are therefore not given. The model performance in the slow responding high reservoir is very high, with a NS_{eff} of 0.891. The performance in the more dynamic low reservoir is much lower (NS_{eff} = 0.315). This reservoir is also much more dependent on different types of fluxes and therefore it is more difficult to model this reservoir. In the simulation also the losses to drinking water extraction and the regional groundwater system where not incorporated. This could result in the bias of the simulated discharge to higher values. Another possible cause of could be the inaccurate simulation of the evapotranspiration, which could result in an overestimation of the discharge and groundwater levels due to a large precipitation excess. This last cause is also partly supported by the low groundwater depths of the low areas in summer (Figure 4.11), which suggest that the evapotranspiration is underestimated by the LGSI-model. Overall, it was concluded that even without parameter optimization the LGSI-model is better capable of discharge simulations than the groundwater model MIPWA.

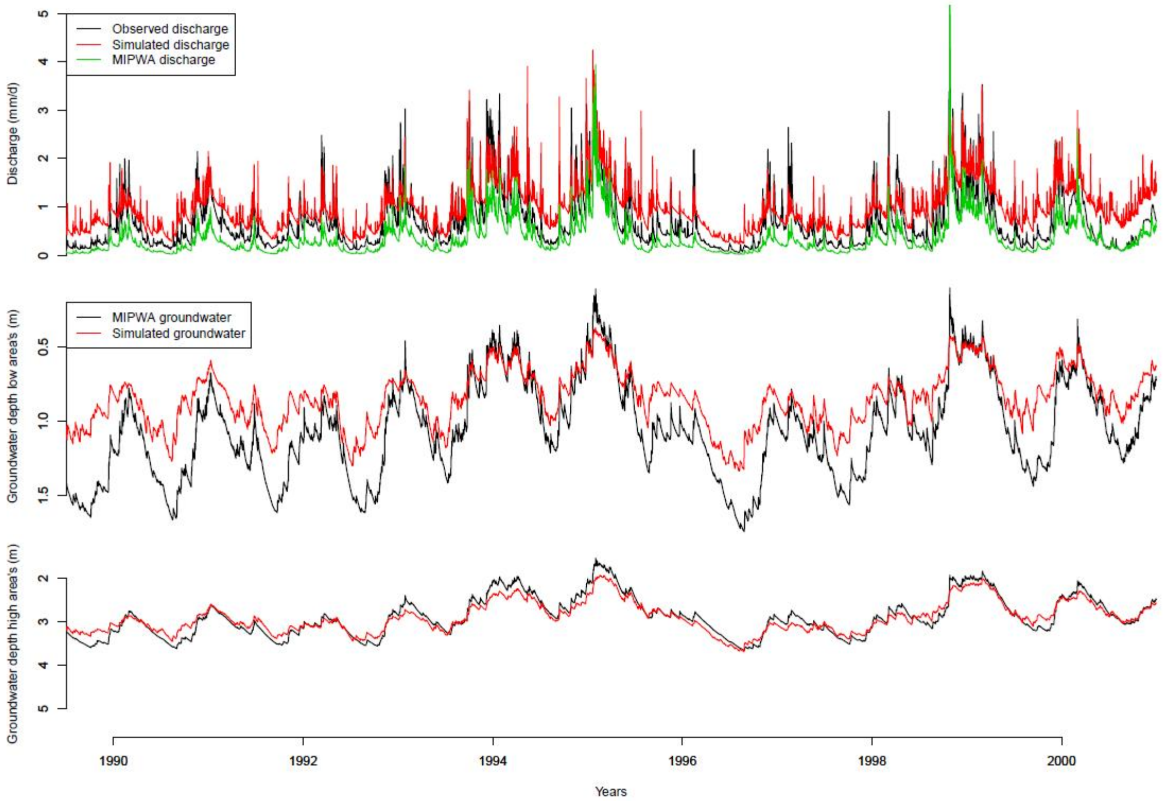

Figure 4.11 Modelled and measured discharge, modelled groundwater levels for the Drentsche Aa catchment for the period 1989-2001. Upper graph gives the observed discharge (black), the modelled discharge (red) and discharge from the MIPWA groundwater model (green) at Schipborg. Middle graph shows the modelled groundwater levels for the low reservoir of the LGSI-model (red) and the corresponding groundwater levels of the MIPWA model (black). Bottom graph indicates the groundwater levels for the high reservoir of the LGSI-model (red) and corresponding groundwater level of the MIPWA model (black)

Table 4.1 Comparison of model performance, between MIPWA and LGSI-model for discharge and model performance of the LGSI-model for groundwater depths.

Model performance	**Discharge MIPWA**	**Discharge LGSI-model**	**Groundwater low reservoir**	**Groundwater high reservoir**
R^2	0.797	0.624	0.862	0.921
NS	0.348	0.410	0.315	0.891
NSlag (1day)	0.468	0.566	-	-

4.5 Discharge routing trough channel network

To account for the channel network of the Drentsche Aa catchment the impulse discharge (direct discharge for every time step) into the channel network needs to be delayed by a simple equation. In Figure 4.12 the difference between a routed discharge and an impulse discharge is depicted. With the use of an impulse discharge, the discharge of the Drentsche Aa could not be modelled adequately. A lognormal distribution is used to delay impulse discharge in order to give an accurate simulation of the discharge at Schipborg. The parameters of the lognormal distribution where determined for each unique parameter combination of the LGSI-model separately to get the best routing equation for every parameter combination. However, all routing was done with a lognormal distribution of which the corresponding peak was often at day one or two from a particular rainfall event. An example of the routing effect is given in Figure 4.12.

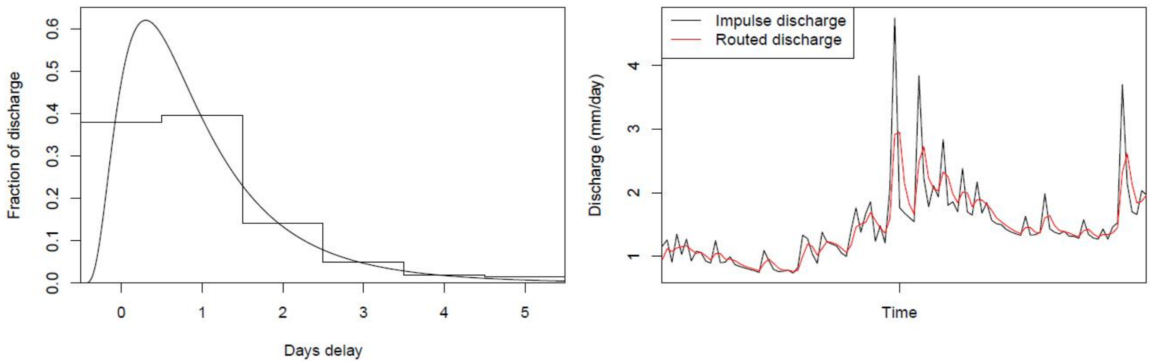

Figure 4.12 Example of routing function used for discharge simulation in the LGSI-model. In the left graph bars indicate the accumulate percentages which is used in the LGSI-model and the lognormal distribution is indicated with a line.

4.6 Model results after calibration with GLUE analysis

The GLUE analysis of the LGSI-model was done for all the model parameters (Table in Annex 10E). In order to perform the GLUE analysis, the LGSI-model was executed for 5.2 million different parameter combinations and model performances for all runs were calculated with the Nash-Sutcliffe model performance (NS_{eff}) (Section 2.4). Subsequently, a selection of parameter combinations with a sufficiently high model performance for all state variables of the model (groundwater depth in low and high reservoir and discharge) was used to calculate possible model solutions. Parameter combinations (total 5.2 million) were regarded sufficient with a NS_{eff} of over 0.7 for discharge and groundwater simulations (both low and high areas) were selected as satisfying combinations. The selection criterion for the discharge was a model performance of over 0.75, since the focus of this study was to be able to have accurate discharge simulations. This resulted in a total of 403 parameters combinations, that satisfied these criteria. These model solutions were then used to determine the amount of variation in the possible model solutions and the sensitivity of the model to each of the parameter. Precipitation, actual evaporation and discharge were also multiplied with a factor ranging from 0.9 to 1.1 to account for errors in the measured data.

The 403 parameter combinations were then used to determine the range of possible model solutions at every time step (bandwidth). After the GLUE analysis the bandwidth is used as the model for simulations, where the median is an indication for the value of observed discharge (Section 2.5). In Figure 4.13 both the bandwidth and median are depicted as a function of time for all three components of the model. The model performance of the median after the GLUE analysis is given by Table 4.2 for the entire calibration period (1989-2001).

Table 4.2 Model performance of the LGSI-model after calibration with the GLUE-analysis.

Model performance	Discharge LGSI-model	Groundwater low reservoir	Groundwater high reservoir
R^2	0.770	0.806	0.942
NS	0.764	0.778	0.872
NSlag (1day)	0.843	-	-

From Figure 4.13 it can be concluded that the temporal variability in the low reservoir is higher than in the relatively slow responding deep reservoir. This also results in a better model performance for the deep reservoir, since these slow temporal variations are easier to simulate. Despite the very large temporal variation in the discharge pattern, the model performance of the median of the GLUE analysis still remains high. The simulation of the peak discharges is less accurate than the simulation for the recessions curves in the discharge. This is probably due to simulated groundwater depths of the LGSI-model which are lower than the groundwater level from MIPWA. This will result in an underestimation of the total storage, especially in the unsaturated zone. This large unsaturated zone, will store part of the precipitation that otherwise would discharge immediately via overland flow and streams. Another reason for the underestimation of peak discharges could be the presence of an impermeable surface layer in villages and the city of Assen, which partly discharges on the Drentsche Aa. In situations with a high precipitation this urban areas will contribute directly to the discharge, since the initial losses of these urban area's are exceeded (Sarma et al., 1973). Another possible cause of the underestimated peak discharge could be the result of exceeding of the infiltration capacity or the presence of perched water table due to impermeable layer in the soil. These processes are not present in the LGSI-model concept and will therefore, not be modelled. The changes in weir levels could also influence the peak discharges, especially the weir at Loon (Section 3.1) could have a major influence on the discharge from the western part of the catchment.

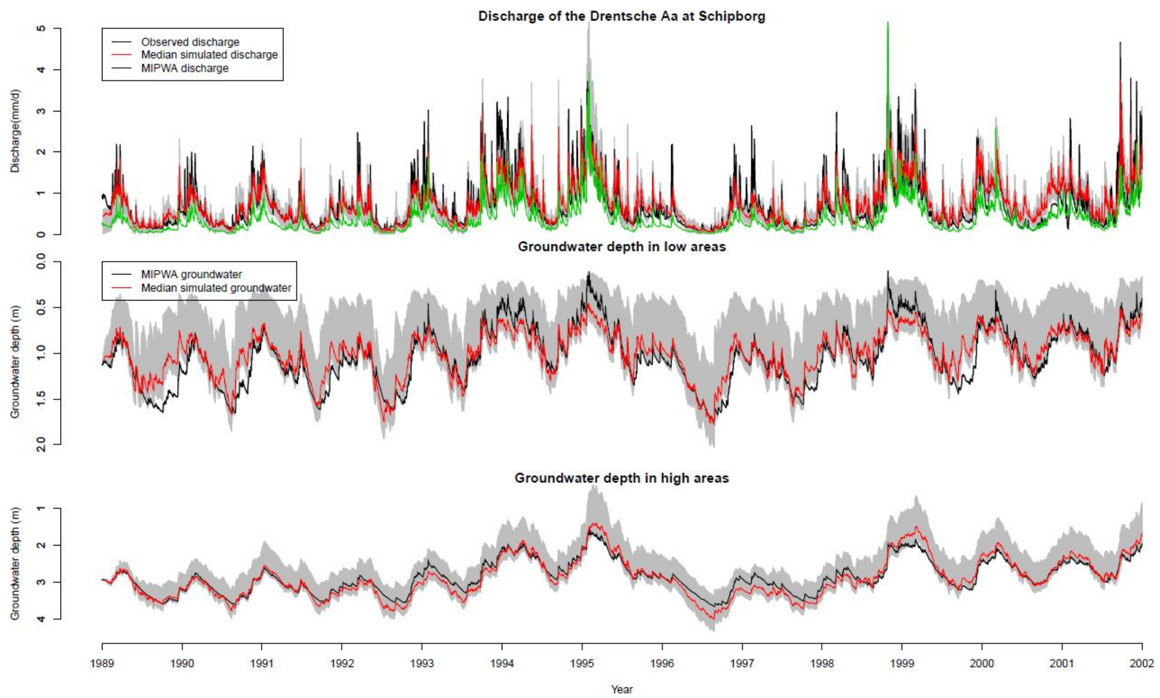

Figure 4.13 Modelled and measured discharge, modelled groundwater levels for the Drentsche Aa catchment for the period 1989-2001. Upper graph gives the observed discharge (black), the median modelled discharge (red) and discharge from the MIPWA groundwater model (green). Middle graph shows the median of the modelled groundwater levels of the low reservoir for the LGSI-model (red) and the corresponding groundwater levels of the MIPWA model (black). Bottom graph indicates the median of the groundwater levels of the high reservoir for the LGSI-model (red) and corresponding groundwater level of the MIPWA model (black). In all graphs the grey colour indicates the bandwidth of the model, as determined with the GLUE analysis.

5 Detailed analysis and sensitivity

In this chapter the sensitivity of the Lowland Groundwater Surface water Interaction model (LGSI-model) to changes in parameters or input is tested. Sensitivity is measured by changes in overall model performance which is indicated by the changes in Nash-Sutcliffe model performance (NS_{eff})(Section 2.4) with respect to the original model from Section 4.6. The results for model performance of all sensitivity analyses are given in Annex 10F by Table . In Section 5.1 the effect of changes in calculation time step is tested by using hourly precipitation as an input for the LGSI-model. The model performance outside the calibration period (1989-2001) is evaluated in Section 5.2. The effect of the calibration of the GLUE analysis is described by Section 5.3, where the changes in some of the parameters of the LGSI-model are shown. Finally the different discharge components of the LGSI-model (Section 5.4) to indicate which flow components is dominant in which time of year. In this section also the possibilities of the model for water quality are briefly described.

5.1 Model dependency to input data of smaller timescales

For operational discharge prediction, it would be desirable if the model would be able to give accurate discharge simulation on a hourly to sub-hourly timescale. This could then be combined with precipitation forecast and/or measured precipitation data of the last hours to be able to do real-time discharge simulations, in order to test the performance of the LGSI-model on smaller timescale like hourly time steps. This would require the model to have a high model performance for smaller timescales like hourly time steps. Therefore, the model has been used with an input of hourly precipitation data from the KNMI (Royal Dutch Meteorological Institute). This resulted in hourly discharges which were then accumulated to daily values to be able to calculate the model performance. Daily values were needed since discharge data is not available for a hourly time step. By using the accumulated hourly discharge, small variation in timing between the simulation and measurement would not result in very low model performance. Results of the simulation with an input of hourly precipitation are given in Figure 5.1. The NS_{eff} of the median of the simulated discharge for discharge on a hourly time scale (0.75) is slightly lower than the NS_{eff} (0.761) on a daily time scale. The NS_{eff} for the median of simulated groundwater depth are 0.788 for the low reservoir and 0.861 for the high reservoir. A full overview of the NS_{eff} of the model runs can be found in Appendix 10F (Table).

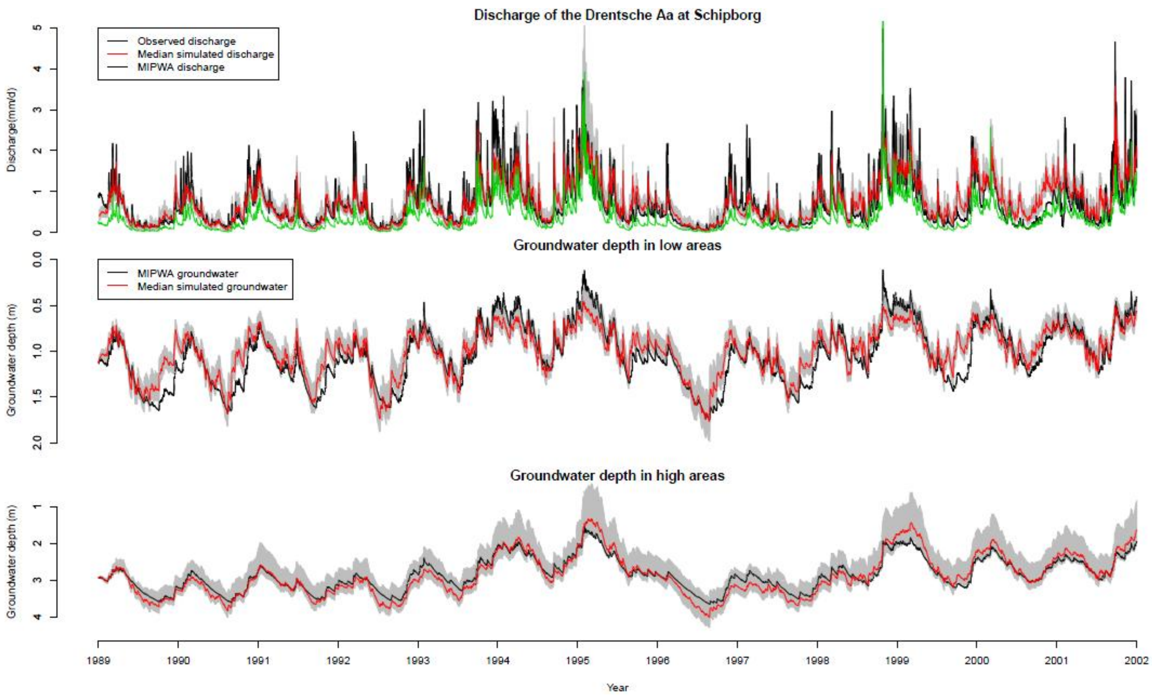

Figure 5.1 Modelled and measured discharge, modelled groundwater levels for the Drentsche Aa catchment for the period 1989-2001 based on timesteps of one hour accumulated to day values. Upper graph gives the observed discharge (black), the median modelled discharge (red) and discharge from the MIPWA groundwater model (green). Middle graph shows the median of the modelled groundwater levels of the low reservoir for the LGSI-model (red) and the corresponding groundwater levels of the MIPWA model (black). Bottom graph indicates the median of the groundwater levels of the high reservoir for the LGSI-model (red) and corresponding groundwater level of the MIPWA model (black). In all graphs the grey colour indicates the bandwidth of the model, as determined by the GLUE analysis.

5.2 Model simulation over the period 1965-2010

Since the MIPWA results are available for the period 1989-2001, the calibration of the model has been done for the same period (Section 4.6). In order to get more insight in the model performance outside of the calibration period, the LGSI-model was used for a simulation of the period 1965-2011. Discharge measurements were available for the period 1980 – 2010 (Section 3.2) while groundwater levels were only available for the calibration period. By taking the period 1965-1980 as a start-up period for the model it is guaranteed that the initial conditions will not have any effect on the groundwater levels, especially for the slowly responding deep reservoir. In Figure 5.2 the results from the 45-years of simulated discharge and groundwater depth are shown. The NS_{eff} of the median simulated discharge is 0.632 which is lower than the NS_{eff} of previous runs (Table). The model performance of the simulation of groundwater depth is also slightly decreased as described in Table . However, from Figure 5.2 can be observed that the groundwater depths seem to be affected by a start-up period (from 1989 onwards) of MIPWA. Discharge simulation in 1989 is rather good, while the simulation of groundwater depths is slightly overestimated. Effects introduced by incorrect initial conditions probably cause the differences in groundwater depth in this first year of the MIPWA simulation.

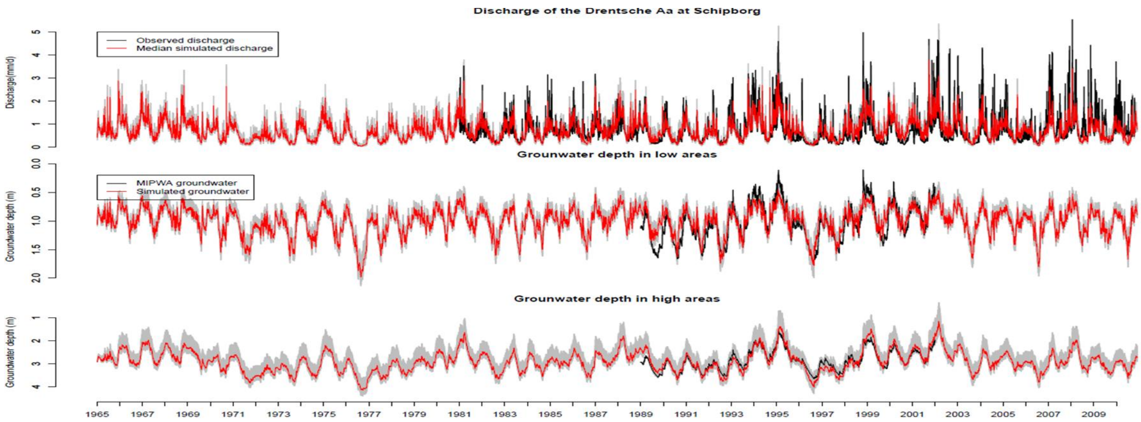

Figure 5.2 Modelled and measured discharge (1980-2010), modelled groundwater levels (1989-2001) for the Drentsche Aa catchment for the period 1965-2010. Upper graph gives the observed discharge (black) and the median modelled discharge (red). Middle graph shows the median of the modelled groundwater levels of the low reservoir for the LGSI-model (red) and the corresponding groundwater levels of the MIPWA model (black). Bottom graph indicates the median of the groundwater levels of the high reservoir for the LGSI-model (red) and corresponding groundwater level of the MIPWA model (black). In all graphs the grey colour indicates the bandwidth of the model, as determined by the GLUE analysis.

The model is able to simulate some events which are well reported in literature like the droughts of 1976 and 2003 (Hannaford et al., 2010; Hannaford et al., 2009). In these years the groundwater levels drop significantly, especially in the high reservoir. Especially after the drought in 1976 it takes several year before the groundwater levels are back to normal and discharge increases (especially peak discharges). The peak discharges remain underestimated by the model; this effect is more profound in the years 1992 - 2010 than in the period before the calibration period (1980 - 1989). The underestimation of the peak discharges in the latter period (1992-2010) could be caused by changes in land use and stream morphology or changes in flood control management by the water board at the weir at Loon. The water board of the Drentsche Aa catchment indicated a changes in policy for the weir at Loon, which could results in more peak discharges for the period 1992-2003. After this period the flood control measurements of the water board were changes again, to allow even more peak discharge and flooding of wetland in the catchment.

Over the entire simulation period of 1965-2011 the model is never adjusted to observed values in order to acquire a better model performance. In real-time simulations recalibration is often be applied in order to reduce errors/uncertainty by adding observed discharge measurement to the model input. Such a data-assimilation procedure is currently not incorporated in the model, however it would be very interesting to test the applicability of the model for real-time simulations as a tool in operational water management.

5.3 Changes in parameters after GLUE analysis

Every parameter of the LGSI-model was randomly varied over the selected range as described in Section 2.5 (minimum and maximum parameter values in Table). All the parameter combinations were used to determine the sensitivity of the model to each of its parameters as a function of the model efficiency and other parameters. The three examples of sensitive parameter combinations are shown in Figure 5.3.

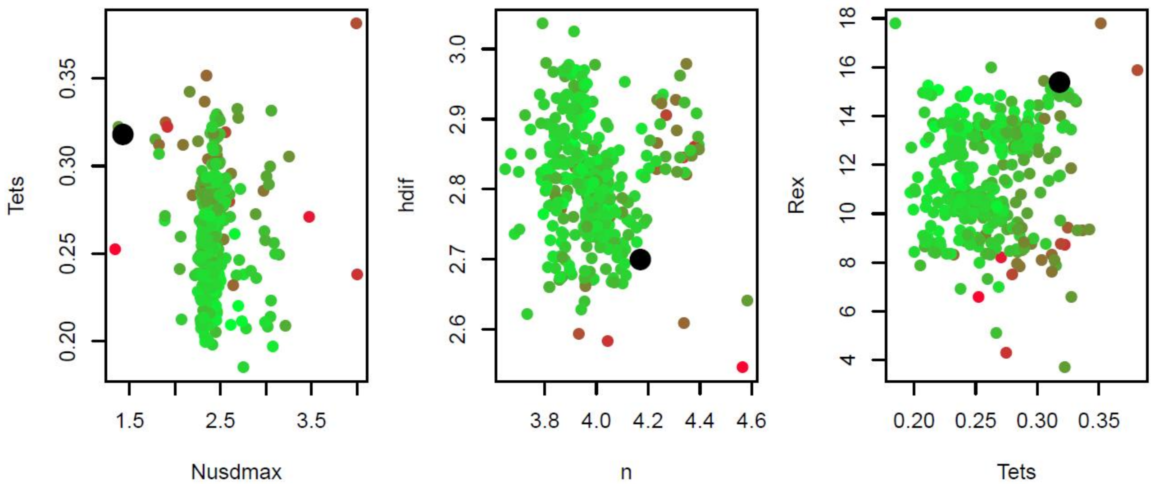

Figure 5.3 Relations between 3 sets of parameters for the LGSI-model, light green points are indicate high model performance for discharge. Decreasing model performance is indicates by red or dark green colours, in black the initial values are indicated. The description of parameters is given in Table

In *Figure* histograms of the parameter combinations which did satisfy the selection criteria where depicted. These results from the GLUE analysis of the LGSI-model could be used to modify spatially distributed groundwater models like MIPWA. Parameters could be changed based upon the shift found with the GLUE analysis, with respect to the initial values derived from the groundwater model. In *Figure* these changes could be detected based upon the median value of the parameter (red line) with respect to the original model parameter derived from MIPWA (black line).

5.4 Annual variation of different discharge components

Due to its` structure (Section 4.2) the LGSI-model enables separation of the different components of the discharge into direct precipitation runoff, overland flow, groundwater exfiltration and drain flow. These modelled components of the total discharge can be used for analysis of the relative contributions to the total discharge. For example these relative contributions can be analysed with respect to the total discharge or peak discharges. Which components will contribute most in absolute or relative value in the case of a peak discharge and which components will be dominant with respect to time. Such analysis can be especially useful when investigating (variations in) water quality of a stream.

For the year 1990 an example is shown in Figure 5.4, where the fractions of the total discharge are depicted over time for each component of the discharge. From Figure 5.4 it is clearly visible that the groundwater exfiltration will be dominant component of the total discharge throughout the year, but especially in the summer months. Drainage is only a component of importance in the winter months when groundwater levels are high.

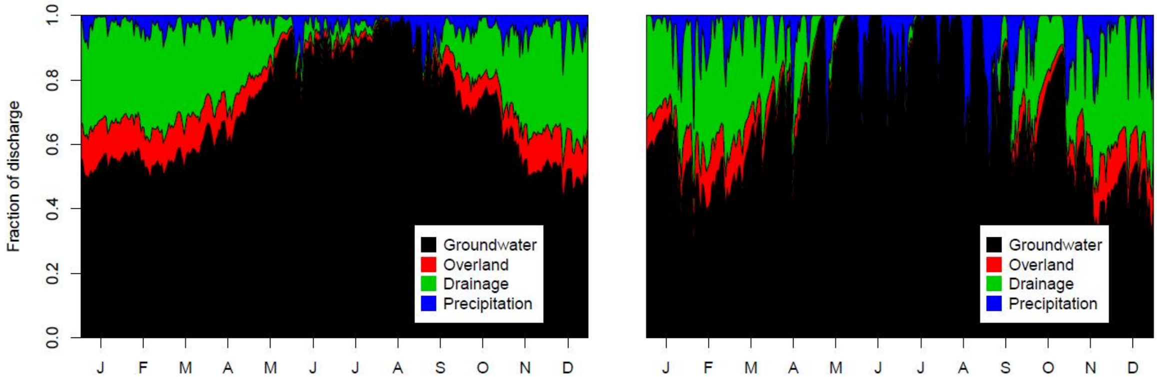

Figure 5.4 Discharge components at the Schipborg, as fraction of total discharge. Left graph indicates the average year fractions over the period 1989-2001, the right graph shows the discharge fractions for the representative year 1990.

6 Discussion

This study on the performance of the LGSI-model for the Drentsche Aa catchment led to some points of discussion, which are described in this chapter.

6.1 Time dependency of storage-discharge relations

Van der Velde et al. (2009) and Van der Velde et al. (2010), assumed that all relations between the different fluxes and average groundwater levels are constant over time. This is a valid assumption as long as catchment characteristics do not change significantly under influence of nature or human impacts. When the stream is modified by creating extra meanders, canalizing the stream or the construction of obstructions like weirs, the response of the discharge to a particular precipitation event can change significantly (Van der Schaaf et al., 2007). Changes in land use could also have a major impact, especially on the evapotranspiration and resistance to overland flow (Hurkmans et al., 2007). Problems could also occur when storage-discharge relations are dependent of the season. For example the resistance to overland flow will depend on the presence and type of vegetation. Resistant vegetation like high grassland will decrease the amount of overland flow, because water will have more time to infiltrate and discharge via the groundwater (Emmett, 1970). The last cause of changing relations between storage and discharges are the changes of parameters in different conditions of wetness. When a series of intensive precipitation events will occur in a small period of time, drains will be flushed by the excessive amount of precipitation. While, in period with low groundwater depths (summer months) the drain flow will be almost zero (Figure 5.4). In this period the drains could fill up with soil and dirt, which can result in an increase in the drain resistance which will have its effect on the drain flow in the first heavy precipitation event after summer. Another parameter that could change over time is the surface area occupied by streams and ditches, A_s (Section 2.3). When groundwater levels are higher and stream levels increase, the total area occupied by streams could increase, especially when large areas are flooded like marches or swamps. These areas will now become part of the stream system and will no longer be part of the ponds and therefore in reality will no longer contribute to overland flow.

Changes by season or dependent on the condition of wetness are very difficult to take into account, and this can only be done by using a function to describe the value of parameter over time. Change made by nature or human influence should be corrected since the total impact of these changes to the storage-discharge relations could be very significant for the total amount of discharge. In the Drentsche Aa the reported changes during the calibration period are not of noticeable size, and are not expected to have a significant effect on the discharge from the catchment.

6.2 Gamma distribution for the description of groundwater depths

An important conceptual innovation of the LGSI-model for the Drentsche Aa catchment is the addition of the use of a gamma distribution instead of the normal distribution for the high parts of the Drentsche Aa catchment that never experiences water storage above the surface (Section 4.1). The use of a gamma distribution can be derived from the Hooghoudt equation and the distribution of modelled groundwater depths from MIPWA. In Figure 4.6 the gamma distribution is fitted for the high reservoir for a very dry and very wet situation in the simulation period. Problems occur when the groundwater depth is negative due to extreme precipitation (water on the surface). These events can not be simulated with the gamma distribution. Because of the mathematical expressions describing the gamma distribution, it can not deal with negative values (Abramowitz and Stegun, 1972). Therefore, the separation between low and high areas must be made in advance, based on the modelled or observed groundwater levels or maps with groundwater statistics (e.g. Figure and Figure) combined with expert hydrological knowledge, in order to get accurate simulations of groundwater depths and discharge.

6.3 Peak discharges

The simulation of peak discharge is less accurate than periods with low or intermediate flow for the Drentsche Aa catchment: peak discharges are slightly underestimated This can have multiple causes, which are often the result of human influences in the catchment. The first possible cause of the inaccurate simulation of discharge peaks could be that part of the city of Assen discharges directly into the Drentsche Aa catchment (Section 3.1). In situations with high precipitation rates, this could lead to more discharge, since (almost) no water will infiltrate in this urban environment (Sarma et al., 1973), while in the model a larger part of the precipitation infiltrates and the amount of simulated fast overland flow is smaller. When precipitation rates are still low, the initial losses will compensate this effect and therefore the discharge is modelled accurately in case of an average event. Another reason for the high peak discharges could be the weir at Loon (Section 3.1), which is controlled by the water board. The discharge via this weir can be varied by the waterboard depending on the expected discharge. The last possible reason could be the contribution of overland flow from the high areas. Although groundwater can not be above the surface level, ponding could still occur due to low infiltration capacities of the soil and perched water tables. In situations with high precipitation rates these ponds could overflow and contribute to the overland flow of the high areas. This effect is not incorporated into the LGSI-model since overland flow can only occur in the model when groundwater depths become negative. Therefore, this could result in an underestimation of the discharge from the high areas via overland flow.

6.4 Simulation of statistical groundwater depth distribution

Every reservoir has a unique relation between groundwater depth and the parameters describing the statistical distribution of groundwater depths. These distributions are calculated from the results of the MIPWA groundwater model, which by itself could have errors in the exact representation of this distribution. When the GLUE analysis was applied for the LGSI-model the relations which showed the best results for discharge and groundwater depth simulation were not exactly the same as the relations determined with MIPWA. In Figure 6.1 it is shown that most of the fitted relations do not intersect with most of the points derived of MIPWA. However, overall groundwater depth distribution are simulated rather accurately as shown in Figure 6.2 which gives the distribution for two randomly selection days in the simulation period.

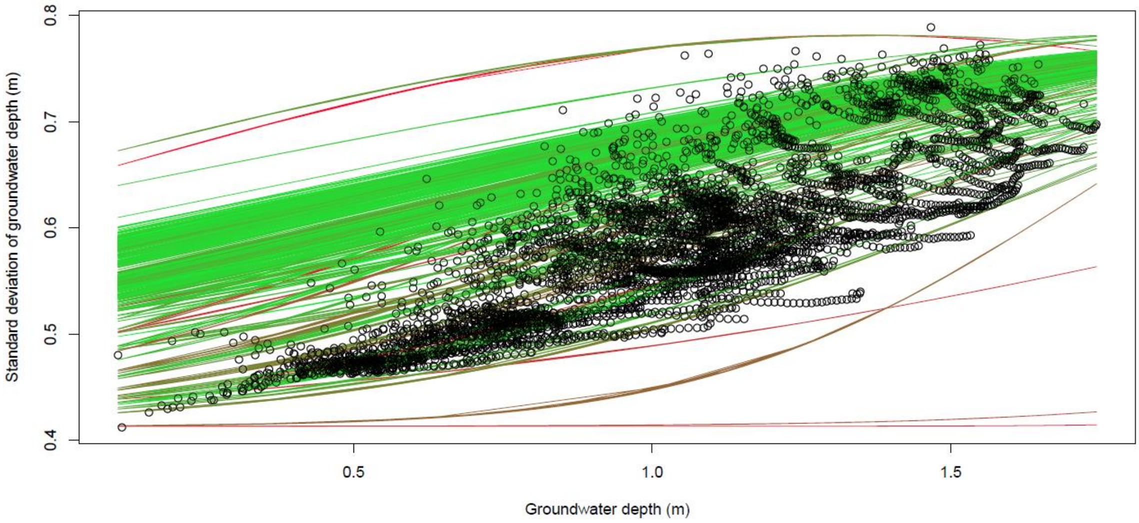

Figure 6.1 Standard deviation as a function of groundwater depth, for the best runs from the GLUE analysis. Light green colour indicates a high model performance for discharge, red colours indicate low model performance. The black points indicate values derived from the spatially distributed MIPWA groundwater model.

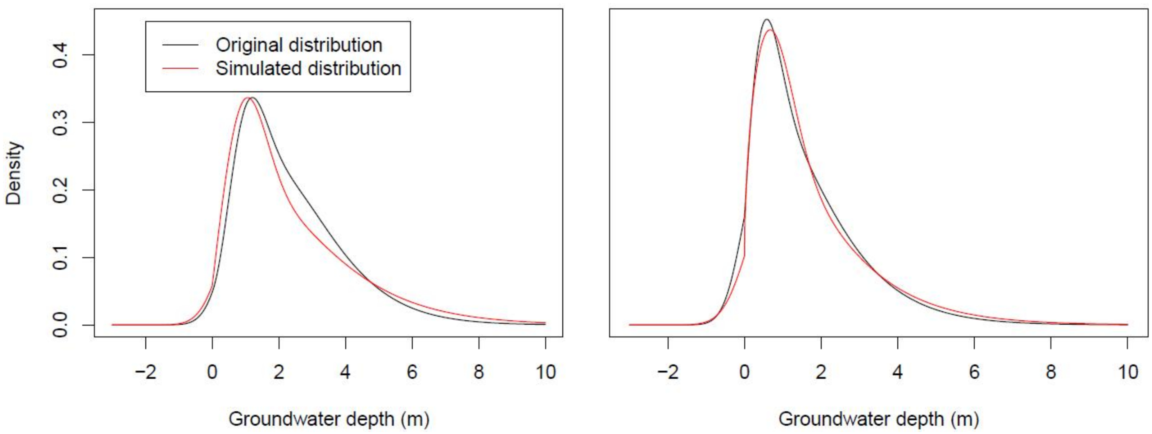

Figure 6.2 Distribution of groundwater depths (in m) of the simulated groundwater of the LGSI-model and the groundwater depth distribution 365000 groundwater depths of MIPWA (original distribution) for two different representative days, respectively 17-03-1990 and 05-04-1994.

6.5 MIPWA in comparison with measured groundwater

Groundwater depths are available in the DINO database (Data and Information of the Dutch subsoil) for a limited number of locations in the Drentsche Aa catchment as shown in Figure . As described in Section 3.3 the locations where groundwater depths are measured are not randomly distributed within the catchment. Therefore, this groundwater monitoring network was not used for initialisation and calibration of the LGSI-model. However, part of these groundwater monitoring locations were used for validation of the spatially distributed groundwater model (MIPWA; Hoogewoud, 2009) that was used for the initial parameterisation of the LGSI-model. In this section the observed groundwater depths are compared with the simulated groundwater depths of the spatially distributed groundwater model MIPWA.

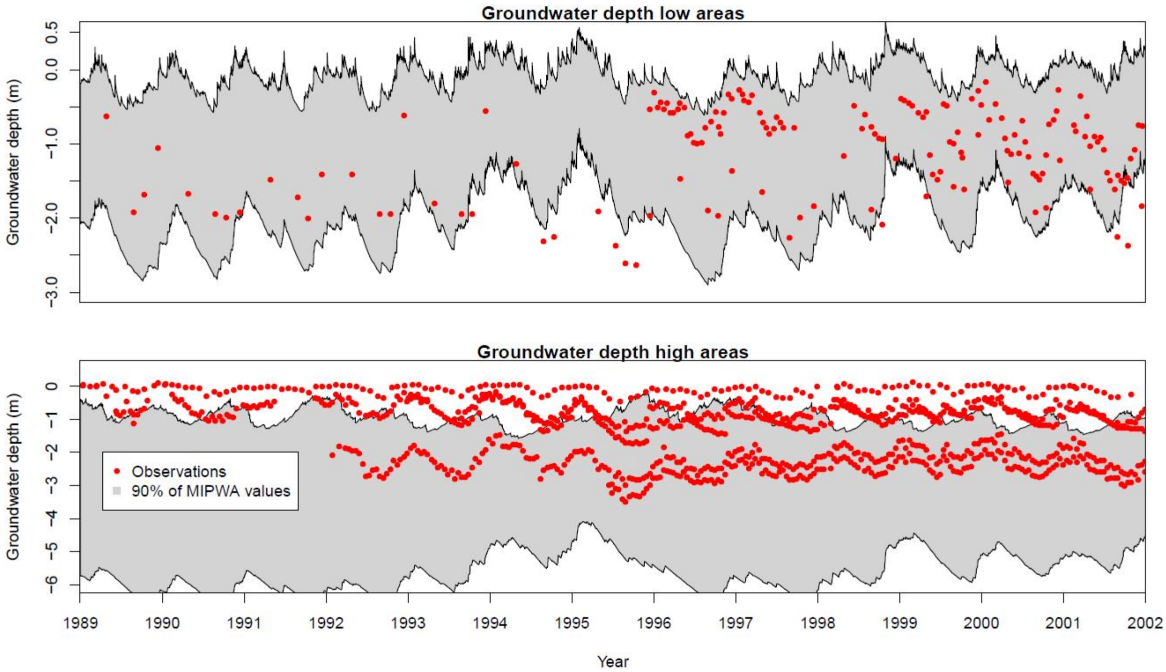

Figure 6.3 Observed groundwater measurements of the DINO database (Data and Information of the Dutch Subsurface) compared to 90% distribution of the MIPWA groundwater depth for the low and high areas

In Figure 6.3 the observed groundwater depths are compared to the MIPWA modelling results for both the low and high areas. In was concluded that MIPWA is able to given an accurate simulation of groundwater depths for the Drentsche Aa catchment for the low areas. The groundwater levels in the high areas are slightly underestimated by the MIPWA model compared to the observations of the DINO database. This could be the result of the uneven spatial distribution of the observations (Figure) or by an overestimation of the groundwater depth in the MIPWA model (Hoogewoud, 2009). Although modelled groundwater from MIPWA showed a possible underestimation of groundwater depth in the high areas, the high temporal and spatial resolution justify the use of the MIPWA groundwater model for the initialisation of the groundwater depths from the LGSI-model. Also, during the calibration phase, the LGSI-model is corrected for the overestimation in the initial groundwater depths.

7 Conclusions

This study on the performance of the LGSI-model for the Drentsche Aa catchment led to several conclusion concerning the LGSI-model concept, which are described in the following paragraphs.

7.1 LGSI as application of spatially distributed groundwater models

In order to create a LGSI-model of a catchment either a spatially distributed groundwater model or a well distributed network of piezometers is required. An advantage over other lumped models like rainfall-runoff models is the extensive amount of information on catchment and groundwater characteristics from the spatially distributed groundwater model that can be used in the LGSI-model. Besides the advantage of including the spatially distributed information of the catchment, the LGSI-model concept as an application of a spatially distributed groundwater model can be very valuable since it has several advantages over the spatially distributed model. An important advantage are the short calculation times (10 sec) compared to the relatively long calculation time of a spatially distributed model (days), which enables extensive calibration of the model parameters to observed data (e.g. GLUE-analysis). As a result of this extensive calibration, discharge simulations will improve compared to spatially distributed groundwater model and uncertainty estimations can be improved. Another advantage of the LGSI-model is the comprehensive output of the model. Specific discharge responses can be easily related to the distribution of groundwater depths and storage, while when using a spatially distributed model a clear relation between groundwater depths and discharge could be difficult to find in the extensive amount of output data. Another advantage of the short calculation times is that it increases the possibilities for coupling of spatially distributed groundwater models to channel flow discharge models.

7.2 Importance of storage with respect to discharge simulations

The storage in the catchment is of high importance for the accurate simulation of discharge. Errors in simulated discharge are often the direct result of errors in the model simulation of the groundwater depth in the low reservoir (Figure 4.13 and Figure 5.2). Storage in the deep reservoir (high and dry areas) will not have a direct effect on the discharge, but does have a large effect on the groundwater depths in the low reservoir by the interdependency of the reservoirs. In situations with a very dry high reservoir, the low reservoir will also have deep groundwater depths and peak discharges will not occur (Figure 4.13, the year 1976). Models that do not have an accurate simulation of the total storage in the catchment will not be able to model base flow and periods of extreme events like droughts in a proper manner. From this study it is concluded that the storage should be taken into account for an accurate simulation of discharge. This is in agreement with the findings of previous research (Winter, 1999).

7.3 Statistical distribution of groundwater depths

From this study it could be concluded that in the Drentsche Aa catchment a combination of a normal and gamma distribution is very well suited to describe the distribution of groundwater depths (Figure 4.6). The ability of the LGSI-model to simulate the distribution of groundwater depths is very important since most relations of the model depend on this accurate simulation of the groundwater depths (Van der Velde et al., 2009). When this distribution is modelled correctly, the storage within the catchment is described in more detail and therefore ultimately will result in better discharge simulation (Seibert et al., 2003; Smits and Hemker, 2004; Winter, 1999). This can only be achieved when the groundwater depths can be described by a single or a combination of statistical distributions, which have the ability to give an accurate representation of the groundwater depths in the catchment (Figure 4.6).

The choice to model the Drentsche Aa with two separate reservoirs which are linked by a Darcy equation (Section 4.2), was based upon the modelled data from MIPWA and hydrogeological expert knowledge. When the catchment was modelled as one reservoir, model performances would drop significantly (Section 4.1). Low areas with a large number of separate fields will satisfy the central limit theory (Section 2.2) and the assumption that groundwater depths can be described by a normal distribution will therefore become valid. In the high areas where overland flow and groundwater exfiltration do not occurs, the central limit theory is not valid since the groundwater depths are distributed over only five ice-pushed ridges (Section 4.1). Theory and results from the MIPWA groundwater model suggest that the gamma distribution will be most suited to model this kind of systems (Section 4.1).

7.4 Variation between catchments

Every catchment will require a specific set of parameters and model set-up. The Drentsche Aa had a very different catchment structure from the Hupsel brook catchment which was used in the study of Van der Velde et al. (2009) and Van der Velde et al. (2010). This resulted in another model set-up as described in Section 4.2 as well as different parameters (Table). From this study it can be concluded that there is not a generic model approach for every catchment. The equations that relate the distribution of groundwater depths to fluxes and storages are universal for every catchment modelled with the LGSI-model. However, the shape and the behaviour of the groundwater depth distribution and the values of the parameters that describe the relations between storage and discharge may differ between catchments. To determine the best configuration of the model and the most suitable statistical distribution to describe the distribution of groundwater depths expert hydrological knowledge is required.

7.5 Overall model performance and GLUE-method

The simulation of discharge in the LGSI-model is the combined value of all different outflow components (groundwater exfiltration, overland flow, and drainage). When groundwater depths are simulated accurately the simulated discharge will be in the correct order of magnitude, compared to observations. The performance of the LGSI-model can be further enhanced by using the GLUE-method: the median of the results of the GLUE-analysis for the LGSI-model was used as a predictor of the observed discharge. Additionally, the bandwidth of all LGSI-model runs in the GLUE-analysis with a Nash Sutcliff efficiency larger than 0.75 gives an estimate of the accuracy of the modelled discharge. In the case of the Drentsche Aa the bandwidth is very narrow, and the observed discharge is within the bandwidth for 70% of the simulation period. This indicates that the simulation results of the LGSI-model are accurate compared to observed discharge. From this study it is concluded that the LGSI-model concept in combination with the GLUE-method generates very suitable discharge simulations for the Drentsche Aa catchment.

8 Recommendations

This study on the performance of the LGSI-model for the Drentsche Aa catchment led to several recommendations concerning the LGSI-model concept, which are described in the following paragraphs.

8.1 Separation of discharge components

As described in Section 5.4 the discharge of different flow components of the catchment could be determined with the LGSI-model. In this study, these components are used to create a better understanding of the dominant flow processes in the Drentsche Aa catchment for every period of the year (Figure 5.4). These components could also be used for water quality purposes. When the aim is to get a better simulation of nitrate concentration, every flow component needs a specific concentration to calculate the total load based upon the total discharge from every component. These specific concentrations could be derived from measurements and simulations of total loads could be compared with observations. However, the possibilities with respect to water quality simulations have not been investigated in this study and are recommended for further research.

8.2 Prediction power of the Lowland Groundwater Surface water Interaction model

The current version of the LGSI-model does not use any observations during its calculations (Section 4.4 and 4.6). When for example discharge observations or groundwater level observations are incorporated into the model, the model performance could increase significantly, since the model is recalibrated every time. These observations could be used to calculate the corresponding groundwater depth from the inverse storage – discharge relations, where storage is plotted as a function of discharge. In combination with 10 day predictions of a meteorological station or real-time precipitation measurements, discharge values for the coming 10 –days could be forecasted. Since the model has a very low calculation time (around 10 sec) compared to a spatially distributed groundwater model in combination with a surface water model, it would be possible to do these calculations real-time. Every calculation can be made for different sets of parameter combinations, which are determined by a GLUE analysis as described in Section 2.5.

Furthermore, in scenario studies the model could be an additional tool to study the effect of different scenarios. When for a specific scenario, a spatially distributed groundwater model is used to calculate the effect on groundwater depths. The LGSI-model could be used to calculate the effect on discharge and simulate groundwater depths for a series of different parameters. Especially in combination with a Kalman filter (Kalman, 1960) the LGSI-model could also indicate the uncertainty and other possible solutions, while the original groundwater model is used as the control run.

8.3 Comparison and integration with surface water models

In this study, a time series of a 1D surface water model (e.g. Sacramento; Deltares, 2004), was not available for the Drentsche Aa catchment. Therefore, the results from the LGSI-model were not yet compared with a detailed surface water model. It is recommended that this comparison should be made in order to give an estimation of the model results with respect to dedicated surface water models. In case the LGSI-model performance is better then or comparable to the performance of 1D surface water models, the LGSI-models can be used as input of a channel flow model (e.g. Sobek; Deltares, 2004). This way, runoff simulations will be physically based to a larger extend. This possibility can be an important improvement in the coupling of spatially distributed groundwater models and channel flow discharge models.

8.4 Seasonal forecasts of discharge

The LGSI-model could also be applied as seasonal predictor for groundwater depths and corresponding discharge in combination with seasonal meteorological forecasts. Seasonal precipitation forecasts comprise a number of possible precipitation patterns, which could be used as input for the LGSI-model. These seasonal forecasts of simulated groundwater levels and discharge could then be used for water management. In situations with a large precipitation deficit, the capillary rise from the groundwater to the unsaturated zone could be used as an indicator for the difference between a droughts or a situation with only a minor water shortage. When we can make this distinction between a moderately dry or a severe dry period, water boards could use this information in operational water management (e.g. decide to store more water in the catchment). This advantage of the LGSI-model can be of importance in the near future, since the current seasonal forecasts for Western Europe are not reliable enough for operational water management (ECMWF, 2008).

8.5 Effect of climate change on stream discharge

As mentioned in this chapter, the LGSI-model could be very useful for short-term predictions as well as seasonal forecast models. The LGSI-model could also be useful for simulations that include the effects of climate change. Several studies (e.g. Haddeland et al., 2011) have been carried out using large-scale hydrological models to determine the effects of climate changes on the characteristics like discharge. These studies (e.g. EU-FP6 project WATCH) are also done on a more detailed scale for several vulnerable catchments with a spatially distributed hydrological model, like MODFLOW. The LGSI-model could be used in a similar manner, and while adding estimations of the uncertainty of those simulations based on the relations determined by the spatially distributed groundwater model in combination with a GLUE analysis. By creating small changes in the initial conditions and the input like simulated precipitation patterns or evaporation rates, uncertainties in the results from the spatially distributed model can be calculated. By using the LGSI-model in this manner, the possibility is created to perform detailed scenario analysis including uncertainty analysis without recalculating the entire spatially distributed model.

8.6 Changes in model set-up

The number of reservoirs of the LGSI-model has been increased for the accurate simulation of discharge in the Drentsche Aa catchment. This adjustment to the original model concept have been done in order to simulate the distribution of groundwater depths of the original MIPWA model. The better the distribution of groundwater depths is simulated, the more accurate the processes which contribute to the discharge are represented by the model (Van der Velde et al., 2009). Therefore, it is suggested that the number of reservoirs should be determined for every catchment separately in order to give an accurate simulation of the discharge and corresponding storage in the catchment.

8.7 Time-dependent parameterization of the LGSI-model

In this study, it is assumed that the parameters of the LGSI-model are constant over time. However, some parameters will change over time (Section 6.1) due to physical changes of catchment properties over time. To get an accurate simulation of the changes in parameter values over time calibration of the model could be done for consecutive period of 5 year every time. The relations between average groundwater depth and different types of fluxes and storage (Figure 4.10) could be determined for each of this period separately. This will enable the model to adjust to changes hydrological properties of the catchment (e.g. changes in morphology or removal of weirs).

9 Acknowledgements

The successful completion of this study would not have been possible without the support of some important people. First, I would like to thank Dimmie Hendriks and Ype van der Velde for their supervision during this internship, critical opinion on my research, nice ideas which helped to improve the quality of this report and a very wet field trip to the study area. Of course I would like to thank Deltares for the possibility to conducted my internship at their office in Utrecht and be part of their team of Groundwater management. In particular, I would like to thank Gerrit Hendriksen, Joachim Hunink, Jacco Hoogewoud for their support in running the MIPWA model and Marijn Kuijper and Perry de Louw for their effort to realize my internship at Deltares. Further I would like to thank Jan Roelsma, Harry Jager and Marian van Dongen for the observed discharge data and information about the Drentsche Aa catchment. Paul Torfs and Matthijs Boersema for reading and marking my internship report. All people of Wageningen University and Deltares, who took part in the discussion session about this study a shared their ideas about the model concept and its applications of the model. Finally I would like to thank Bas van der Grift, Ruth Heerdink and Janneke Klein for sharing their office with me.

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A Photographs of Drentsche Aa catchment taken on 19 January 2011

Photograph 11.1 Drentsche Aa at Schipborg

Photograph 11.2 Drentsche Aa in the low wet areas

Photograph 11.3 Overland flow into the Drentsche Aa

Photograph 11.4 Seepage in the low areas of the Drentsche Aa

Photograph 11.5 Weir at Loon

Photograph 11.6 Landscape in the high and dry areas of the Drentsche Aa

Photograph 11.7 Landscape in the low areas an wet areas of the Drentsche Aa

B Map of observed groundwater levels of the DINO database for the Drentsche Aa catchment

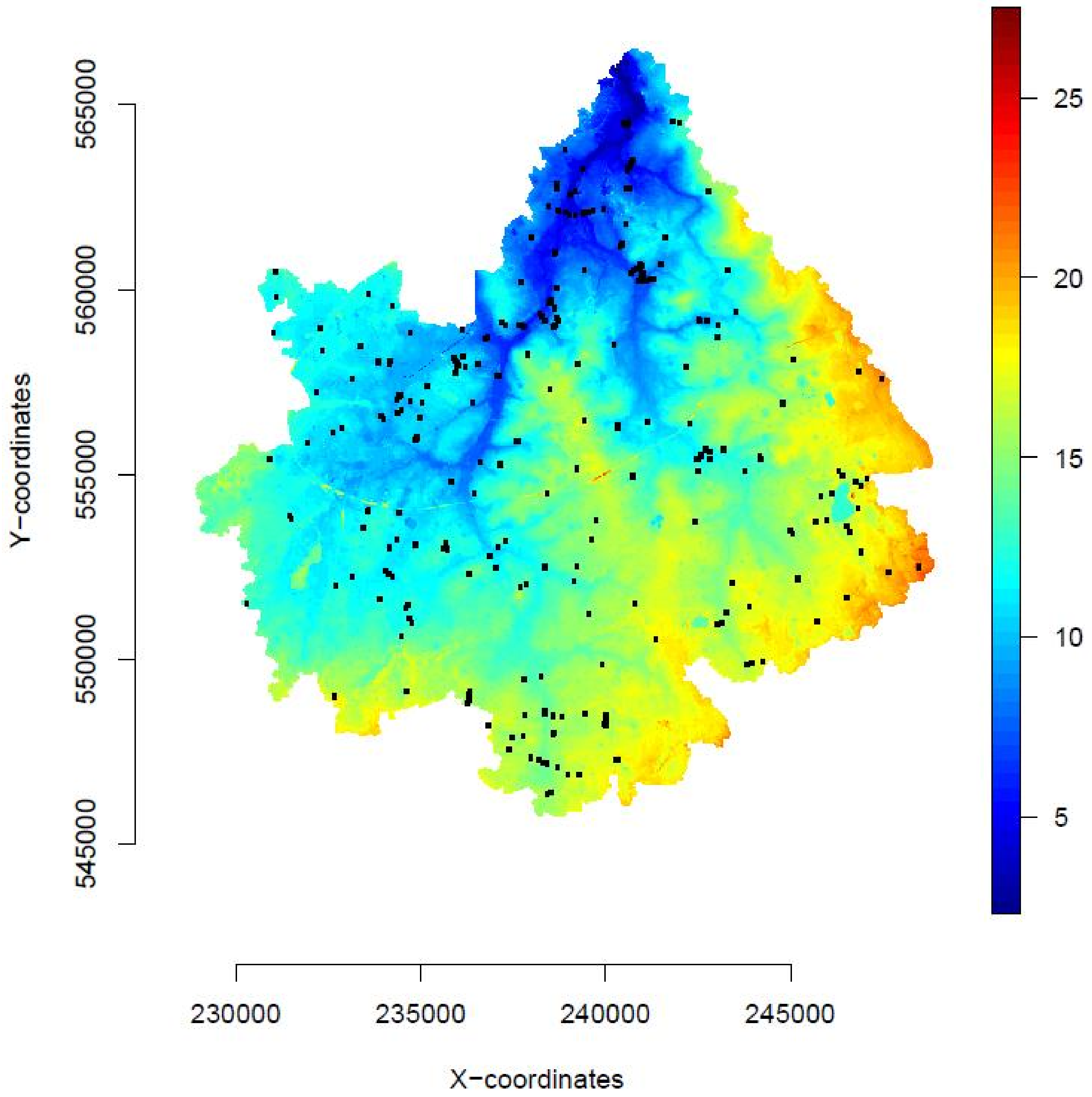

Figure 11.1 Spatial location of observed groundwater levels for phreatic aquifer, of the DINO database (Data and Information of the Dutch Subsurface) for the Drentsche Aa catchment.

C Maps of average, minimum and maximum groundwater depth (1989-2002)

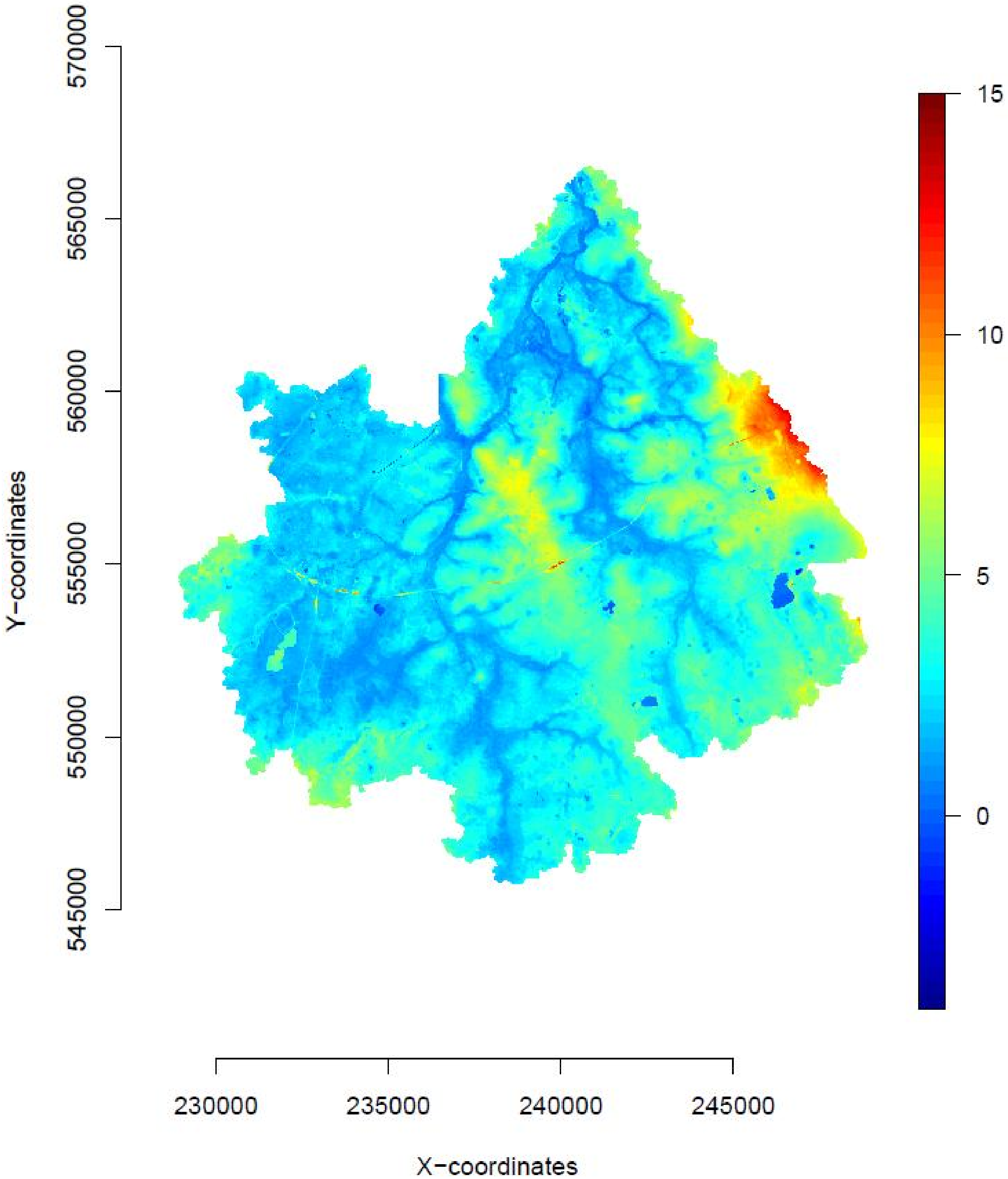

Figure 11.2 Maximum groundwater depth (in m) as calculated by the MIPWA groundwater model over the simulation period 1989-2002, for the Drentsche Aa catchment.

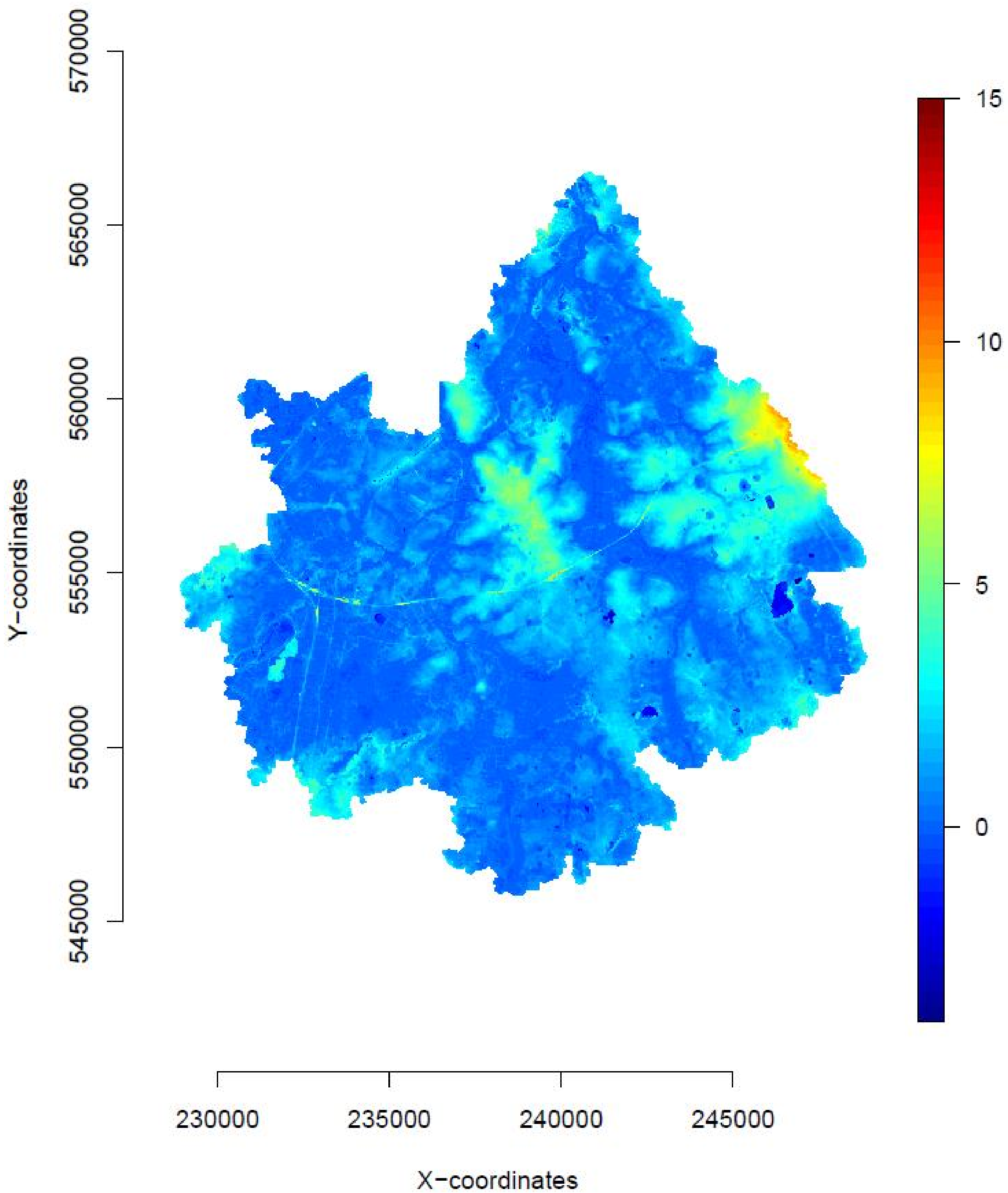

Figure 11.3 Minimum groundwater depth (in m) as calculated by the MIPWA groundwater model over the simulation period 1989-2002, for the Drentsche Aa catchment.

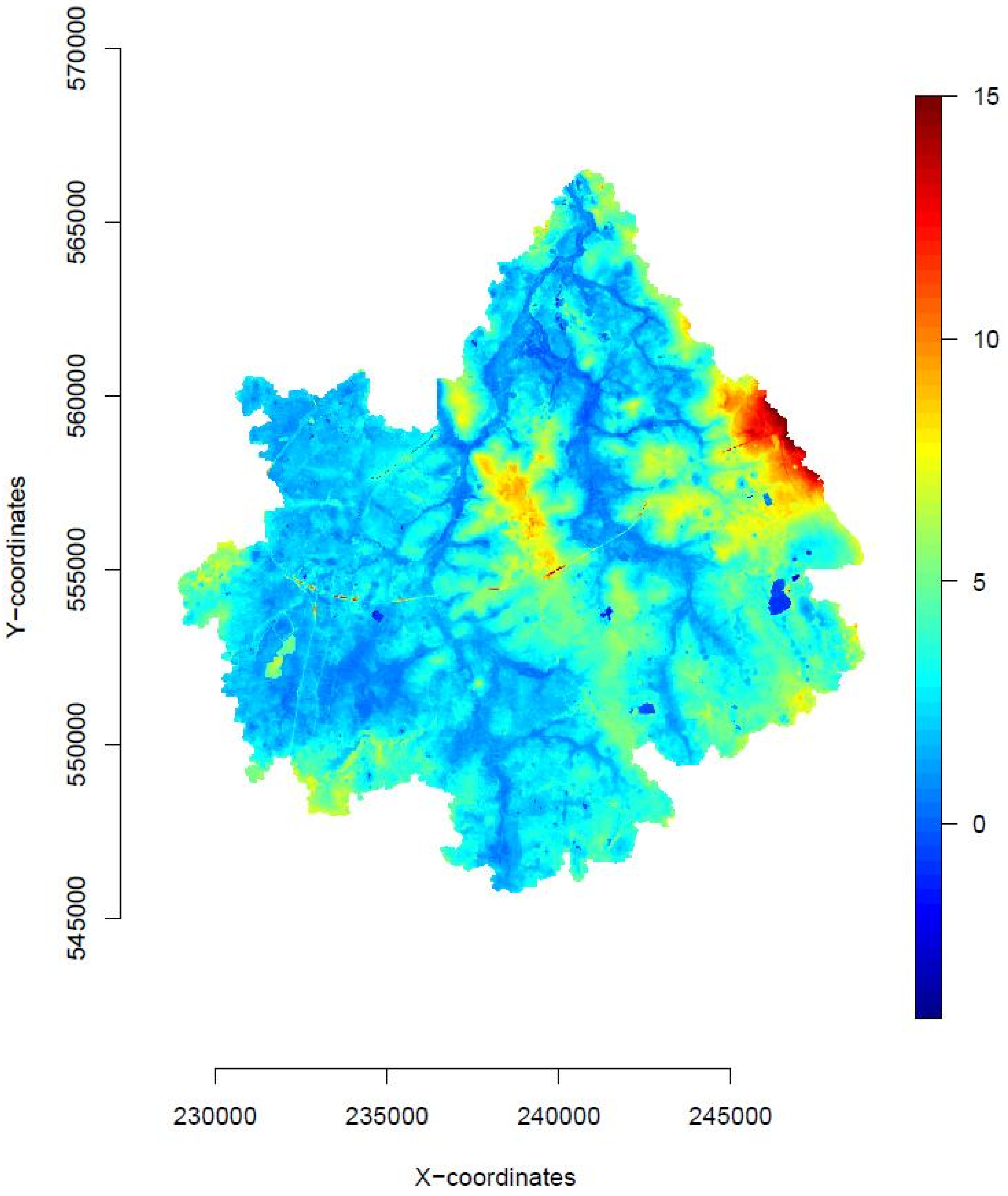

Figure 11.4 Average groundwater depth (in m) as calculated by the MIPWA groundwater model over the simulation period 1989-2002, for the Drentsche Aa catchment.

D Map of low and high areas of the Drentsche Aa catchment

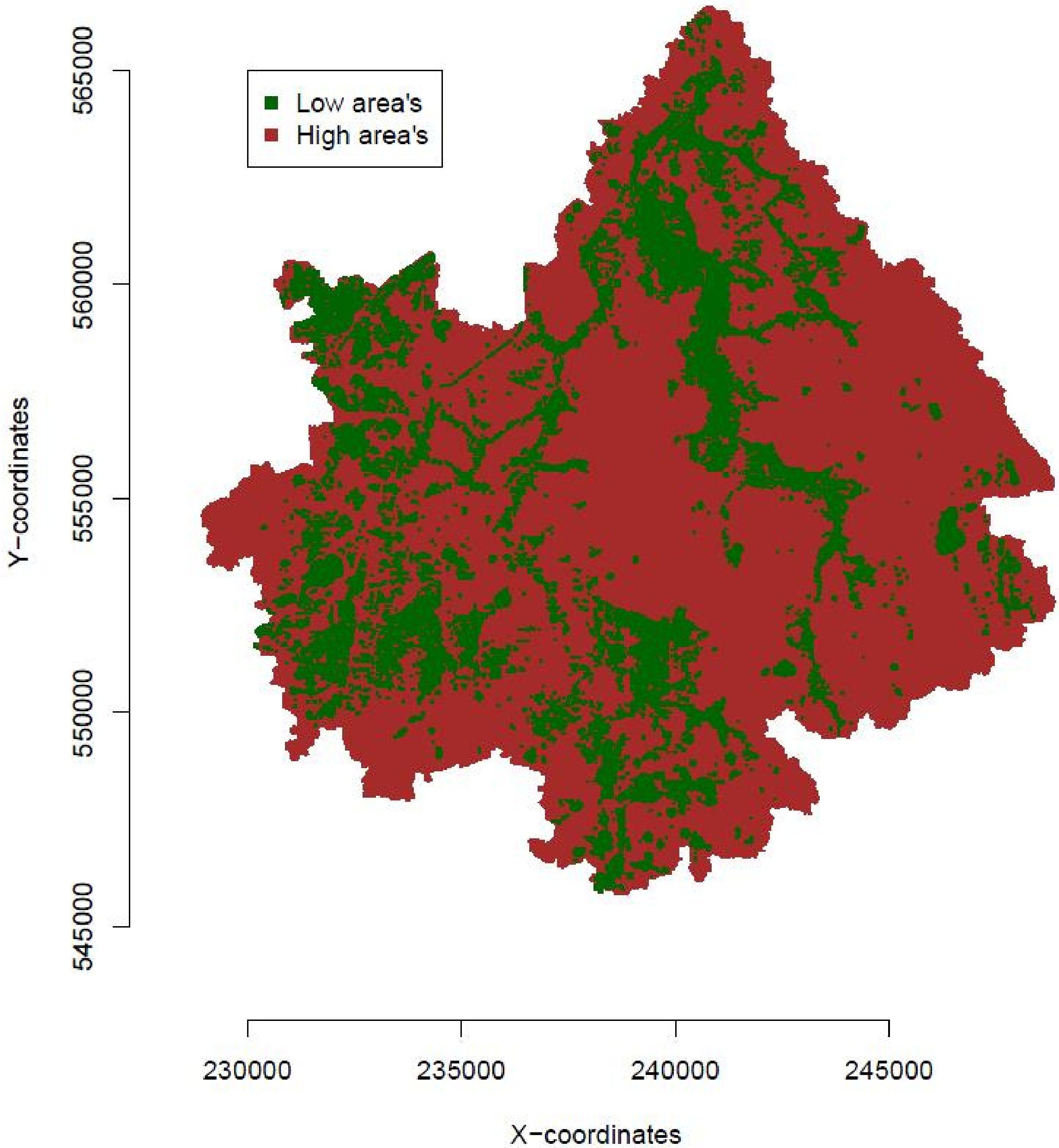

Figure 11.5 Division of low and high areas for the Drentsche Aa catchment, based on the criteria given in Section 4.1.

E Parameters of the LGSI-model

Table 11.1 Initial parameter set of the LGSI-model and possible ranges possible for GLUE analysis.

	Description	Initial value	Minimum	Maximum	Unit
b	Shape parameter	2.04	0	4	m
$u_{sd\,\max}$	$\langle u \rangle$ with max variance	1.43	0.43	2.43	m
a	Angle parameter	0.52	0.02	1.02	-
off	Offset parameter	0.7	0.2	1.2	m
m	Fraction of ponding	0.057	0	1	-
R_{ex}	Stream flow resistance	15.4	0	100	d
R_{ov}	Overland flow resistance	15.8	0	100	d
θ_s	Porosity of soil	0.318	0.225	0.475	-
α	V.G. parameter	0.88	0.63	1.13	m-1
n	V.G. parameter	4.17	3.67	4.67	-
h_{dif}	Height difference reservoirs	2.7	2.4	3.0	m
c	Resistance interflow	650	617	753	d
Q_{out}	Outflux from low reservoir	4.0 e-4	0	2.5 e-3	m/d
E_{mL}	Average depth of reduction low area	1.4	0.4	2.4	m
$\sigma_{E_{mL}}$	Standard deviation reduction low area	0.2	0.05	0.35	m
E_{mH}	Average depth of reduction high area	3.0	1.0	5.0	m
$\sigma_{E_{mH}}$	Standard deviation reduction high area	1.3	0.3	2.3	m
R_{dr}	Drain resistance	778	0	2000	d
D_{drL}	Drain depth low area	0.89	0.39	1.39	m
A_{drL}	Drain area low area	23	0	72	km^2
D_{drH}	Drain depth high area	1.09	0.59	1.59	m
A_{drH}	Drain area high area	12	0	72	km^2
A_{sL}	Undrained and wet low area	11	0	72	km^2
A_{sH}	Undrained and wet high area	5	0	72	km^2
A_s	Area with ponding for overland flow	21	0	72	km^2

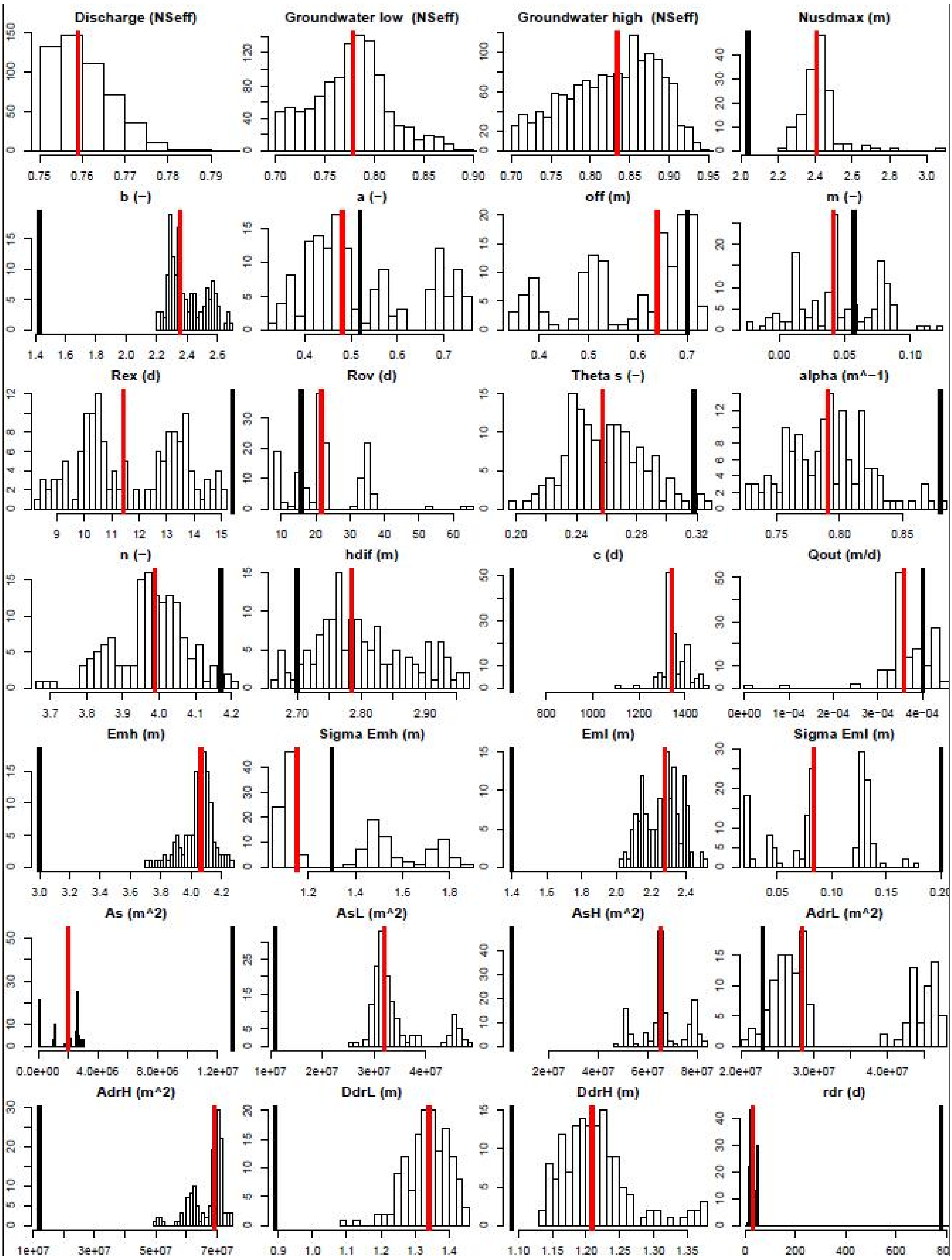

Figure 11.6 Histograms of all parameters of the LGSI-model, parameters and dimensions of the x-axis are given in the title of each plot. The red line indicates the median of the histrogram and the black line indicates the original value derived from MIPWA.

F Model efficiency results for all simulations

Table 11.2 Model efficiency for all simulations of the LGSI-model,

Simulation	**Component**	R^2	NS_{eff} ('89-'01)	NS_{eff} ('80-'10)	NS_{lag} ('89-'01)
Daily simulation (1989-2001)	Discharge	0.770	0.764		0.843
	Groundwater depth (low)	0.806	0.778		
	Groundwater depth (high)	0.942	0.872		
Daily simulation (1965-2010)	Discharge	0.636	0.738	0.632	0.825
	Groundwater depth (low)	0.786	0.748		
	Groundwater depth (high)	0.904	0.830		
Hourly simulation (1989-2001)	Discharge	0.755	0.750		0.835
	Groundwater depth (low)	0.818	0.788		
	Groundwater depth (high)	0.951	0.861		