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INTEGRATING VEGETATION MAPPING IN GROUNDWATER MODELLING FOR ECOHYDROLOGICAL PREDICTIONS WITHIN AN ECOSYSTEM VISION

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Abstract: In general, groundwater models need readily available data of measured heads for calibration. In some cases timeseries of measured heads are not readily available, do not exist or are of insufficient quality in order to carry out a sound calibration. In this article, an alternative methodology for calibrating groundwater models is presented, based on a feedback from ecology towards hydrology. On the basis of the available vegetation survey and with the use of GIS, area-covering maps of different hydrological parameters were created and compared to the output of the groundwater model. A number of different evaluation criteria were established to facilitate this comparison. By adopting this methodology a successful calibration of the model was obtained. The presented groundwater model was developed in the framework of an ecosystem vision for four brook valleys at the southern side of the Campine Plateau in Flanders in order to make ecohydrological predictions for hypothetical scenarios.

INTRODUCTION

An ecosystem vision is a decision support tool for the environmental policies of the Flemish government. It is used to optimise the quality and the structure of ecosystems in an ecologically valuable area. The ecosystem vision for four brook valleys at the southern side of the Campine Plateau in Flanders provides insight in the possibilities for nature development and restoration, within the boundary conditions imposed by the abiotic environment, management, regulations and legal possibilities.

In the studied brook valley ecosystems the possibilities for nature are highly influenced by the hydrological situation. This situation consists of a regional hydrological system combined with local human influences as the effects of

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drainage, water abstractions, use of weirs, etc. In this paper first a groundwater model is presented, which aims to give insight to the functioning of the hydrological system and which allows delineation of infiltration and discharge areas, and calculation of groundwater levels and travel times. The model can also be used to predict the effects of changes in hydrological conditions. Finally the knowledge obtained from the hydrological model can be fed as abiotic boundary conditions to ecological models, to analyze the interaction between the hydrological and ecological condition. The design and elaboration of specific hypothetical scenarios allow the evaluation of predicted potencies for nature on the basis of changes in hydrology.

The integration of hydrology and ecology is here not treated as a one-way process, since knowledge about the actual vegetation and vegetation-groundwater interactions was also used to calibrate the groundwater model. In the absence of measured groundwater levels in the study area, a different methodology had to be developed. On the basis of the available vegetation survey and with the use of GIS, area-covering maps of different groundwater related parameters were created, which could be compared to the output of the groundwater model. A number of different evaluation criteria were established to facilitate this comparison. By evaluating the differences between vegetation based and model generated maps, and by optimising the evaluation criteria, a successful calibration of the model was obtained (Corluy et al., 2003; Jalink & Grijpstra, 2003).

Description of model and study area

The study area consists of four brook valleys: Asbeek, Zutendaalbeek, Bezoensbeek and Munsterbeek, at the southern side of the Campine Plateau. The Campine Plateau is situated in the southeast of the province of Limburg in the east of Flanders near the rivers Demer and Maas. Fig. 1 shows the delineations of the model area (groundwater model) and the study area (ecological model). The boundary for the model area is formed by watercourses (Demer in the southwest and Ziepbeek in the northeast) and local drainage divides. The Albert Canal intersects the model area from east to west. The total model area is more than 80 km².

The model area has a pronounced topography and the highest parts can be found on a north-south axis centred in the model area (up to ca. 110 m). The Campine Plateau with this central north-south ridge thus forms the drainage divide between the catchments of the Maas and the Demer (elevation ca. 40 m). The slope of the study area ranges from steep (ca. 12 %) at the sides of the plateau, to very gentle (near 0 %) near Demer and Maas.

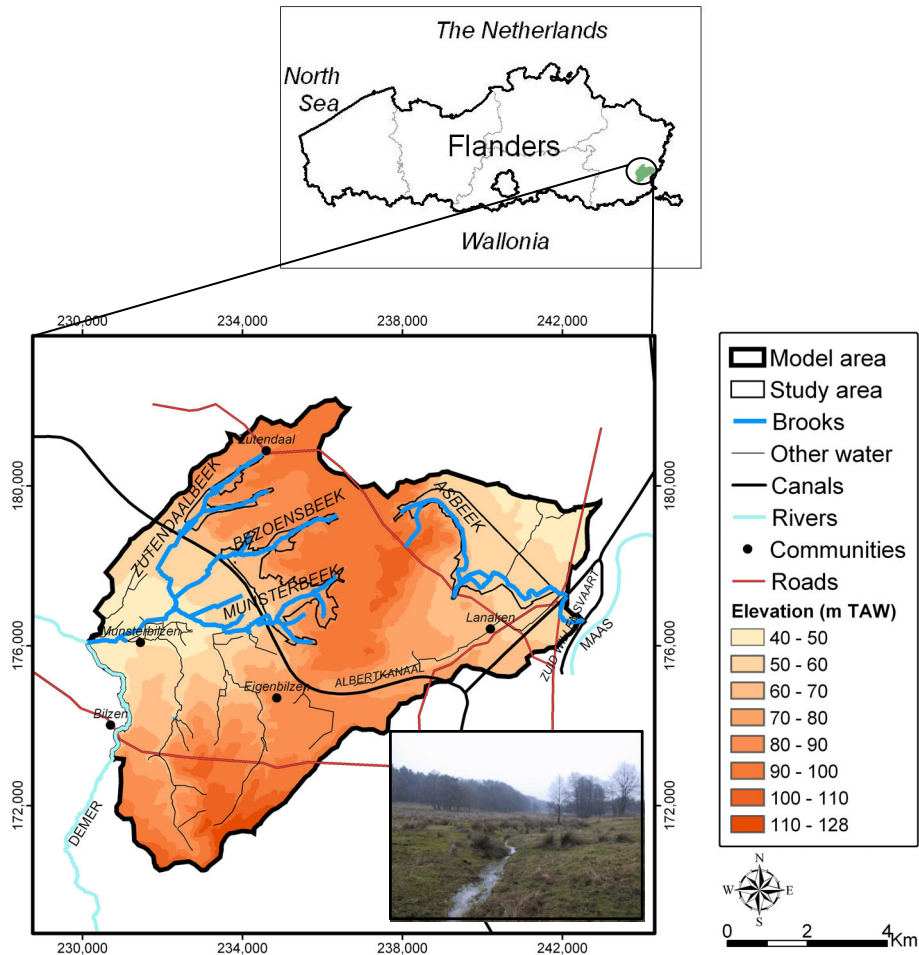


Figure 1. Model and study area, together with brooks and watercourses and DEM, situated in Flanders. The inset on the lower left shows an upstream part of the brook “Asbeek”

The geology consists of layers of tertiary origin, which are covered by a thin quaternary layer. The quaternary layer consists of eolian depositions of loams and sands, and alluvial depositions of coarse sands and gravel. The tertiary layers are inclined slightly towards the north-northwest and towards the north successively younger layers crop out. These layers, in order of decreasing age, are known as: the Formations of Sint-Huibrechts-Hern (fine sand), Borgloon (clay-sand), Bilzen (sand-clay-sand), Boom (heavy clay), Eigenbilzen (fine sand – clayey fine sand) and Bolderberg (fine sand – sand). In general the Tertiary surface resembles the shape of the topographic surface, dominated by the valleys of Demer and Maas.

GROUNDWATER MODEL

A groundwater model was developed with MODFLOW (Harbaugh & McDonald, 1996) to study the hydrological condition of the study area. The three dimensional stationary groundwater movement can be described by following differential equation:

$$\frac{\partial}{\partial x} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial h}{\partial z} \right) + N = Q \quad (1)$$

with K = hydraulic conductivity of the layer (m d⁻¹), h = saturated head or groundwater potential (m), N = groundwater recharge (m d⁻¹), Q = groundwater discharge (m³ m⁻² d⁻¹)

The hydrogeological concept of the model area consists of four model layers. Each represents one or more geological layers. The geological layers were combined or treated as separate model layers based on their hydrogeological properties. The model layers together with their description and hydraulic conductivities are given in Table 1.

Table 1. Hydrogeological concept of the model area

Geological description	Symbol	Model layer	Hydr. conductivity (m d ⁻¹)
Quaternary layer	Kw	Layer 1	0.001 - 25
Formation of Bolderberg	Bb	Layer 2	0,5
Formation of Eigenbilzen	Eg		
Formation of Boom	Bm	Layer 3	0.001
Formation of Bilzen	Bi	Layer 4	2
Formation of Borgloon, Member of Henis	BoHe	Lower model boundary	-

For every layer the horizontal and vertical hydraulic conductivities were assigned based on the known spatial distribution of the geology and on values from literature for the geological materials. These values were calibrated as described in the following section.

A steady state model consisting of four layers was developed. The cell size is 20 by 20 m. The model area is 80.6 km² and the model contains 806,000 active cells. The boundary conditions of the model are assumed to be dominantly no-flow boundaries at the drainage divides and constant head boundaries at the watercourses of Demer and Ziepebeek. The groundwater recharge was modelled with the WetSpa model (Batelaan & De Smedt, 2001) on the basis of precipitation, temperature, potential evapotranspiration, wind speed, and maps of land use, soil type, slope and groundwater depth. Because WetSpa needs groundwater depth as an input, Modflow and WetSpa were run iteratively to

obtain the modelled groundwater recharge. 24 groundwater abstractions or wells were identified in the area and are input to the model. The two biggest abstractions have licenses for 1,095,000 and 4,380,000 m³ y⁻¹, while the others have licenses ranging between 50 and 120,000 m³ y⁻¹. The drainage depths of the known network of brooks and ditches in the study area were measured in situ, interpolated along the draining network and are used as DRAIN conditions in the model. The depth ranges from a few centimetres to more than 2.5 m below ground level.

Outputs of the groundwater model comprise simulated groundwater depths, delineations of infiltration and discharge areas, discharge rates and travel times.

MODEL CALIBRATION

As stated before, generally groundwater models need measured groundwater levels in order to be calibrated, i.e. measured and simulated heads are compared to each other and the calibration process aims at minimizing the differences between the two. In some cases timeseries of measured heads are not readily available, do not exist or are not continuous or not measured at enough locations in the study area to be able to carry out a sound calibration. In this study for example, only two representative locations existed where hydraulic heads were measured. Moreover none of the measuring locations were situated in the ecological zone of interest. Nevertheless, it could be seen that the measured and simulated heads showed a reasonable match. The average difference was 0.45 m. Unfortunately it is impossible to draw any conclusions with regard to the precision and accuracy of the model based on this data. Therefore another methodology to calibrate the model had to be adopted. An approach was elaborated to calibrate the model on the basis of available data, other than directly measured heads, but which could be linked indirectly to hydrological parameters.

Available data that could be linked to groundwater conditions indirectly was found in the vegetation survey (Knuysen & Meire, 2002). This vegetation survey was carried out on a parcel level and two types of groundwater-related information could be extracted from this survey. Firstly, for 436 parcels, observations of moisture and discharge conditions were mapped and rated on a scale from 1 (dry) to 5 (standing water) for the moisture condition and from 1 (none) to 3 (in drains and parcel surface) for the discharge condition. Secondly, for 433 parcels, groundwater levels were derived on the basis of the vegetation survey. For every parcel, those plant species that required the wettest conditions were identified by means of Ellenberg moisture classes. (Ellenberg et al., 1991). These Ellenberg classes then were used to describe the wettest spot in the parcel in terms of a mean groundwater level, a mean highest and a mean lowest groundwater level (all for the wettest point in the parcel). Additionally, an indication of the variation in moisture content over the parcel was estimated (Jalink & Grijpstra, 2003).

Evaluation criteria

On the basis of these surveyed and derived data, a number of evaluation criteria were developed in order to facilitate a calibration of the groundwater model (Table

2). The criteria indicated with U correspond to parcel based observations, the ones indicated with K correspond to evaluations of the wettest point in the parcel.

There are 7 qualitative criteria, which check the quality of discharge simulations within the parcels against discharge and moisture observations (U1 to U3) and against Ellenberg-derived groundwater level (K1 to K4). E.g. U3 is the percentage of parcels that were evaluated to be dry during the vegetation survey and show no discharge in the model. Then there are 2 quantitative criteria (K5 and K6) which check the differences between Ellenberg-derived groundwater level and model simulated groundwater level at the wettest point in the parcels, in terms of SSE (Sum of Squared Errors) and RMSE (Root Mean Squared Error).

Table 2. Overview of evaluation criteria for calibration, based on field observations and Ellenberg-derived groundwater depths

	Criteria	Observation	Model
Qualitative	U1	Discharge (surface)	Discharge
	U2	Discharge (ditches & surface)	Discharge
	U3	Dry	No discharge
	K1	Shallow GW table	Discharge
	K2	Dry – no variation	No discharge
	K3	Deep GW table	No discharge
	K4	Deep GW table	No discharge > 1 mm/d
Quantitative	K5	SSE	
	K6	RMSE	

Calibration result

Table 3 shows the values of the different criteria after model calibration. Under optimal conditions criteria U1 to K4 have a value close to 100 % and K5 and K6 are as small as possible. Changing the horizontal and vertical hydraulic conductivities of the different model layers over more than 30 model runs, made it possible to optimise the evaluation criteria.

Table 3. Optimised values for the evaluation criteria (the second row shows the number of parcels that were evaluated for every criterion)

	U1	U2	U3	K1	K2	K3	K4	K5 (m ²)	K6 (m)
%	56.0	80.0	72.8	86.9	71.4	85.7	92.9	194.13	0.66
Tot. # parcels	25	45	235	244	7	4	14	433	433

Based on the evaluation criteria it was possible to calibrate the groundwater model, whereas otherwise this wouldn't have been possible. On the basis of the evaluation criteria it can be concluded that the model is able to simulate both groundwater levels and discharge locations fairly well.

Only U1, the correspondence between discharge observation on the parcel surface only and discharge simulated by the model, shows a lower value. However, it was found that the parcels where the model simulated no discharges, were located close to discharge areas and on average had a shallow groundwater level of around 0.5 m. Small topographical differences which are not comprised in the model's 20 m DEM probably can account for this deviation. On the other hand, U2, which represents the correspondence between observed discharge in ditches and the parcel surface and simulated discharge, shows a very good value of 80 %.

The RMSE (K6) gives an indication of the mean difference between the derived and modelled groundwater level. Over the course of calibration this value was reduced to 0.66 m for a total of 433 parcels, which indicates a reasonable fit for the groundwater levels.

To give a spatial evaluation of the model performance, the map in Fig. 2 shows for every parcel the comparison between the derived and simulated groundwater level at the wettest point of the parcel. This map is also very valuable with regard to assessing where the model gives reliable results and where it doesn't.

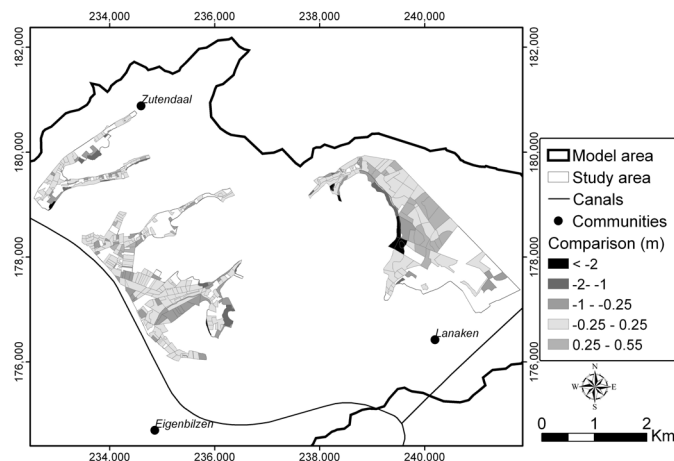


Figure 2. Comparison of simulated and Ellenberg-derived groundwater depths for the wettest point in the parcel (m)

For 64.1 % of the parcels the difference is less than 25 cm, so at these parcels the model gives very reliable results. From the figure it can be seen that the model only gives poor results at some parcels along the Asbeek at the flank of the Campine Plateau. The reason for this can probably be found in the complex geology, which shows a fault near this location. Of course, one has to bear in mind when looking at the figure that the comparison presented is based on Ellenberg-derived groundwater depths instead of measured ones.

RESULTS

The groundwater model was mainly used to calculate groundwater depths, discharge rates and discharge areas. As an illustration, some results are shown in this section.

The model was run for the actual situation and for a hypothetical wetting scenario where human influence was eliminated as much as possible (Fig. 3). For the latter the drainage depth of the brooks and ditches in the whole study area was reduced to maximum 0.40 m under topographic surface level. For some selected brooks the drainage depth was even reduced to 0.25 m or no drainage at all. Moreover, in the wetting scenario all groundwater abstractions are closed. The scenario provides some useful insight in possible changes in hydrology, which in turn will induce changes in vegetation (Mitsch & Gosselink, 2000).

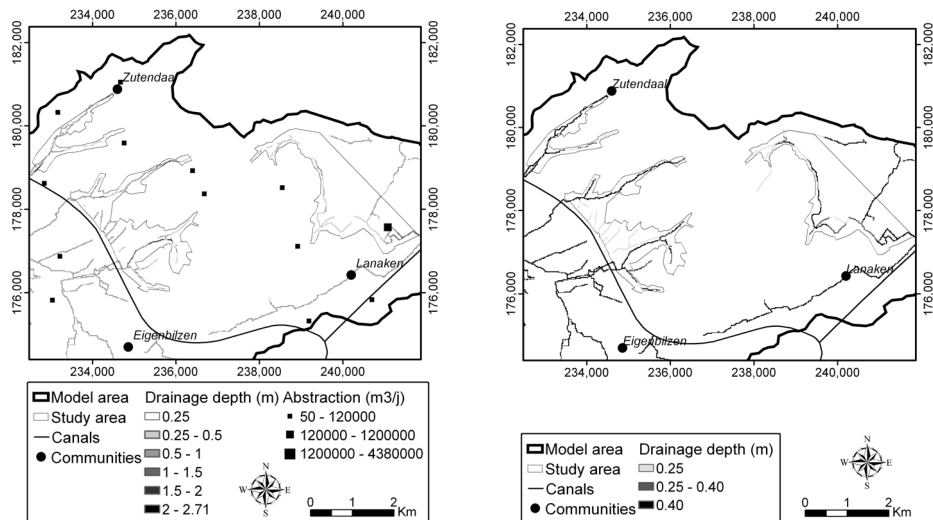


Figure 3. Drainage depths (m) for the brooks and groundwater abstractions ($m^3 y^{-1}$) for the actual situation (left) and the wetting scenario (right)

Groundwater depths

Fig. 4 gives the difference in groundwater depth between the actual situation and the wetting scenario for the study area. The groundwater level for the wetting scenario is on average 15 cm higher than for the actual situation. The most important difference, however, can be found near a water abstraction in the valley of the eastern Asbeek, which amounts to more than six meters. In the valleys of the three westerly brooks the difference increases up to 1.60 m.

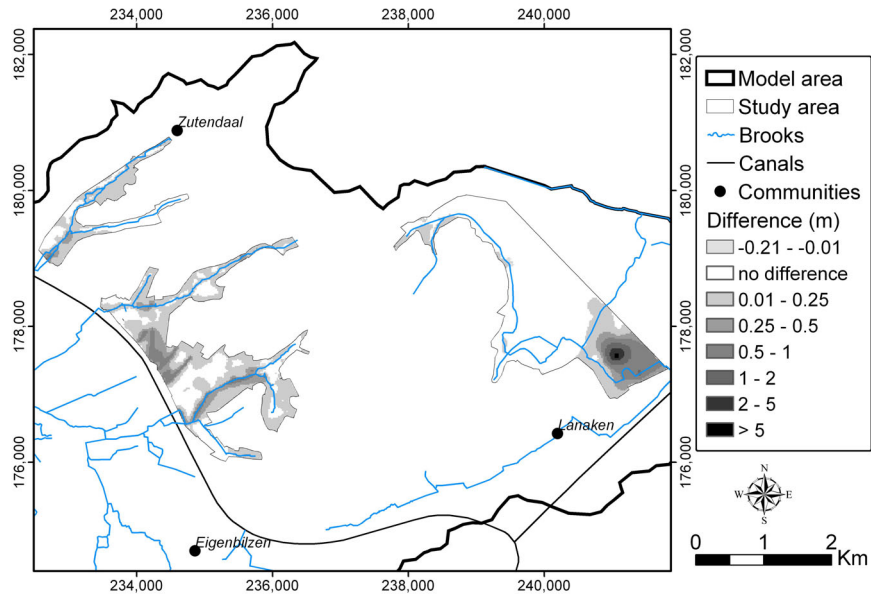


Figure 4. Difference in ground water depth between actual situation and wetting scenario, positive numbers indicate a deeper ground water level for the actual situation.

When the influence of the different measures is evaluated independently, it's seen that closing of the abstractions has a big influence for the site in the southeast of the Asbeek valley, whereas at the other sites this hardly has any influence. Decreasing the drainage depth has an influence for a considerable part of the three westerly brook valleys, but hardly any influence in the Asbeek valley.

Discharge areas and intensities

The discharge areas and discharge intensities were calculated with the model. Fig. 5 shows results of this for the actual situation and wetting scenario in the valleys of the westerly brooks. In the actual situation 28.6 % (2.19 km²) of the study area is discharge area, whereas this value is 36.6 % (2.80 km²) for the wetting scenario. Otherwise stated; the discharge area itself increases by 27.9 %. This increase is mainly due to the fact that in the actual situation the brooks are so much deepened that they lower the local groundwater table, hereby preventing discharge on the parcel's surface

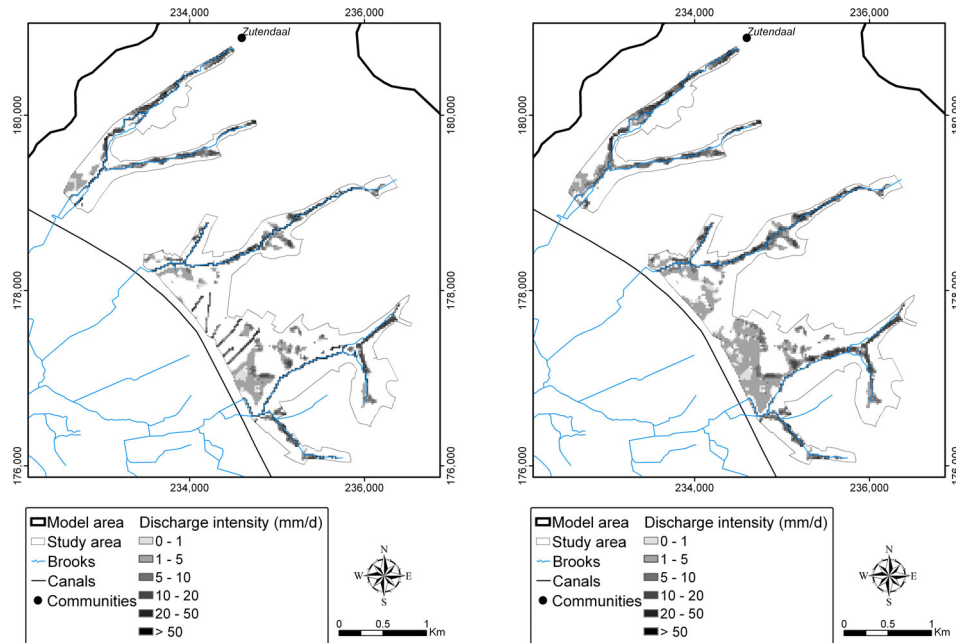


Figure 5. Discharge areas and intensities (mm d^{-1}) for the actual situation (left) and wetting scenario (right) for the brooks Zutendaalbeek, Bezoensbeek, Munsterbeek

Not only the location, but also the intensity of the discharge changes. If the discharge in the brooks is not taken into account, the mean discharge intensity is 1.2 and 1.6 mm d^{-1} for the actual and wetting situation respectively. The same trend of increasing discharge intensity can be observed in Fig. 5.

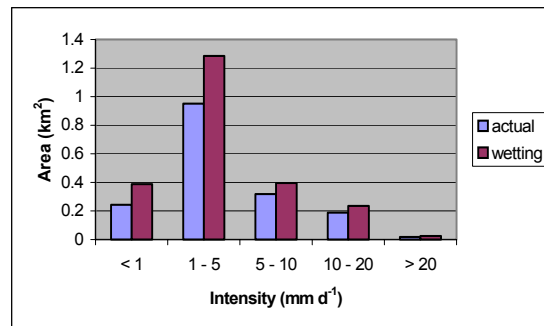


Figure 6. Discharge intensity (mm d^{-1}) for the discharge areas in the model area

CONCLUSION

Groundwater models can be used to predict and evaluate changes to hydrology, which can have a big influence on the present vegetation. Indeed the factors most affecting vegetation are the quantity and quality of available water. In this paper a groundwater model was presented for four brook valleys of the Campine Plateau. For calibration there was a lack of readily available measured heads. So another approach had to be adopted in which information about groundwater depths was derived indirectly from qualitative field observations and the vegetation survey by means of Ellenberg values. Upon comparison of calculated and Ellenberg-derived groundwater depths, and after optimising a number of specially elaborated evaluation criteria, the groundwater model could be considered to be calibrated. Of course, it is still preferable to compare to directly measured data. Nevertheless, if that's not possible, the methodology presented provides an alternative approach. This approach can also be applied in addition to a regular calibration, in order to compare to more variables than only measured heads.

After calibration, it was possible to simulate the actual situation and a hypothetical wetting scenario where human influence was eliminated as much as possible. The results showed that the groundwater depth for the wetting scenario is at maximum more than 6 m higher than the actual situation upon closing of a water abstraction and ca. 1.6 m upon decreasing the drainage levels (brook depths). Finally, an increase of 27.9 % in the discharge area and a change in the discharge intensity pattern could be observed.

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