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The impact of land-use changes on the groundwater in the Grote Nete river basin, Belgium

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ABSTRACT

A GIS based hydrological scenario modelling methodology has been set up to simulate the effects of land-use changes on groundwater recharge and discharge. GIS is used in handling the input and output data from the model and creating a common environment for the hydrological models. The effect of land use on the groundwater recharge is simulated with the WetSpass model, while the groundwater flow is simulated with a modified form of the MODFLOW model. Modelling results are verified by comparison with measured river discharges and groundwater heads. The occurrence and extend of discharge areas is verified by mapping phreatophytic vegetation in the field. Based on the simulation of the actual situation two different hydrological scenarios, a pre-development and a future scenario have been simulated for the Grote-Nete river basin, Belgium. Three approaches to represent the hydrological effects of land-use change in the future scenario simulation are discussed. The results identified the sensitivity and impact of changes in groundwater discharge amount and sizes of recharge and discharge areas.

INTRODUCTION

Studying the effect of land-use changes on ground water is a key issue in setting up a sound land-use planning project, especially since nowadays land-use planning is also important for protection of ecologically valuable areas. The effect on the ground water system can be derived from combined technologies like groundwater modelling, vegetation mapping, GIS and remote sensing, as shown by Batelaan *et al.* (1998), who used this approach to study natural ground water discharge in a nature reserve. The objective of this study is to assess the impact of land-use changes on the groundwater system in a river basin, in particular the extend and magnitude of groundwater recharge and discharge, thereby identifying the areas most sensitive to land-use changes.

The study area covers a major part of the Grote-Nete river basin, located about 60 km Northeast of Brussels (Fig. 1). The area is 293 km^2 and topography ranges from 14 to 65 m above sea level. The dominating soil type in the area is sand, but in the valleys also sandy loam, loamy sand and silt loam occurs. The land-use has been derived from remote sensed images and consists of: 30% agricultural crops, 18% deciduous forest, 18% urban areas, 15% grass land, 12% coniferous forest, 5% heath land, and 2% open water. Precipitation is almost uniform throughout the year. The average precipitation in the area ranges from 743 to 800 mm/year. There are also 155 pumping wells in the region abstracting in total 66,580 m^3/day.

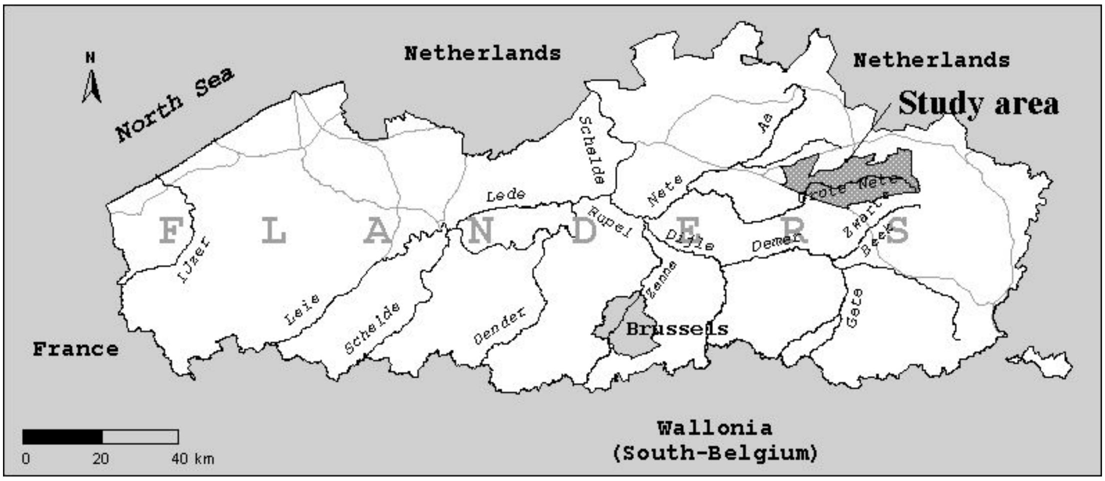

Figure 1 - Study area.

METHODS AND APPLICATIONS

Calculation of groundwater recharge

The effect of land-use on the groundwater recharge is simulated with the WetSpass model [Batelaan and De Smedt, 2001], which estimates spatially distributed runoff, evapotranspiration, and recharge in function of land cover, soil type and topography. This model is a seasonal based version of the Water and Energy Transfer between Soil, Plant and Atmosphere (WetSpa) model of Batelaan *et al.* [1996] and Wang *et al.* [1997]. The model has been integrated with Arc/Info and ArcView [Asefa *et. al.*, 1999; Batelaan and De Smedt, 2001]. WetSpass is a raster semi-physically based distributed model, in which the groundwater recharge is estimated from a seasonal water balance

$$R = P - S - E \qquad (1)$$

where R is the groundwater recharge, P is the precipitation, S the surface runoff, and E the evapotranspiration; all variables have dimensions [L/T]. The surface runoff S is calculated from the slope, soil type, land use, and precipitation intensity, while E is calculated from potential evapotranspiration, soil moisture storage capacity, and soil cover.

The calculations where performed for the study area on grid cells of 50 m; details are given by Asefa *et al.* [2000]. The results for the present situation are shown in Fig. 2. The recharge values range from -375 to 408 mm/y, with an average of 282 mm/y. High recharge values occur where soils are sandy, in flat areas, and on favourable soil cover as grassland or deciduous forest. In the valleys the recharge is negative or very low, due to the shallow groundwater table and high evapotranspiration. These results were verified by calculating and comparing the total calculated surface runoff and groundwater recharge with discharge measurements of 2 gauging stations, located in the Grote-Nete basin. The measured discharges were separated in direct runoff and base flow using standard procedures, and average yearly values were determined. These values compared favourably with the predicted surface runoff and groundwater recharge calculated with WetSpass.

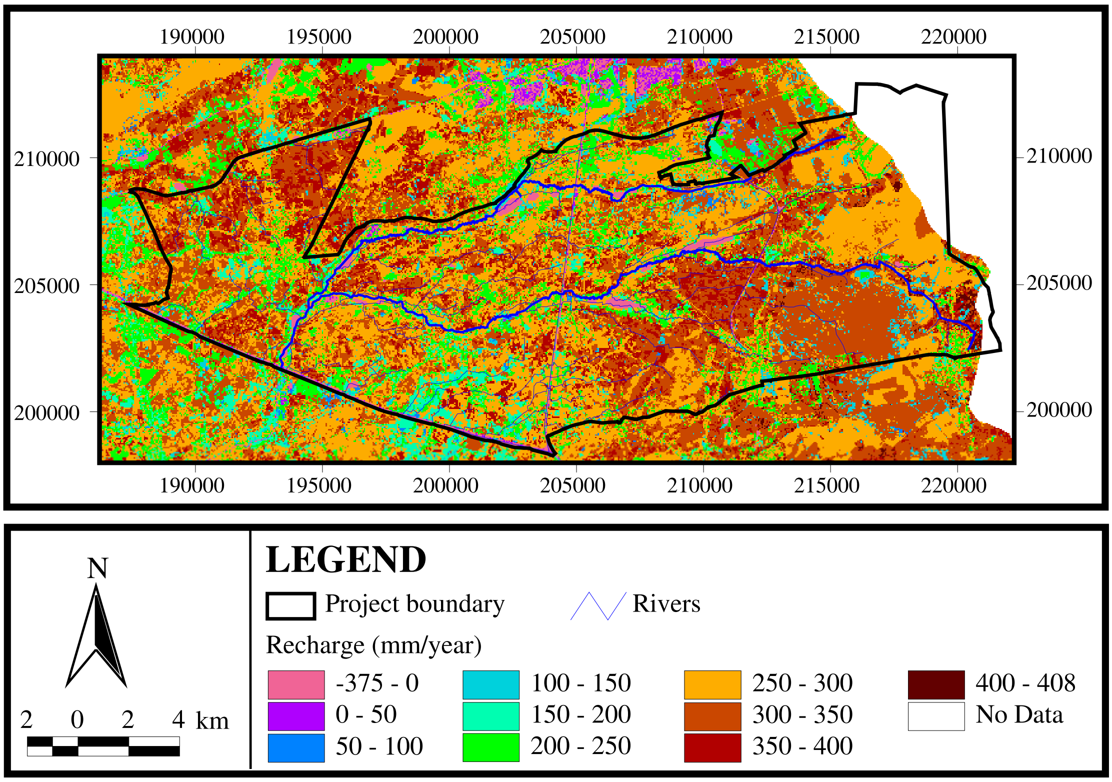

Figure 3 – Recharge calculated with WetSpass.

Groundwater modelling

The groundwater modelling is based on the well-known USGS modular three-dimensional finite-difference groundwater model, MODFLOW [Harbaugh and McDonald, 1996]. This model has been selected because it is well documented, public domain and it has been applied and tested world wide. In order to simulate recharge and discharge areas, the code has been modified slightly as follows. The flow in the phreatic groundwater layer is simulated in steady state using following equation

$$\nabla(T\nabla h) + R - D \pm Q = 0 \tag{2}$$

where ∇ is the divergence or gradient operator $[L^{-1}]$, h the groundwater head [L], T the transmissivity $[L^2/T]$ which depends upon h, R the recharge [L/T], D the groundwater discharge [L/T], and Q the interactions with the underlying groundwater layers or the effects of pumping wells $[L^3/T.L^2]$. However, this equation cannot be solved because both h and D are unknown. Therefore, the area is divided into recharge and discharge areas; in recharge areas D is zero and the groundwater head can be calculated with equation 2, whereas in discharge areas h is known and D can be calculated as

$$D = \nabla(T\nabla h_D) + R \pm Q \tag{3}$$

where h_D is the groundwater drainage or seepage level, which can be derived from topography and the presence of discharge features as springs, ditches, marches, rivulets, etc. Hence, the procedure consists of determining in an iterative way the position of recharge and discharge areas using the equations given above, such that everywhere $h \leq h_D$. In order to achieve this with the MODFLOW model, a SEEPAGE package has been developed by Batelaan and De Smedt [1998].

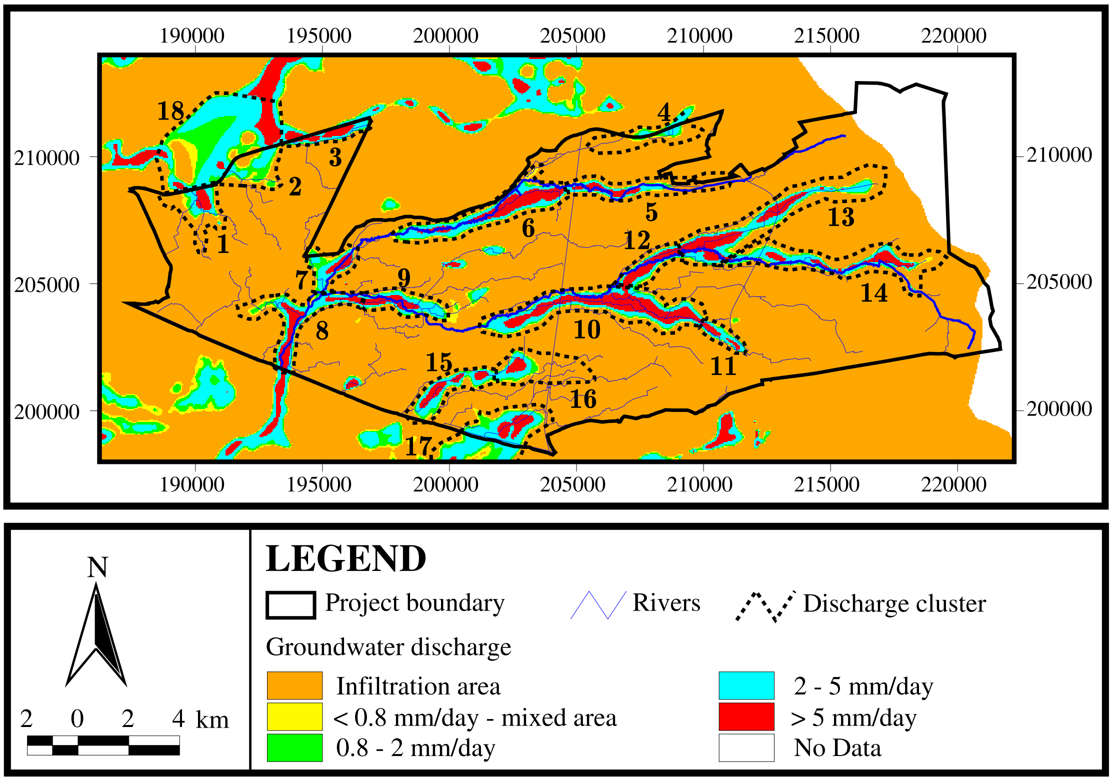

Figure 3 - Calculated discharge areas for the Grote-Nete basin.

The groundwater model was applied to the study area using 50 m grid cells. The inputs to the model consists of hydro-geological characteristics of the basin, pumping wells, the regional distributed recharge calculated previously, and the drainage levels which are assumed to be 0.5 m below topography in order to account for local depressions and actual surface water levels as they occur in ditches and ponds. Figure 3 shows the resulting groundwater discharge areas for the Grote-Nete basin for the present conditions; 18 different discharge cluster areas can be identified, all located in valleys. The obtained groundwater heads (not shown) where verified by 25 piezometers in the area having a long range of measurements. It follows that calculated and average observed groundwater heads are in good agreement, with no systematic error, a root mean square error of 0.45 m and a mean absolute error of 0.35 m. Also, the simulated positions of the discharge areas were verified by a field mapping campaign of phreatophytic vegetation, i.e. plants that obtain their water from a shallow water table. The mapped vegetation coverage is shown in Fig. 4, and compares nicely to the obtained discharge map of the region.

Once the discharge areas are known, the recharge areas associated with each discharge area can be determined with the three-dimensional tracking code MODPATH [Pollock, 1989]. First, flow lines are traced with MODPATH, starting from any grid cell. Secondly, a special program selects all flow lines that ends in a certain discharge area and saves characteristic values, like starting point, discharge flux and total flow time. Figure 5 shows the discharge and associated recharge areas and the flow times. Table 1 lists the size of the discharge and recharge areas, and the average groundwater flow time between recharge and discharge area. Comparing the individual clusters contributes to increasing the level of understanding of the flow systems in the area and the role they play in the landscape.

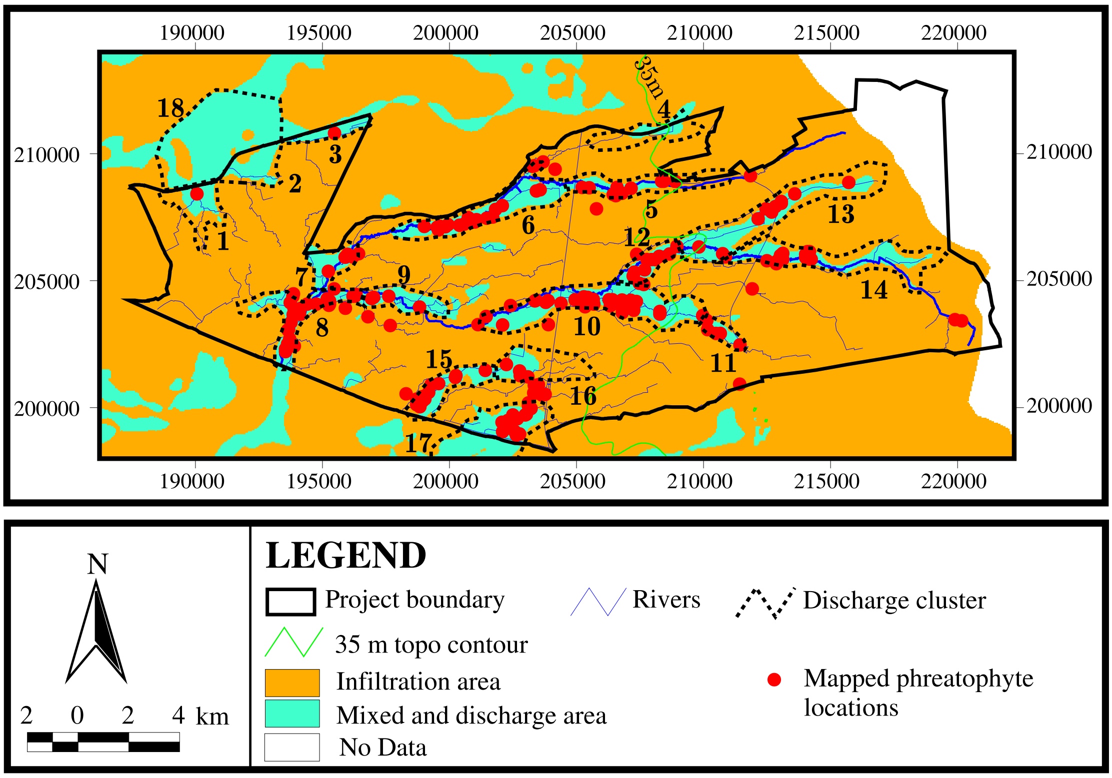

Figure 4 - Mapped phreatophytes in or near simulated discharge areas.

Analyses of scenarios

The clusters of groundwater discharge identified with the groundwater model are subjects for analyses of impact of possible changes in land-use. Based on the simulation of the actual situation the following scenarios were studied:

1) Pre-development: representing a groundwater system from before major human influence in extracted groundwater volumes and a recharge uniform over the area.
2) Future situation: representing a groundwater system, which includes the effects of planned land-use changes.

Within the framework of the land-use project for the Grote-Nete, two types of land-use changes are planned for the future situation:

1) in region 1 recharge will be increased by reducing evapotranspiration and runoff;
2) in region 2 recharge will be reduced due to increased evapotranspiration and shallow subsurface drainage for agricultural improvement.

For studying the impact of these land-use changes, three different simulation approaches have been followed:

1) changing the amount of recharge, positively for region 1 and negatively for region 2, and calculating the impact on the groundwater discharge by accounting the water balance, assuming that the groundwater system is conservative;

2) changing the amount of recharge, positively or negatively respectively, and calculating the impact by re-simulation of the groundwater system;
3) changing the amount of recharge positively in region 1 and by lowering and fixing the groundwater head with 0.5 m compared to the actual situation, due to the subsurface drainage, in region 2. The changed conditions are also re-simulated to infer the impact.

In the future scenario the increase in recharge in region 1 is assumed to be 25% for recharge areas, but no increase is assumed where groundwater discharge is occurring. Since reduction of recharge is assumed to be easier than an increase, the reduction in region 2 is set to 50% for the soils with poor drainage, because in land-use planning areas with poor drainage are generally considered for agricultural improvement. No reduction is considered in other areas. Also approach 3, lowering of the groundwater head with 0.5 m, is only applied in the areas with poor soil drainage.

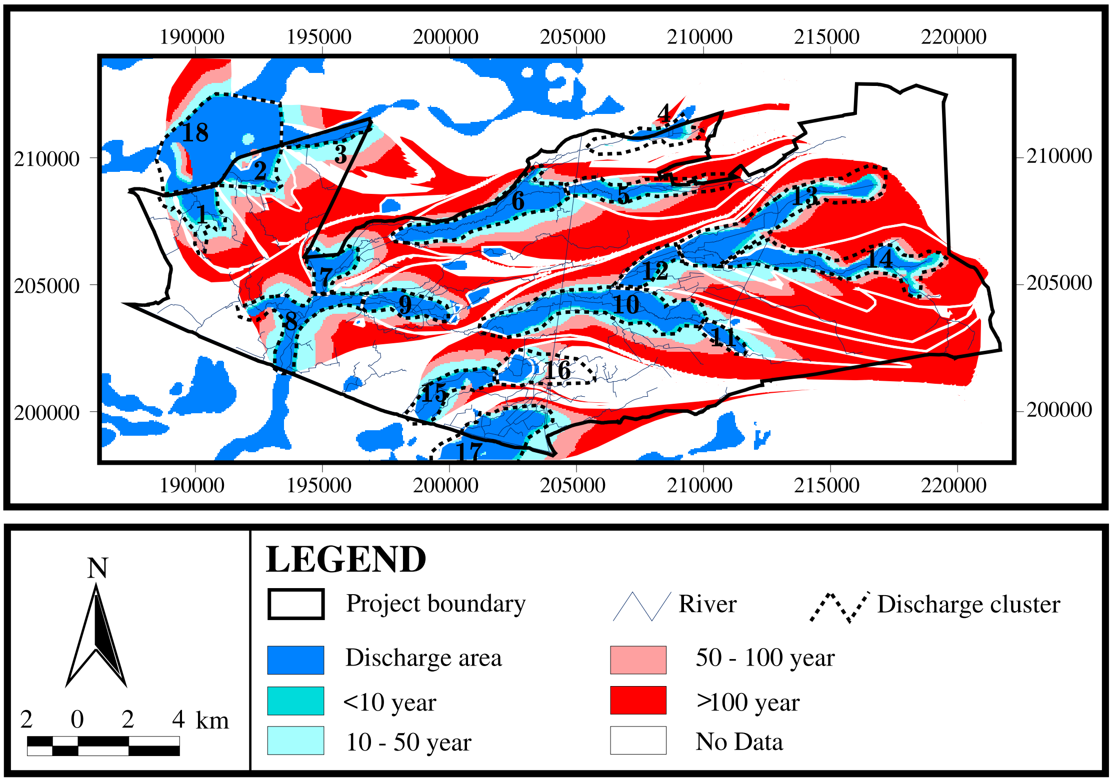

Figure 5 – Discharge and associated recharge areas and flow times.

Table 1 summarises the characteristics of the 18 clusters of discharge areas and associated recharge areas for the actual, pre-development and future situation, respectively. The future scenario results that are shown are based on the second approach of re-simulation of the groundwater system. For the pre-development situation it is observed that in general the size of the discharge areas increases with 10%, and the flow times also increase significantly. The results in Table 1 show that about one third of the discharge clusters decrease in discharge amount, one third increase and one third seems to be relatively uninfluenced. With the second approach the obtained change in groundwater level ranges from an increase of 55 cm to a reduction of only 7 cm. This relatively small reduction is due to the fact that region 1 with increased recharge is almost three times bigger than region 2 with reduced recharge. The first simulation approach for the future situation gives very similar results with respect to the changed discharge amounts, as the above described second approach. Advantage of this approach is that it is very easy to estimate; it can be done purely in a GIS environment. Disadvantage is that no change in discharge area size or flow time can be obtained. The third approach has a much more severe impact on the groundwater system. The total discharge area size reduces with 35%. The average groundwater level reduces with 22 cm; in part of the area there is even a 50 cm lowering of the groundwater level. However, as in the other approaches the same discharge clusters 1, 2, 3, 10, 12 and 18 are most severely reduced in discharge.

Tabel 1- Size of recharge and discharge areas, and flow times for the actual, the pre-development and the future situation, for which also total discharge is given (the order is from highest increase in discharge to highest decrease).

	Actual situation			Pre-development situation			Future situation (change in percentage compared to actual situation)						
Cluster	Recharge area	Discharge area	Flow time	Recharge area	Discharge area	Flow time	Recharge area		Discharge area		Total discharge		Flow time
	km^2	km^2	year	km^2	km^2	year	km^2	%	km^2	%	Mm^3/y	%	year
14	16.0	4.4	184	13.4	3.9	157	16.1	0.5	4.6	2.7	6.6	6.0	175
13	26.4	5.8	239	31.1	6.0	269	26.1	-1.2	6.0	4.4	10.5	5.3	213
4	2.8	1.4	216	3.6	1.7	245	2.9	3.3	1.4	4.4	1.2	4.2	217
16	4.2	1.1	146	9.6	3.1	174	4.1	-1.2	1.3	24.5	1.5	3.5	127
11	3.8	1.0	94	3.1	0.9	84	4.0	3.8	1.0	0.5	1.6	2.8	101
5	9.7	2.0	190	11.0	2.4	219	9.9	1.9	2.0	2.3	3.6	2.2	190
9	9.2	2.1	148	9.2	2.2	156	9.2	0.2	2.1	0.2	3.1	0.4	150
6	25.5	5.2	208	25.9	5.3	223	25.3	-0.8	5.2	0.0	8.7	0.1	202
15	8.4	2.3	132	10.7	2.6	152	8.4	0.0	2.3	0.0	3.0	0.0	122
17	11.7	5.2	120	13.5	5.7	138	11.5	-1.5	5.2	-0.1	5.8	-0.3	118
7	8.0	1.9	20	7.7	1.9	143	7.9	-1.2	1.8	-0.7	2.7	-0.3	136
8	16.1	3.6	114	17.3	3.9	120	16.1	-0.1	3.6	-0.7	5.4	-0.4	116
10	33.9	7.1	220	38.5	7.3	249	33.7	-0.7	7.1	-0.4	12.0	-0.9	218
12	8.6	1.6	227	9.2	1.7	254	8.9	3.3	1.6	-0.8	3.0	-1.2	228
18	27.6	12.5	154	30.0	12.9	172	28.0	1.6	12.3	-1.2	11.8	-1.5	157
1	5.1	1.5	68	6.7	2.2	67	5.1	-0.5	1.5	-1.8	1.8	-2.4	68
3	5.8	1.3	69	5.6	1.2	69	5.9	1.4	1.2	-2.6	2.0	-3.7	70
2	2.4	1.8	24	2.1	1.8	24	2.5	4.5	1.7	-5.8	0.9	-12.3	25

CONCLUSION

The impact of land-use changes on recharge and discharge areas has been assessed using hydrological models within a GIS framework. The model uses detailed basin characteristics and is especially useful to analyse the effects of topography, soil type, and land-use or soil cover on the hydrologic behaviour of a river basin. The model was applied to the Grote-Nete basin in Belgium. The effect of land use on the groundwater recharge is simulated with the WetSpass model, while the groundwater flow is simulated with a modified form of the MODFLOW model. Modelling results are verified by comparison with measured river discharges and groundwater heads. The occurrence and extend of discharge areas is verified by mapping phreatohytic vegetation. The usefulness of the model was demonstrated by forecasting the most sensitive recharge and discharge areas with respect to land-use changes. The methodology developed here can also be used for analysing the effects of land-use changes on discharge/recharge relationships in other river basins.

References

Asefa, T., Wang, Z. M., Batelaan, O., and De Smedt, F., “Open integration of spatial water balance model and GIS to study the response of a catchment”, H. J. Morel-Seytoux (ed.), Proceedings of the Nineteenth Annual American Geophysical Union Hydrology Days, Colorado State University, Fort Collins, Colorado, 11-22, 1999.

Asefa, T., Batelaan, O., Van Campenhout, A., and De Smedt, F., “Characterizing recharge/discharge areas of Grote-Nete (Belgium) using hydrological modeling, vegetation-mapping and GIS”, ERB2000 Conference on monitoring and modelling catchment water quantity and quality, Ghent, Belgium, 2000.

Batelaan, O., Wang, Z. M., and De Smedt, F. “An adaptive GIS toolbox for hydrological modeling", In: Application of Geographical Information Systems in Hydrology and Water Resources (ed. By K. Kovar and H. P. Nachtnebel), IAHS publ. no. 235, 3-9, 1996.

Batelaan, O., De Smedt, F., De Becker, P., and Huybrechts, W., “Characterization of a regional groundwater discharge area by combined analysis of hydrochemistry, remote sensing and groundwater modeling”, In: Shallow Groundwater Systems (ed. By P., Dillon and I., Simmers), IAH publ. Rotterdam, Netherlands, Chapter 7., 75-86, 1998.

Batelaan, O., and De Smedt, F., “An adapted DRAIN Package for SEEPAGE problems”, Poeter, E., Zheng, C., and Hill, M. (Eds.), MODFLOW ’98 Proceedings, Volume II, Colorado School of Mines, USA, 555-562, 1998.

Batelaan, O., and De Smedt, F., “WetSpass: a flexible, GIS based, distributed recharge methodology for regional groundwater modelling”, Gehrels, H., Peters, J., Hoehn, E., Jensen, K., Leibundgut, C., Griffioen, J., Webb, B. and Zaadnoordijk, W-J. (Eds.), Impact of Human Activity on Groundwater Dynamics, IAHS Publ. No. 269, 2001.

Harbaugh, A. W., and McDonald, M. G., “User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model”, Open-File Report 96-485, 56 pp., 1996.

Pollock, D.W., “Documentation of computer programs to compute and display pathlines using results from the USGS modular three-dimensional finite-difference groundwater model”, USGS, Open File Report 89-381, 81pp., 1989.

Wang, Z. M., Batelaan, O. and De Smedt, F., “A distributed model for water and energy transfer between soil, plants and atmosphere (WetSpa)”, *Phys. Chem. Earth*, Vol 21, no 3, 189-193, 1997.