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Regional groundwater discharge: phreatophyte mapping, groundwater modelling and impact analysis of land-use change

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Abstract

The relationship between groundwater recharge and discharge is one of the most important aspects in the protection of ecologically valuable areas. Knowledge of groundwater systems is therefore a pre-requisite for up-to-date integrated land and water management. A methodology is presented for assessing the relative importance of different recharge–discharge systems, with respect to ecological status or development, including mapping of regional groundwater systems, and recharge and discharge areas. This methodology is applied to a land-use planning project in the Grote-Nete basin, Belgium. Discharge regions are delineated on the basis of their spatial discharge contiguity, position in the landscape and alkalinity of the plants habitat. The simulated discharge areas are verified by field mapping of phreatophytic vegetation. Particle tracking is used to delineate the recharge area associated with each discharge area, and to characterize each recharge–discharge groundwater system. Three groundwater flow and two vegetation parameters are used in a cluster analysis to obtain four different clusters of groundwater discharge systems. It is shown that the discharge clusters are significantly different in discharge intensity and alkalinity. The effects on the groundwater system due to anthropogenic impacts on the land-use are studied by simulation of the present, pre-development, and future situation. The results indicate the sensitivity and impact of the changes on the recharge and discharge areas, and groundwater discharge fluxes. The impact of the changes for the different areas for both the pre-development and the future situation appears to differ from large decrease to large increase in total groundwater discharge. Of additional ecological importance is the fact that some areas show an opposite behaviour regarding the changes in groundwater discharge area and fluxes. The delicate shifts in the groundwater systems, which cause the changes in the recharge and discharge, clearly show the need for hydrological modelling. The synergy of hydrological modelling and vegetation mapping proves advantageous and reveals some of the ecological differences in the catchment.

Keywords: Recharge–discharge; Plant–groundwater relation; MODFLOW; Groundwater systems; Belgium

1. Introduction

One of the main objectives of modern land planning is the protection of ecologically valuable areas and land-use that supports integrated water management. Special attention should be given to

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the effect of land-use changes on the hydrological cycle and the protection of groundwater systems, especially discharge and recharge areas (Boeye and Verheyen, 1992; Bernáldez et al., 1993; Pucci and Pope, 1995).

Groundwater discharge, seep or spring wetlands have often developed in discharge areas (Mitsch and Gosselink, 2000). These are, from an ecological point of view, very valuable wetlands, since they mostly have an almost permanent shallow water table, and a constant lithotrophic water quality.

In order to be able to formulate a sound land-use planning strategy, analysis of the groundwater flow system connecting recharge and discharge areas is required. This information can be derived from different technologies like hydrological mapping, vegetation mapping, groundwater modelling and hydrochemical analysis, usually in combination with geographical information system (GIS) techniques and remote sensing.

Groundwater interacts with surface water in nearly all landscapes, ranging from small streams, lakes, and wetlands in headwater areas to major river valleys and sea coasts. It is generally assumed that groundwater recharge occurs in topographically higher areas, and groundwater discharge in topographically lower areas. This is true primarily for regional flow systems, but the superposition of local flow systems makes the interaction between surface and groundwater more complex (Winter, 1999).

Discharge areas occur in that part of the drainage basin where, the net saturated flow of groundwater is directed upward towards the water table. In these areas the groundwater level is at or near the surface. On the other hand, recharge areas occur where, the net saturated flow of groundwater is directed away from the water table (Freeze, 1969). In these areas the groundwater usually is situated at a deeper level below the soil surface.

Different landscape physiographic features can be used to obtain information on the groundwater systems and especially the groundwater discharge areas. Tóth (1966) used a hydrological mapping procedure to identify regions with upward and downward groundwater movement. He found a correlation between mapped physiographic features, as springs, seepages, vegetation types, salt precipitates etc., and the direction of natural groundwater movement. Tóth (1971) explained a variety of naturally occurring geologic, morphologic and physiographic phenomena by having a common generator: groundwater discharge at the ascending end of gravity flow systems. de Vries (1977, 1994, 1995) showed by way of a theoretical model that for the sandy Pleistocene part of The Netherlands the stream network is genetically coupled with groundwater discharge systems of various extents. In addition to physiographic features of the landscape also different direct measurements of the groundwater can be used to obtain information on the groundwater system. Salama et al. (1993) explained the distribution of recharge and discharge areas from four observed trends in water level changes. Shedlock et al. (1993) showed the complex dependence of wetlands on multiple groundwater systems, based on sedimentological, geophysical and hydrochemical data from test holes and wells. Roulet (1990) mapped groundwater discharge in a small headwater wetland by flownets derived from measured piezometry. Hunt et al. (1996) determined groundwater inflow to a wetland from water levels, stable isotope mass balances, and temperature profiles.

It is long known that there is a clear relation between phreatophytes and groundwater discharge in arid and semi-arid regions (Tóth, 1971; Nichols, 1994). For more humid regions this relation is less obvious and has only been investigated recently. van Wirdum (1991) pioneered the relation between fen vegetation and hydrology. Klijn and Witte (1999) reviewed the new research field of ecohydrology and paid special attention to the influence of groundwater seepage on site factors in plant ecology. They concluded that plant species may be used as seepage indicators in rapid assessments and surveys, but that constant awareness of the limitations is required. Rosenberry et al. (2000) also came to this conclusion, using the Marsh marigold plant species as an indicator of focused groundwater discharge to a Minnesota lake. De Becker et al. (1999) mapped in detail phreatophytes in an entire floodplain. The spatial distribution of the plant species was statistically explained in relation to the groundwater regime, chemistry, soil texture, chemical composition and land management.

Although analytical and numerical modelling of groundwater discharge areas were developed several decades ago, only a limited number of studies deal with this approach. Tóth (1962, 1963) developed a theoretical understanding and analytical formulation of groundwater systems and distribution of recharge–discharge areas in small drainage basins. Freeze and Witherspoon (1966, 1967, 1968) extended Tóth's work with analytical and numerical solutions for regional flow under different conditions. By simulation of theoretical examples they showed that groundwater discharge occurs under the influence of at least six distinguishable cases of water table configuration and geologic setting. In their two-dimensional hypothetical models, the discharge areas occupied between 7 and 40% of the total basin. Winter (1978) simulated three-dimensional groundwater flow near lakes and investigated the conditions of seepage.

Bronders and De Smedt (1985, 1986) developed and applied regional groundwater models specifically aimed at predicting groundwater discharge and the location of the saturated source areas. They found for the Demer and Dijle basins (Belgium) groundwater discharge area-fractions of, respectively, 28 and 30%. Batelaan et al. (1993, 1996) used the same approach to simulate regional flow to a concentrated groundwater fed wetland and to predict discharge with a high spatial resolution on a regional scale. Ophori and Tóth (1989) simulated the groundwater flow in a basin by formulation of stream functions. The water table in the basin was assumed to coincide with the topography and by analysing the stream lines the location and amount of groundwater discharge was calculated. The calculated groundwater discharge area covered 24% of the basin.

Stoertz and Bradbury (1989) used the budget calculation of MODFLOW with a specified, measured water table configuration, to calculate flows to (discharge) and away from (recharge) the water table. Hunt et al. (1996) followed this approach for simulation of groundwater inflow to a wetland system. Gilvear et al. (1993) quantified water balance terms and hydrochemistry of a small groundwater fed wetland. They showed that MODFLOW simulated upward head differences below the wetland, which confirmed the groundwater discharge to the wetland. Reeve et al. (2001) used MODFLOW in modelling the regional groundwater flow to peatlands, and the DRAIN package to remove surface runoff and to constrain the simulated phreatic water level to the land surface. A particle tracking methodology was applied by Buxton et al. (1991) and Modica et al. (1997, 1998) to analyse the configuration of theoretical and realistic flow systems, groundwater residence times, and recharge areas.

Groundwater chemistry and isotopes are often very supplemental in characterising groundwater discharge areas (Pedroli, 1990). Wassen et al. (1989) and Schot (1990) explained vegetation gradients in a fen by the chemistry of the seeping groundwater. Gerla (1992) showed that the chemical characteristics of discharging groundwater in the Red River Valley (North Dakota) suggested mixing of spatially varying proportions of local recharge and more evolved, deeper groundwater. Batelaan et al. (1998) delineated different zones in a regional groundwater discharge wetland and linked these to specific groundwater paths through different aquifers. Kehew et al. (1998) used chemical and isotopic composition of shallow groundwater around a wetland to spatially delineate areas of groundwater discharge to the wetland and groundwater recharge from the wetland. These data alleviated the inconclusive hydraulic head data with respect to the determination of the recharge–discharge function of wetlands.

The objective of this study is to set up a methodology for mapping regional groundwater systems, recharge and discharge areas. The methodology combines both hydrological modelling as well as vegetation mapping, integrated in a GIS environment. Purpose of the methodology is to allow assessment of the relative importance of the quantitative flow characteristics of different recharge–discharge systems, which should contribute to the evaluation of the ecological status or development of an area. The methodology is tested for the land planning project in the Grote-Nete basin, Belgium. Discharge areas and associated recharge areas are identified using groundwater modelling and vegetation mapping. Differences and advantages of these methods are discussed. The second objective of the study is to assess the effects of anthropogenic impacts on the groundwater system, in particular the size and intensities of discharge areas.

2. Methodology

A methodology is presented for characterizing discharge and recharge areas making use of hydrological modelling and vegetation mapping within a GIS framework. The result of the methodology should allow the comparison of the different thematic approaches and therefore increase the understanding of the ecohydrological system. The methodology consists of the following components:

(a) Setting up a groundwater model. Calibration of this model with head data and river discharge and simulation of the groundwater head distribution as well as identification of groundwater discharges (location and fluxes).
(b) Mapping of phreatophytic vegetation for identification of shallow groundwater table conditions and comparing those results with the groundwater modelling results.
(c) Delineation of regions of discharge areas with similar topographical, hydrological and ecological characteristics, based on numerical model results and vegetation mapping.
(d) Identification of recharge areas associated with a discharge region, using particle tracking.
(e) Statistical grouping of different recharge–discharge systems into clusters.
(f) A GIS procedural interface to embed the previous steps in a structured way and to increase the efficiency of analysis.

2.1. Groundwater modelling

The USGS modular three-dimensional finite-difference groundwater model, MODFLOW (Harbaugh and McDonald, 1996) has been used to build an updated and Grote-Nete area specific version of the regional model of Batelaan et al. (1996). In order to simulate recharge and discharge areas, the model code has been slightly modified as follows. The flow in the phreatic groundwater layer is simulated in steady state using the following equation:

$$\nabla(T\nabla h) + R - D \pm Q = 0 \tag{1}$$

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 either recharge or discharge areas; in recharge areas D is zero and the groundwater head can be calculated with Eq. (1), whereas in discharge areas h is known and D can be calculated as:

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

where, h_S [L] is the groundwater seepage level, which can be derived from topography and the presence of discharge features such as springs, ditches, marches, rivulets, etc. Hence, the procedure consists of an iterative method to determine the position of recharge and discharge areas using the equations given above, such that everywhere $h \leq h_S$.

In order to achieve this with the MODFLOW model, a SEEPAGE package has been developed (Batelaan and De Smedt, 1998). The basic idea of this package is an adaptable head boundary condition, i.e. the head is variable unless the groundwater rises above the seepage level in which case the head becomes constant. Seepage level input to the package can be in different formats, e.g. the matrix format can be used for digital terrain models. The SEEPAGE package enables the iterative determination of the position of recharge and discharge areas in a robust way.

The DRAIN package (McDonald and Harbaugh, 1988) provides a different method for estimation of the groundwater discharge; in this case the discharge can be calculated as:

$$D = C(h - h_D) \quad \text{for } h > h_D \tag{3}$$

$$D = 0 \quad \text{for } h \leq h_D \tag{4}$$

where, the coefficient C [L^2/T] is a conductance, describing the relationship between head difference and resulting flux in a lumped way and h_D is the drainage level. The DRAIN package has the disadvantage that the conductance is difficult to quantify and that the phreatic level can rise above the topography. The latter can be prevented by using a very large, arbitrary, conductance value, but this often results in numerical instability (Batelaan and De Smedt, 1998). In a regional groundwater flow modelling approach, fine vertical discretization is often limited. Necessary local adaptations (e.g. due to convergence of flow) of the regional conductivities is therefore often lacking. However, the DRAIN conductance can take this into account and adapt conductivities to the local conditions.

Therefore, the most suitable solution procedure consists of combining SEEPAGE and DRAIN in the following way. The seepage level is set equal to the topography, which will assure that the phreatic water table has an absolute maximum equal to the soil surface. The DRAIN level is set equal to the surface water level with a realistic value for the conductance, which avoids numerical instability.

The spatial variation in the recharge due to distributed land-use, soil type, slope, groundwater level, meteorological conditions, etc. can be significant and should be accounted for. Hence, a quasi-physically based methodology for estimation of the long-term average spatial patterns of surface runoff, actual evapotranspiration and groundwater recharge was developed; this methodology has been termed WetSpass (Water and Energy Transfer between Soil, Plants and Atmosphere, under quasi Steady State) (Batelaan and De Smedt, 2001). The groundwater recharge in WetSpass is estimated from a seasonal water balance:

$$R = P - S - ET \tag{5}$$

where R is the groundwater recharge, P is the precipitation, S the surface runoff, and ET the evapotranspiration; all variables have dimensions [L/T]. The surface runoff S is calculated from the slope, soil type, land-use and precipitation intensity ratio, while ET is calculated from potential evapotranspiration, soil moisture storage capacity and soil cover. The model has been integrated with Arc/Info (Asefa et al., 1999) and ArcView (Batelaan and De Smedt, 2001).

The calibration of the MODFLOW and WetSpass models is based on comparison of observed and calculated groundwater levels as well as on the surface and groundwater balance of the basin.

2.2. Vegetation mapping

The aim is to use particular plant species as groundwater discharge indicators. Phreatophytes or groundwater plants are taxa that occur exclusively in or are largely limited to the sphere of influence of the water table (Londo, 1988). Hence, a concise vegetation (phreatophytes) mapping can be performed as an indication of the occurrence of groundwater discharge in the valleys. These results can be used for verification of the groundwater model.

The habitat, also referred to as the site, is the place where a plant species or plant community grows and which provides the conditions in which the plant can live (Klijn and Witte, 1999). Ellenberg (1991) defined indicator values for more than 1750 vascular plants species with respect to their habitat for Middle European locations. He defined two groups of three indicators. The first group refers to the tolerance with respect to climatic conditions: light exposure (L-value), temperature (T-value) and continentality (K-value), the second group refers to soil factors: wetness (F-value), acidity (R-value) and nitrogen (N-value). The wetness and acidity indicators are regarded to be the most useful indicators for characterisation of groundwater discharge areas with phreatophytes. The R-value ranges from 1, highly acidic, to 9, highly alkaline conditions. The F-value ranges from 1, dry, to 12, very wet habitat conditions. Some plants are indifferent with respect to these environmental parameters. Hill et al. (1999) redefined the indicators for British conditions. Since these conditions correspond better to the western European and Belgian conditions, we used Ellenberg indicator values adjusted according to Hill et al. (1999).

A list of 23 phreatophytic plant species has been identified on basis of literature study and regional field knowledge (Londo, 1988; Ellenberg, 1991; Hill et al., 1999). In Table 1 these phreatophytes are listed together with their wetness and acidity indicator values. A vegetation mapping was performed for the study area, consisting of checking the occurrence or abundance and spatial extent of the 23 phreatophytes at different locations in the valleys of the Grote-Nete basin. An ARC/INFO GIS database was created from the mapped vegetation sites. The attributes of the coverage are the number of phreatophytic species present per habitat locality, the areal extent of the species per locality, and the adjusted Ellenberg R- and F-values.

In addition, the Biological Evaluation Map (BEM) (Rombouts et al., 2000; Berten et al., 2000) was also used. This digital map gives an evaluation of every

Table 1
Selected plant species (phreatophytes) for vegetation mapping and their Ellenberg wetness (1 dry to 12 wet) and alkalinity (1 acidic to 9 alkaline) indicator value adjusted after Hill et al. (1999); × means indifferent

Plant species	Ellenberg-*F* wetness	Ellenberg-*R* alkalinity
Caltha palustris	9	6
Calla palustris	9	6
Carex sp	×	×
Crepis paludosa	7	6
Equisetum fluviatile	10	6
Equisetum palustre	8	6
Filipendula ulmaria	8	6
Hottonia palustris	12	7
Hydrocotile vulgaris	8	6
Hypericum tetrapterum	8	6
Juncus acutiflorus	8	4
Lychnis flos-cuculi	9	6
Lysimachia vulgaris	9	7
Lythrum salicaria	9	7
Mentha aquatica	8	7
Myrica gale	9	3
Nasturtium officinale	10	7
Peucedanum palustre	9	7
Scirpus sylvaticus	8	6
Scutellaria galericulata	8	6
Solanum dulcamara	8	7
Stellaria palustris	9	6
Stellaria uliginosa	8	5

ecotope on the basis of four criteria: rareness, biological quality, vulnerability and replaceability. The map is based on a phytosociological vegetation mapping on parcel level, scale 1:10,000, using a system of hierarchical vegetation units. On basis of best professional judgement of the occurrence of different plant species in each vegetation mapping unit, six environmental evaluation indicators were defined by De Baere (1997). From these indicators, the alkalinity and trophic status are selected. The alkalinity ranges from 1 very acidic environment ($\mathrm{pH} \approx 4$) to 5 slightly basic ($\mathrm{pH} > 7$). The trophic level of the environment ranges between 1 for a very oligothrophic environment to 5 for a very nutrient rich environment. Both the BEM alkalinity and trophic status indicators are used in this study to obtain a relative qualitative assessment of the groundwater discharge.

A next step is the delineation of wetland or discharge regions with 'similar' characteristics. Basis for the delineation is the contiguity of the groundwater model based discharge areas, topographical and landscape ecological position of the discharge area and the similarity of the vegetation types, as given by the adjusted Ellenberg indicator values.

2.3. Recharge areas

For ecological protection it is important to locate the recharge areas linked with each discharge region. The size and location of the recharge area, and the flow time from the recharge area to the discharge area can be used as indicators for the mineralisation level, and the buffer, adsorption and decay capacity of the groundwater. This knowledge can be used to evaluate the vulnerability with respect to changes in groundwater quantity and quality.

The particle tracking code MODPATH (Pollock, 1994) is used to post-process the results of the groundwater flow model, and to delineate the recharge areas. In a first step, a particle is seeded in every model cell. All particles are consequently tracked forward until they reach a weak or strong sink. For every tracked particle path, begin and end point and flow time is saved. In the second step, all water particles are selected that discharge in a certain region. The contributing recharge area is obtained by finding all starting points of paths that discharge in the selected region. Hence, every recharge cell is linked to one discharge cell, but a discharge cell might be linked to several recharge cells. This tracking procedure results in a more accurate determination of the contributing recharge area than if back tracking from the discharge area would be used, since it is not known where, and how many particles should be seeded in a discharge cell, in order to determine all its recharge cells. Also, since the direction of the groundwater flow velocity changes faster in the neighbourhood of a discharge cell than close to a recharge cell, back tracking, starting with a small inaccuracy, will diverge to a relatively large error in the determination of the recharge cell. Using forward tracking, these inaccuracies do not arise because convergence of flow lines is less problematic.

2.4. Statistical grouping and GIS interface

After delineation of the different groundwater systems, a relative comparison of these systems is required in order to increase our knowledge about the relationship between regional groundwater and phreatophytes. A comparison is chosen on the basis of a number of characteristic parameters which describe the groundwater flow between the recharge and discharge areas, as well as parameters which describe the ecological status of the groundwater discharge areas. Cluster analysis is used to aggregate the different recharge–discharge systems into a reduced number of significantly different types of systems. Since the cluster analysis requires an extensive set of parameters, it is also investigated if similar results can be obtained in a more simple way by plotting the recharge–discharge systems in a two parameter plot.

All analyses require abundant spatial data. A GIS is therefore the preferred tool to capture, convert, visualize and manage these data. Input to the models as well as output is processed through a command interface that links the models with GIS Arc/Info. The interface is made up of Arc Macro Language (AML) scripts, C/C++ programs, and UNIX shell scripts. For example, there is a conversion program for setting the drainage and seepage level from the surface level and to generate a MODFLOW format input file. Another conversion program prepares the groundwater extraction data in MODFLOW format and correctly handles multiple wells in a grid cell. Other utilities automatically export Arc-GRID maps and other data to prepare the inputs for MODFLOW and MODPATH and import modelling results back into the Arc/Info system as GRID maps.

The GIS-model interface allows the automatic running of MODFLOW and MODPATH for different conditions in a consecutive way. The interface makes the model results immediately available in GIS: these results can now be analysed more efficiently, compared with other data-sets, and visualized.

3. Application and discussion

3.1. Study area

The study area (Fig. 1) is located about 60 km north-east of Brussels and is 293 km^2 in size. It covers a major part of the Grote-Nete basin and is part of the Central Campine region. The region shows a moderate rolling landscape cut by the Grote-Nete River and its many tributaries, resulting in long stretched hills, very slightly elevated interfluves and broad swampy valleys (Wouters and Vandenberghe, 1994). The Grote-Nete and its tributaries rise from the foot of the north-western edge of the Campine plateau. This plateau was formed during the Elster ice age as a large scree of the Meuse River (Goossens, 1984). Geologically the area belongs to the Campine basin, a subsidence area north of the Massive of Brabant. From Late Cretaceous until end of the Tertiary, the basin went through a second strong subsidence period with deposition of marine sediments. During the Quaternary thick sediments were deposited by the Rhine and Meuse in the eastern part of the area, which now constitute part of the Campine Plateau (Gullentops and Vandenberghe, 1995). The Quaternary and Tertiary (until Miocene) deposits consist mainly of sandy formations, the most important being the glauconite rich Diest Formation with a thickness of up to 90 m (Schiltz et al., 1993). The early Oligocene heavy clay of the Boom Formation forms the base of the sandy aquifer system. The transmissivity of the aquifer system increases from about 1000 m^2/d in the west of the area to about 3000 m^2/d in the east. Groundwater is extracted in the region from 155 pumping wells, extracting in total 66,580 m^3/d.

The topography ranges from 14 to 65 m, with an average of 34 m above sea level. The mean slope is 0.3%. After an initial strong drop in elevation from the Campine Plateau the topography decreases very gradually from east to west. The boundary between the Campine Plateau and the lower western area is situated around the topographic level of 35 m. The average precipitation in the area ranges from 743 to 800 mm/y. The dominant soil type is sand, though in the valleys there is also sandy loam, loamy sand and silty loam. The land-use types in the area are: 30% crop/mixed farming, 18% deciduous forest, 12% coniferous forest, 15% grasslands, 5% heather, 2% open water and about 18% built-up area, as shown in Fig. 2 (OC GIS-Vlaanderen, 1996).

In the framework of the land-use planning project Grote-Nete 'optimalisation' and 'compensation' land-use changes are considered. Areas which will undergo optimalisation are intended for agricultural improve-

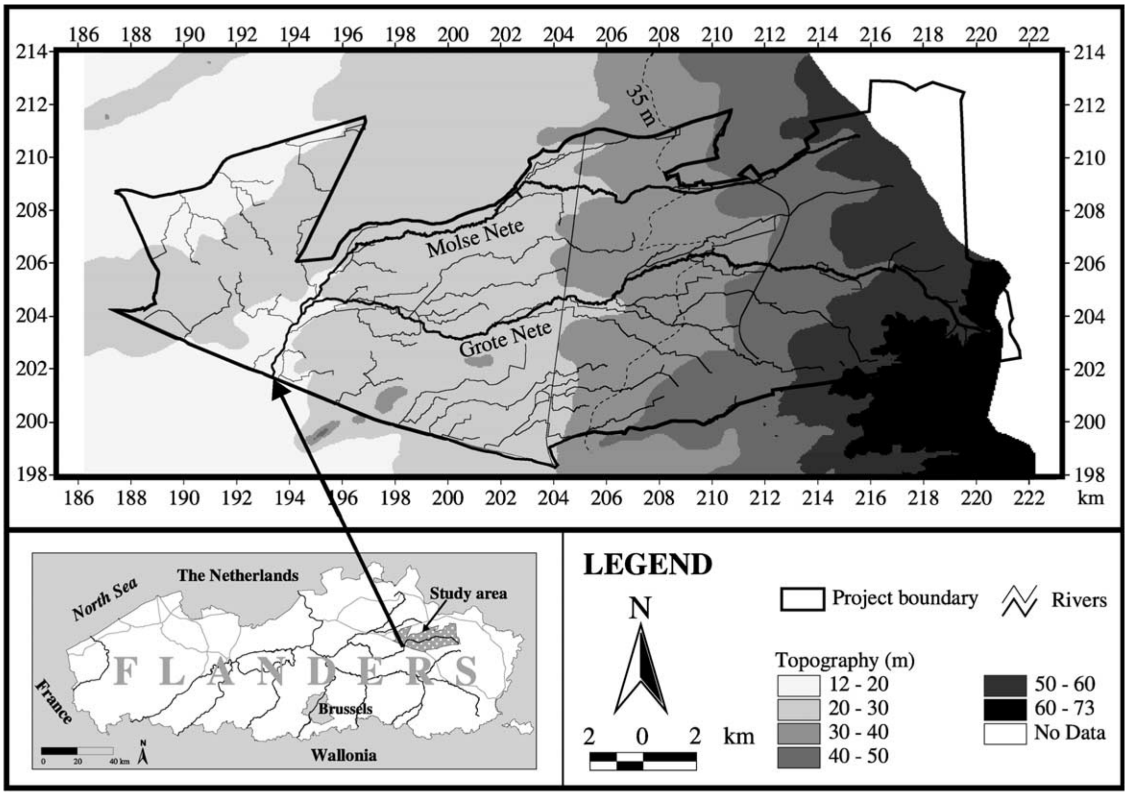

Fig. 1. Grote-Nete study area and topography.

ment. This improvement involves artificial drainage, such that recharge will be reduced as a consequence. To counterbalance the adverse effects of these changes, compensating measures will be implemented in other areas. These measures intend to increase the recharge by reducing surface runoff and evapotranspiration, by means of closing ditches, installing weirs and changing the vegetation type, etc. In Fig. 3 the areas of agricultural optimisation and compensation are presented. Target for the agricultural optimisation are the soils with poor and very poor drainage conditions, indicated as the dark grey zones within the lighter grey agricultural optimisation areas in Fig. 3. The very light-grey zones are the areas intended for compensation measures.

3.2. Groundwater modelling of discharge areas

The discharge areas are modeled with the technique described before. In order to obtain the surface level for SEEPAGE a digital elevation model was created from the Digital Terrain Model of the Belgian National Geographic Institute (DTM-NGI). This Digital Terrain Model is based on digitized elevation contours of the topographic map, on scale 1:50,000.

Since in this study, the interest is in identifying regional discharge and recharge areas, the model was set up as a steady state groundwater flow problem. Because the model boundaries do not coincide with natural boundaries, boundary conditions were taken from a regional flow model for the entire Nete basin (Batelaan et al., 1996). This procedure for using boundary conditions from regional models in local models was described by Leake et al. (1998).

The WetSpass calculated recharge for the study area is presented in Fig. 4. The groundwater recharge varies between, −375 and 408 mm/y, with an average of 282 mm/y. The negative and low recharge values occur in the river valleys, and are due to the high transpiration by the vegetation. On average

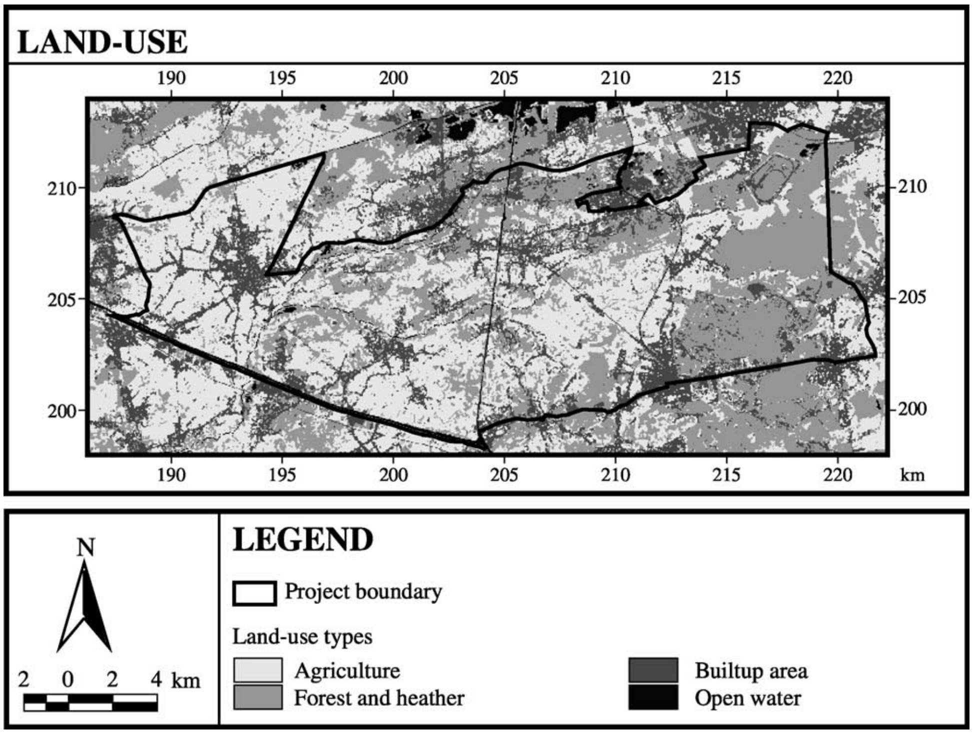

Fig. 2. Simplified land-use map for the Grote-Nete land planning project area (OC GIS-Vlaanderen, 1996).

the recharge in the valleys is about 60 mm/y lower than in the interfluves. This is explained by the shallow groundwater table and groundwater discharge leading to high evapotranspiration in the valleys. In the upper part of the basin the forest and heather area clearly have higher recharge rates.

Fig. 5 shows the resulting calculated groundwater heads and a north-south and west-east profile of the groundwater system. The profiles show the topography, simulated groundwater level and position of the aquifer. The locations along the profiles where, groundwater discharge occurs are easily recognised by the groundwater level reaching the topographic level.

Fig. 6 gives the groundwater discharge map as predicted by the groundwater model for the present conditions. As expected, the discharge areas are located in the valleys and depressions of the area. Most discharge areas appear as bands of 500 m wide along the main water courses in the area. Of the land planning area 16% is mixed or discharge area, with an average discharge of 4 mm/d. High intensity discharge areas, with a flux larger than 5 mm/d, are located in the lowest parts of the valley and are surrounded by a 100 m zone with medium discharges of 2–5 mm/d.

3.3. Calibration of the groundwater modelling

Calibration of the model is achieved by using long-term groundwater level observations in 38 piezometers in the area, in Fig. 5 the location of the piezometers is indicated. Fig. 7 shows the comparison between the calculated groundwater levels and average measured values. As can be seen from the figure there is a good agreement, with a correlation coefficient of 0.99. Other indicators of the goodness of fit are the root mean square error of 0.45 m and the mean absolute error of 0.35 m. Hence, all tests indicate a very good correspondence between simulated and measured groundwater levels.

A verification of the model results is obtained by analysing 10 years of discharge data from a gauging station downstream of the area. The observed average specific discharge for the basin is

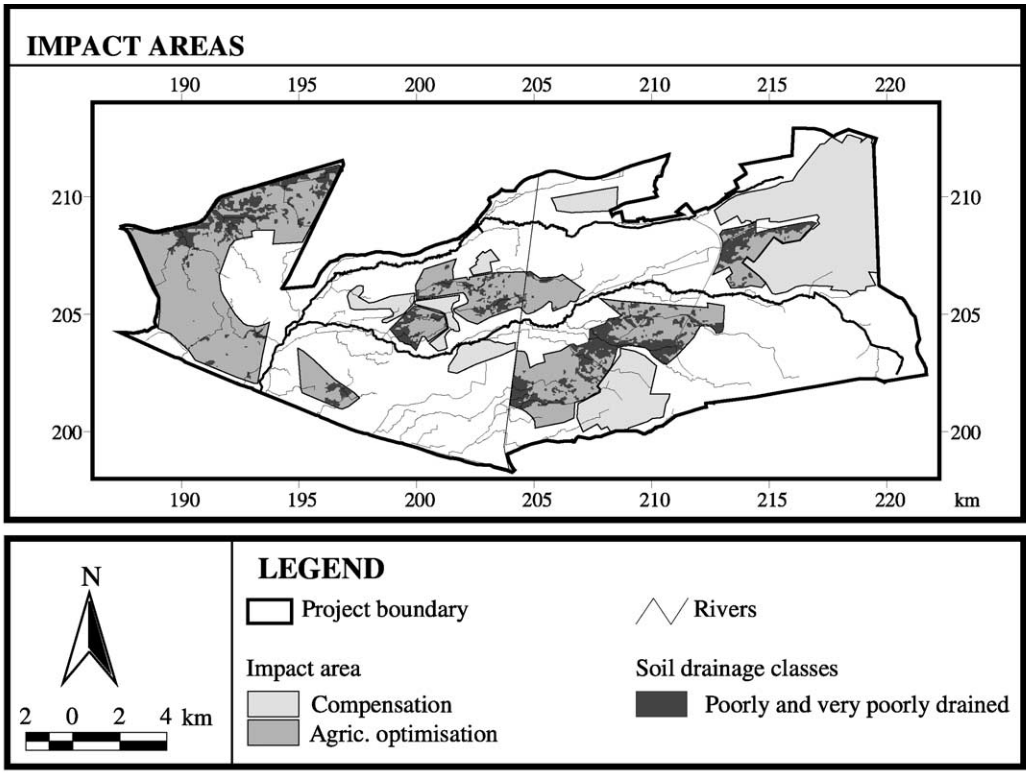

Fig. 3. Impact areas designated for agricultural improvement and compensation measures.

329 mm/y. Comparing this value to the sum of 43 mm/y simulated WetSpass-surface runoff and the 279 mm/y baseflow (resulting from the groundwater model coupled with WetSpass simulated recharge), results in an error of less than 2%.

3.4. Phreatophyte mapping of discharge areas

In order to check the coincidence of phreatophytes and simulated groundwater discharge, the valleys were randomly visited to map occurrences of phreatophytic indicators. 193 phreatophytic sites were identified, ranging in area from 5 to 100,000 m^2, with an average of 4500 m^2. In total 564 occurrences of phreatophytes were counted in the 193 locations, which gives a rather low average of 3 indicators per location. Fig. 8 shows the frequency of occurrence of the different mapped plant species in the study area. Plant species *Lysimachia vulgaris* and *Lythrum salicaria* occur most abundantly, respectively, in 75 and 54% of the locations. They show a broad response curve to environmental factors, because they also have been mapped in places where, there is no indication of groundwater discharge, such as on lush banks where, the nutrient content of the soil is very high. Hence, they appear to be not exclusively selective with respect to indicating groundwater discharge conditions. Klijn and Witte (1999) emphasized that although phreatophytes are fairly reliable as indicators for groundwater discharge, the whole abiotic environmental context should be taken into account. Typical mapped vegetation types are Alder brook forests and mesotrophic meadows. Alder brook forest is characterised by discharge indicators such as *Solanum dulcamara* which was observed in 41 locations, *Equisetum fluviatile* in 33, *Scirpus sylvaticus* in 14, and *Caltha palustris* in three locations. Also, mesotrophic meadows have a high abundance and can be considered as good discharge indicators, as *Lychnis flos-cuculi* was found in 26 locations. *Calla*

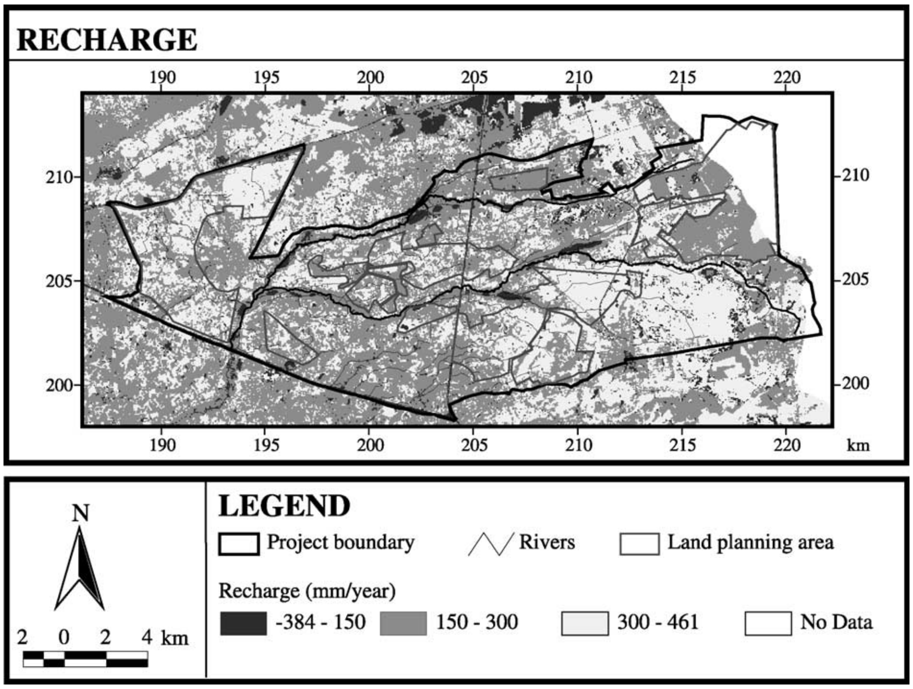

Fig. 4. Recharge for present situation calculated using WetSpass.

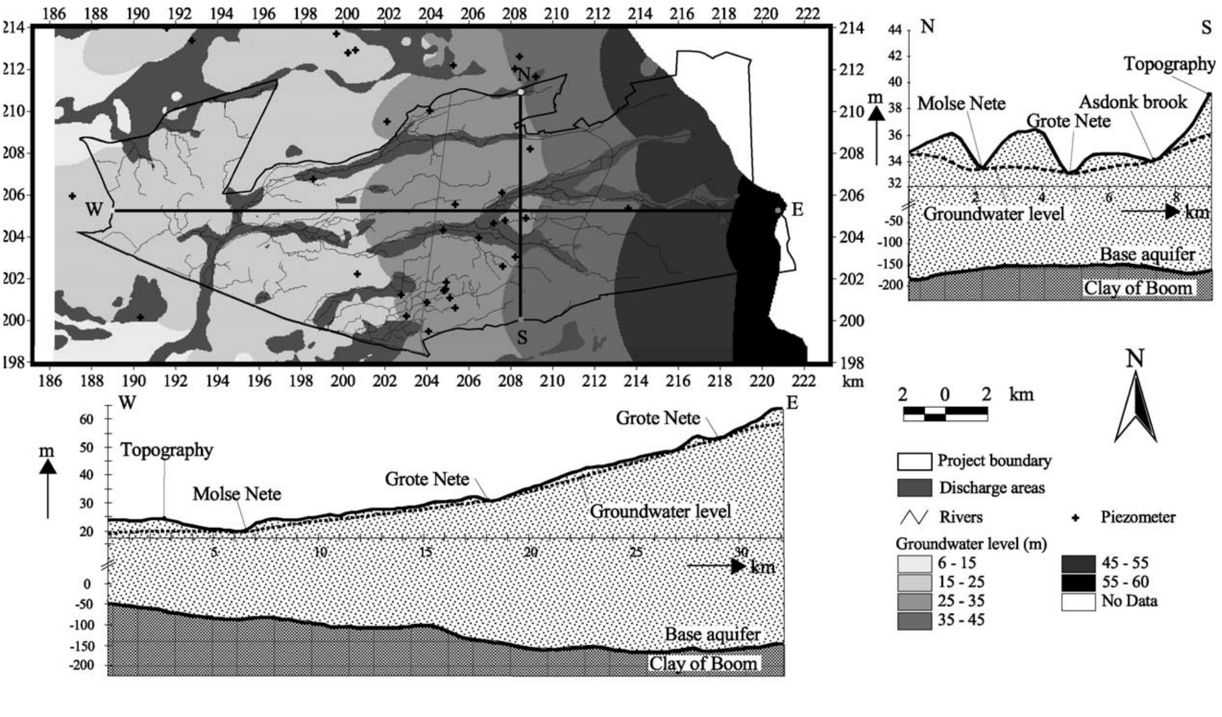

Fig. 5. Simulated groundwater levels and north–south and west–east profiles over the groundwater system in the land planning project area Grote-Nete.

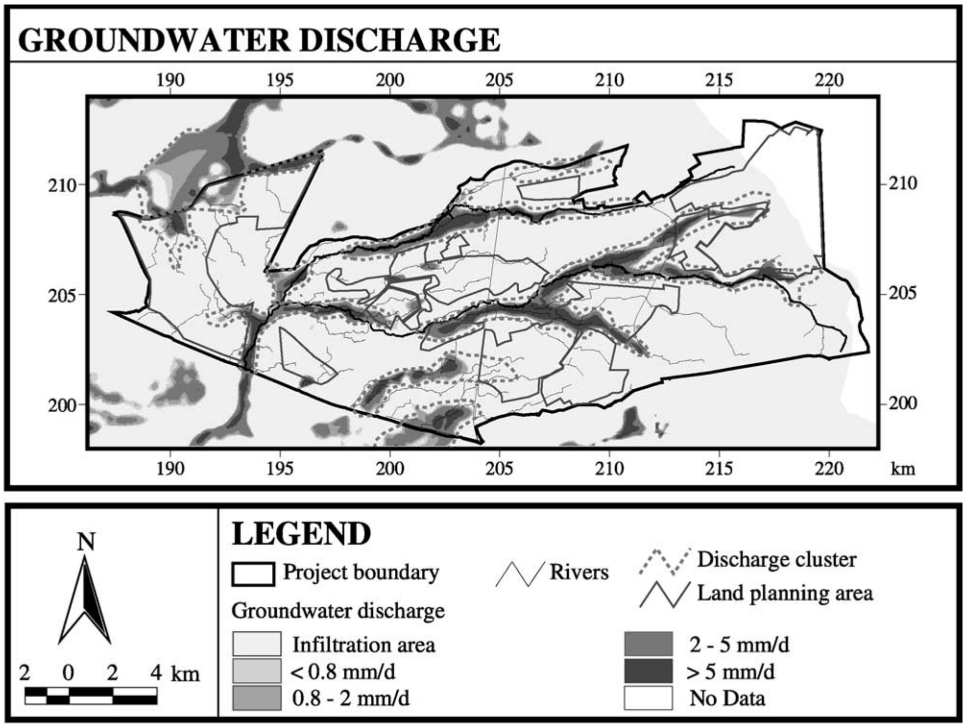

Fig. 6. Simulated groundwater discharge areas for the present situation.

palustris and *Hottonia palustris* are not occurring in any of the visited locations in the study area.

As shown in Fig. 9, discharge areas predicted by MODFLOW's SEEPAGE-DRAIN package compare favourably with the results obtained from the vegetation mapping. Within the study area of Grote-Nete, 79% of the mapped phreatophytic plant locations are found to lie within discharge areas as calculated by the model. Most of these locations correspond to medium or high discharge fluxes. The remaining 21% or 41 plant locations fall outside the simulated discharge zones. Most of these 'mis-matches' are due to scale limitations of the simulations and uncertainty in the phreatophyte mapping. 11 of these 'mismatch' locations have a mapped area larger than 2500 m^2. Since 2500 m^2 is the minimum surface area for a simulated groundwater discharge zone, the other 30 locations have an area too small and isolated to represent or indicate regional discharge zones. If a buffer zone of 100 m (twice a cell size) is considered around the discharge areas, then three out of the remaining 11 plant locations fall within this buffer. Although, at these 3 locations no groundwater discharge is simulated, the groundwater depth is still less than 1 m, which is likely a favourable condition for phreatophytes. Another five locations have a groundwater depth of 1–2 m, and only three have a depth of more than 2 m. However, at two of these

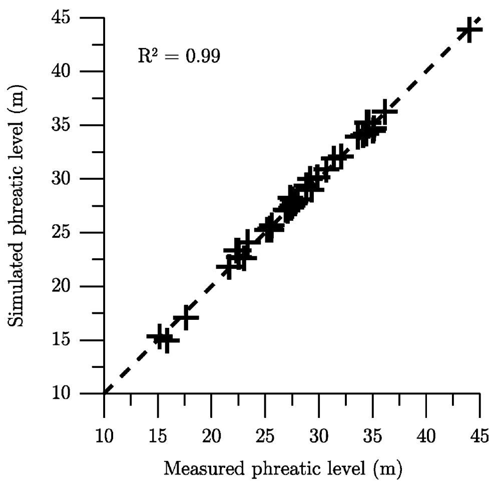

Fig. 7. Comparison of measured and calculated groundwater levels for Grote-Nete study area.

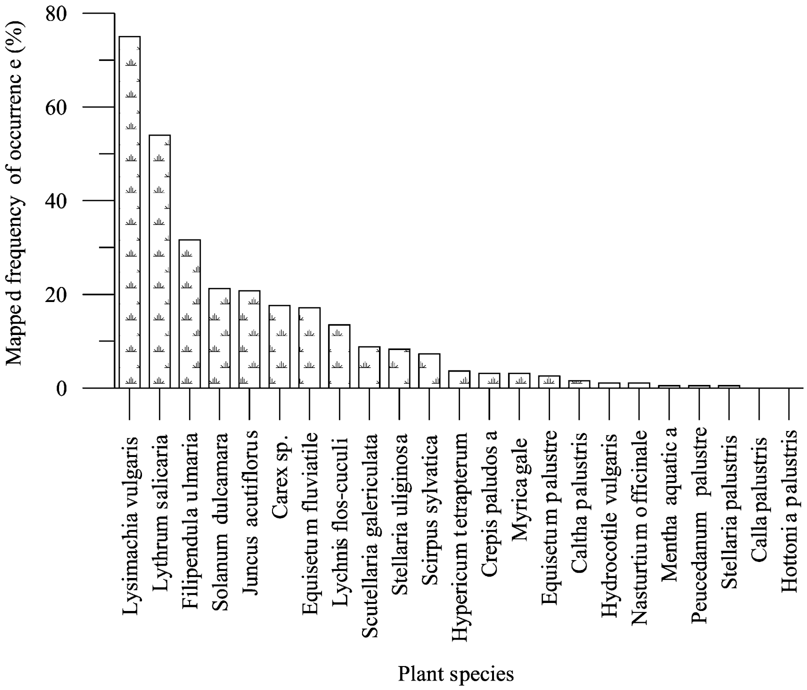

Fig. 8. Mapped frequency of occurrence of phreatophytic plant species.

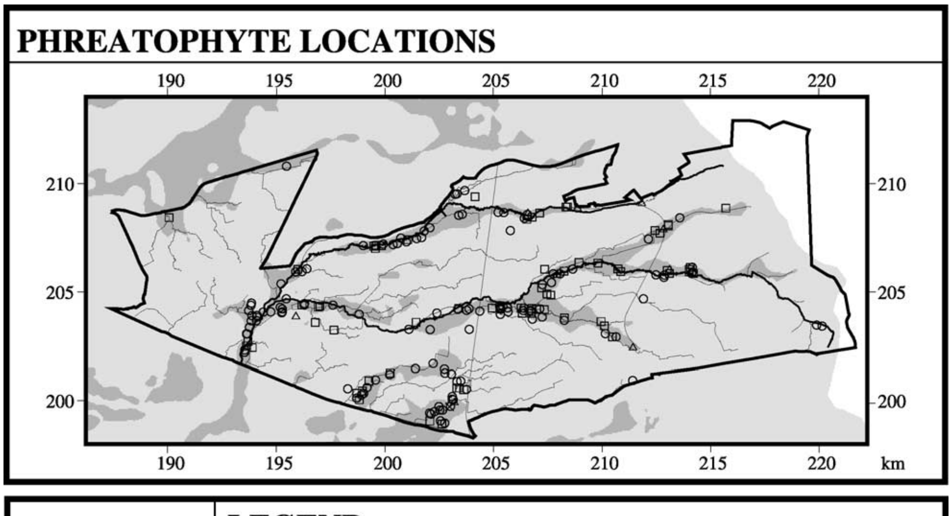

Fig. 9. Location of mapped phreatophytes and their weighted mean Ellenberg *R*-value, adjusted after Hill et al. (1999).

three plant locations only the plant *Myrica gale* has been found, despite the fact that these locations did not have the typical physiognomy of a *Myrica gale* wetland. This indicates that these 2 locations do not have favourable conditions for phreatophytes. Therefore, it can be concluded that in general a good fit exists between the calculated groundwater discharge areas and the phreatophytes indicated by the field mapping.

Fig. 9 shows the average *R*-value (acidity) of the occurring phreatophytic vegetation. In the upper reaches of the valleys, these values are generally lower than in the downstream parts of the valleys. The average *R*-values for the downstream and middle reaches are about 7, which is relatively high. This shows that the water available for the plants is becoming more alkaline in the downstream locations. However, the transition is not smooth but rather abrupt. On one hand, this can be explained by local groundwater discharge systems in the upper reaches, with relatively local infiltrated water of atmotrophic quality (low *R*-values). On the other hand, the downstream locations are most likely linked to much larger recharge–discharge systems, resulting in a more lithotrophic water quality (high *R*-values). The particle tracking results will reveal more clearly these observed relationships, as will be explained further on.

3.5. Recharge areas

Areal contiguity of discharge locations along the different water courses is used as a criterion to delineate 18 different discharge regions, and their associated recharge areas, as shown in Fig. 10. Besides contiguity, boundaries between discharge regions were also determined by landscape ecological characteristics and branching of the river system. In addition, the differences in Ellenberg *R*-value between the lower and upper locations have been used to draw the boundary between regions 10 and 11, and 12 and 13. Once the discharge regions are delineated, the associated recharge areas can be obtained with the groundwater flow model and the flow path tracking procedure. Table 2 gives characteristic values related to each region, such as recharge and discharge area, amount of discharge, and average groundwater flow time. Comparing the individual regions increases our level of understanding of the flow systems occurring in the area and the role they play in the landscape.

Fig. 10 shows the resulting groundwater flow systems. It indicates the different discharge areas, their contributing recharge areas, and groundwater flow times. From this figure the size and extent of the recharge area contributing to each discharge region can be clearly observed. The groundwater flow time at a certain location indicates how long it will take for a water particle, from reaching the groundwater table after infiltration, to flow underground and reach one of the delineated discharge areas. Recharge areas are classified in zones with a certain flow time range to the discharge regions, respectively, 0–10, 10–50, 50–100 and >100 years.

3.6. Ecohydrological differentiation of discharge regions

The different discharge regions are also investigated from an ecohydrological point of view, by taking into account the plant species and their habitat indicators. Ideally, we would like to use the results of the vegetation mapping, but this is not feasible, because the data is on a point basis and does not cover the whole study area, or all discharge areas. Therefore, the ecotope from the BEM was used instead; BEM ecotopes were determined for every groundwater model raster cell located in a discharge area and converted into two BEM indicators, one for alkalinity and one for the trophic status. In order to show that this information is consistent with the vegetation mapping, Ellenberg *R*-values for the mapped phreatophytes are compared with the corresponding BEM alkalinity indicator values in Fig. 11. The correlation coefficient between both variables is 0.7, which shows that the two alkalinity indicators are reasonably equivalent. Hence, this gives confidence in the use of the BEM indicators as a spatially continuous representation of the plant habitat characteristics.

Analyses of the BEM alkalinity indicator for all simulated groundwater discharge areas result in an average alkalinity of 3.1, with a standard deviation of 0.6. This average corresponds to slightly acidic environments, with a pH of about 6. The more upstream located discharge areas have lower values, i.e. are more acidic type of environments, while the downstream areas show the opposite

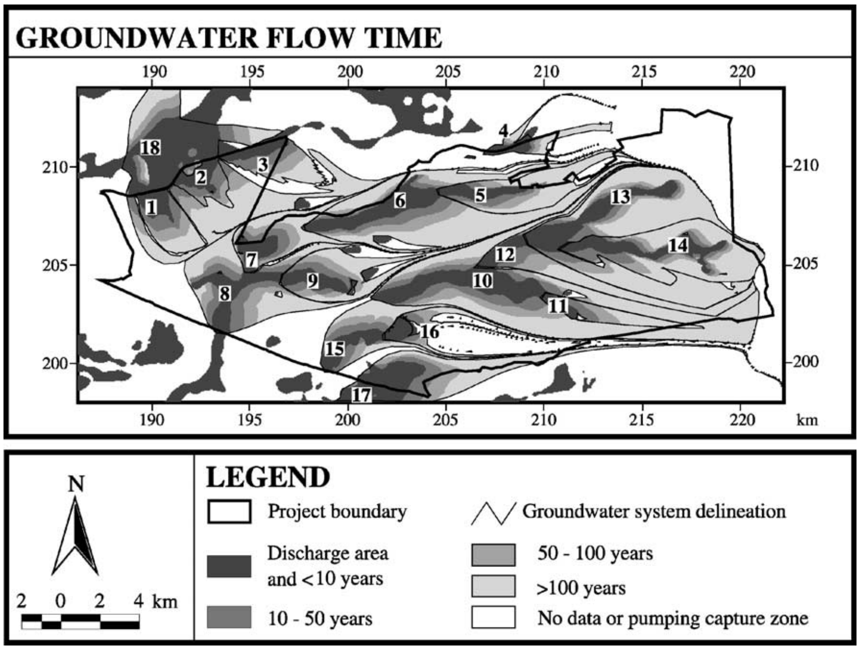

Fig. 10. Simulated groundwater flow systems for the present situation: the numbers (1–18) indicate the different discharge areas (for their delineation see Fig. 6), their contributing recharge areas are delineated by thin black lines, and the groundwater travel time from each recharge location to the indicated discharge location within a groundwater flow system is shown by means of grey scale contours.

trend, i.e. higher values or more alkaline. The average BEM trophic value is 3.9, with a standard deviation of 0.8, which corresponds to relatively nutrient rich conditions. In this case the more upstream located areas have lower trophic levels, and the downstream higher levels.

The BEM indicators are two additional parameters which can help in the description of the ecohydrological properties of the different regions. Other hydrologic parameters with descriptive power are average flow time from recharge to discharge area, the ratio of the recharge area over the discharge area and the discharge flux. The recharge over discharge area ratio is a good indicator for the regional extend of a groundwater flow system. Small values tend to indicate more local systems, while large values correspond to regional flow systems. Average values for all parameters are calculated for the 18 groundwater flow systems and analysed by a cluster analysis. The cluster analysis is based on Ward's method of almagation with squared euclidean distances (Seyhan et al., 1985). Fig. 12 shows the resulting dendogram. Two different mega-clusters are observed, which can

Table 2
Characteristics of each delineated groundwater flow system for the present situation: size of recharge and discharge areas, average groundwater discharge, and average groundwater flow time

Region	Recharge area (km^2)	Discharge area (km^2)	Average discharge (mm/d)	Average flow time (years)
1	5.1	1.5	3	68
2	2.4	1.8	2	24
3	5.8	1.3	4	69
4	2.8	1.4	2	216
5	9.7	2.0	5	190
6	25.5	5.2	5	208
7	8.0	1.9	4	20
8	16.1	3.6	4	114
9	9.2	2.1	4	148
10	33.9	7.1	5	220
11	3.8	1.0	4	94
12	8.6	1.6	5	227
13	26.4	5.8	5	239
14	16.0	4.4	4	184
15	8.4	2.3	4	132
16	4.2	1.1	4	146
17	11.7	5.2	3	120
18	27.6	12.5	3	154

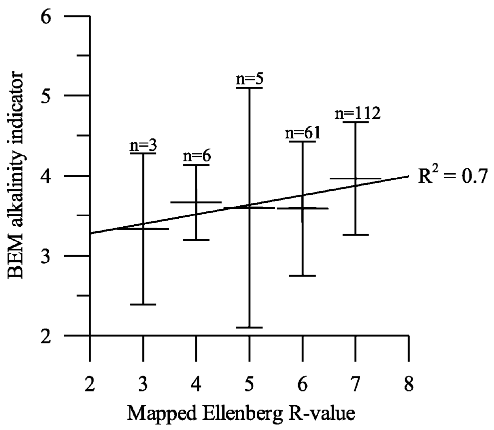

Fig. 11. Comparison of mapped Ellenberg *R*-values, adjusted after Hill et al. (1999), with corresponding BEM alkalinity indicator values (average and standard deviation are shown and the number of mapped locations is indicated).

each be split on a lower level, such that all discharge areas can be classified in four distinct clusters. These clusters are indicated by Roman numbers I–IV.

Clusters I and II consist of discharge areas that all are located in headwaters in the geomorphologically highest locations of the study area. The groundwater flow times are very similar and characteristic for relatively local but deep groundwater systems, with infiltration areas extending to the regional groundwater divide. The alkalinity is also similar, and clearly lower than for the other clusters, indicating atmotrophic seepage water. The difference between cluster I and II is that cluster I has a higher recharge/-discharge area ratio and discharge flux and a slightly lower trophic level than cluster II. This difference can be explained as an expression of the geomorphological position of the two clusters, i.e. cluster I regions (1, 3, 11, 13 and 14) are located upstream in a relatively narrow part of the valley, while cluster II regions (2, 4, 17 and 18) are located in relatively broad valleys and therefore have large discharge areas with low seepage fluxes. In summary, cluster I can be characterized as relatively local, but deep, flow systems, situated upstream with relatively atmotrophic seepage water quality. Cluster II can be characterized as relatively local, but shallower, flow systems, situated downstream and with relatively atmotrophic seepage water quality. Clusters III and IV are situated, respectively, in the centre and most downstream part of the study area. All average parameter values for clusters III and IV are higher than for clusters I and II (except for flow time and flux of cluster IV). This indicates their more regional, lithotrophic character. Cluster III (regions 5, 6, 10 and 12) has the most regional flow system of all clusters, characterized by long flow times, high recharge/discharge area ratios, and high seepage fluxes. This is mainly due to the central location, enabling it to receive deep and regional groundwater flow with a relatively lithotrophic quality. Cluster IV (regions 7, 8, 9, 15 and 16) also consists of regional systems with large recharge areas, resulting in high recharge/discharge area ratio, fluxes, alkalinity and trophic levels. However, it differs from cluster III due to its more downstream location, such that the groundwater flow occurs in a much shallower part of the aquifer, which explains the shorter flow times. In summary, cluster III are regional, deep and relatively lithotrophic groundwater systems, discharging in the central part of the study area, while cluster IV are also regional and relatively lithotrophic systems, but shallower and situated more downstream.

The qualitative differences between the groundwater systems in relation to their ecohydrologic and hydrologic characteristics can more simply be discerned by plotting the most important hydrologic parameter, the groundwater discharge flux versus the most important ecohydrologic parameter, the BEM alkalinity indicator (Fig. 13). The four different clusters can be identified and delineated clearly, as shown in Fig. 13. It appears that all clusters are the same as before, except that regions 9 and 11 have changed places. The delineation of the clusters in the graph is rather striking. It follows that on the basis of these two parameters, significant ecohydrological characteristics of groundwater systems are revealed. It is suggested that this graph can help in identifying major ecohydrological zoning in a catchment, which are due to differences in groundwater flow on a regional scale.

3.7. Scenario simulations

The delineated groundwater flow systems are the subject of an analysis of the impact of changes in land-use. The following scenarios are considered:

- *Pre-development*: this scenario concerns the groundwater systems prior to any significant

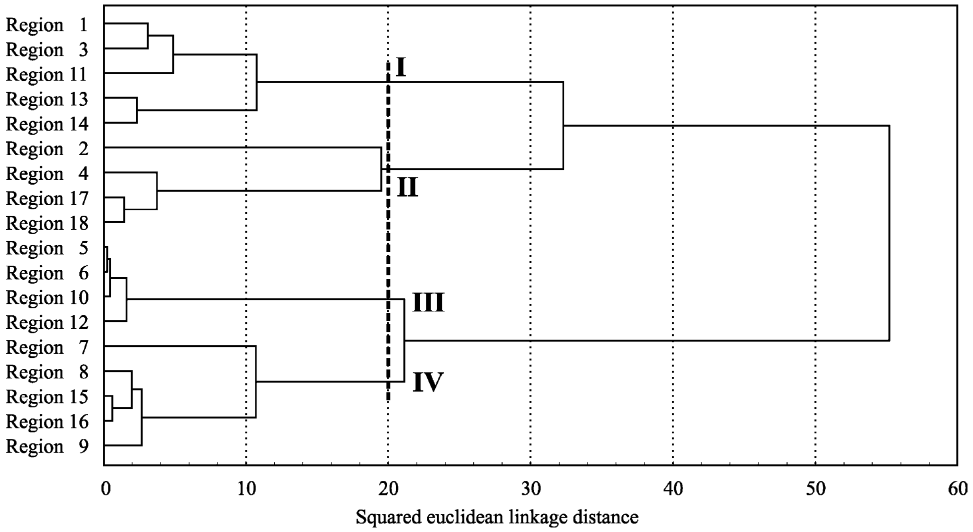

Fig. 12. Cluster dendrogram for the 18 groundwater flow systems.

human influence, i.e. no groundwater is extracted from the system and the recharge is natural, i.e. not influenced by anthropogenic changes in land-use.

- *Future situation*: this scenario concerns the groundwater systems in which the effects of possible future changes in land-use, due to the land-use planning project Grote-Nete, have been accounted for.

A pre-requisite within the land-use planning project is to take into account the recharge–discharge conditions as determined for the present situation, in order to preserve valuable ecological conditions. Therefore, the optimalisation and compensation measures for the future situation are only considered on part of the area of the land-use planning project; these areas are called the impact areas and are shown in Fig. 3. The optimalisation impact areas consist of the soils with Belgian soil classification drainage classes e or f, situated within the recharge part of the area designated for optimalisation. Drainage classes e and f indicate, poorly and very poorly drained soils, respectively, both with a reduction horizon. In land planning the areas with these drainage classes are usually targeted for agricultural improvement, and the resulting reduction in recharge is estimated as 50%. In the remaining areas no reduction of recharge will take place. In the area of compensation measures the recharge will be increased. However, since an increase in recharge is more difficult to realize than a reduction, the increase is set to be 25% only. Additionally, these impact areas are restricted to the recharge parts of the compensation areas.

The characteristics of the 18 groundwater flow systems for the present situation, shown in Table 2, are used as reference for comparison with the pre-development and future scenarios. Tables 3 and 4

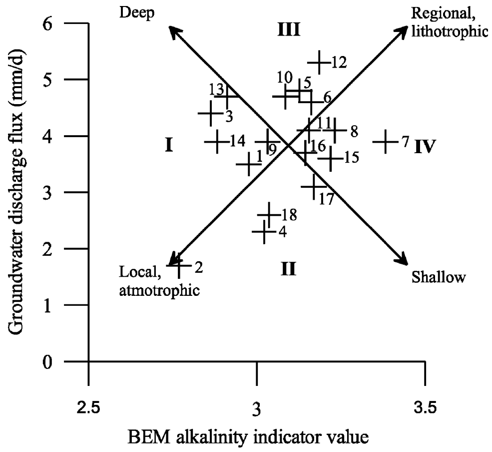

Fig. 13. Comparison of average BEM alkalinity indicator values with the groundwater discharge flux per groundwater discharge region. The clusters I (local, deep, upstream and atmotrophic), II (local, shallow, downstream and atmotrophic), III (regional, deep, central and lithotrophic) and IV (regional, shallow, downstream and lithotrophic) are indicated.

show, respectively, the results for the pre-development and future situation, obtained with the modelling methodology explained in Section 2.

For the pre-development scenario all the groundwater extractions have been ignored and the recharge is calculated without agricultural or urban land-use. The effect on the groundwater system of these changed conditions is determined by re-simulation of the groundwater model. Table 3 summarizes the results obtained for the 18 regions. As the discharge flux is strongly dependent on the changes of both the recharge and discharge areas, the regions are ordered according to their change in total groundwater discharge, which is calculated as the size of the discharge area times the average seepage flux.

For the pre-development scenario, the groundwater discharge areas increase in total with 7.9% compared to the present situation, while the recharge areas increase with 10.2%. The whole groundwater system therefore expands considerably, which is due to the absence of groundwater abstractions and their intake areas. However, the change in size of the recharge and discharge areas vary strongly per region. The largest increase in recharge and discharge surface area is found in region 16, with, respectively, 128.6 and 181.8%. The largest decrease in recharge surface area is −18.4% in region 11. Groundwater system 14 has the largest decrease in groundwater discharge surface area: −11.4%. The change, compared to the present situation, in groundwater discharge flux is between 13.9 and −19.5%. The total discharge increases in 14 of the 18 regions, ranging from 3.2 to 146.7%. In regions 3, 11, and 14 the total discharge decreases, while in region 2 there is no change. The changes in region 16 are directly caused by the absence of some very large groundwater abstractions. It looks like a paradox that region 16 has the largest increase in total discharge but also a marked decrease in discharge flux of −10.8%. However, both changes can be explained by the large increase in the recharge, and also in discharge area, such that the increased recharge is divided over a bigger discharge area, resulting in lower discharge fluxes. In regions 1, 5 and 12 the same phenomenon occurs, i.e. the total discharge increases while the average discharge flux decreases. But in region 3 the reverse occurs, i.e. the total discharge reduces and the discharge flux increases. Also, groundwater travel times increase significantly for most of the regions. From Table 3 it appears that the change in flow time is proportional to the change in recharge area. The general cause of these changes is the shift in groundwater systems as a consequence of changed internal conditions.

It can be concluded that for the pre-development scenario almost 80% of all regions receive more discharge. However, in about 25% of these cases the increase in discharge is due to an increase in discharge area, while the discharge flux decreases. This phenomenon can be important for vegetation, dependent on groundwater discharge because with lower seepage fluxes temporary desiccation of the habitat can occur sooner due to seasonal fluctuations in groundwater level and discharge intensities.

Table 4 summarizes the characteristics of the 18 groundwater systems for the future scenario. The results are also based on re-simulation of the groundwater flow with, respectively, the decreased recharge in the agricultural optimalisation areas and the increased recharge in the compensation areas as explained before (Fig. 3). The discharge clusters in Table 4 are also ranked according to their change in total discharge.

It follows that about one third of the discharge regions receive less discharge, one third more discharge, and one third is unaffected. A rise in total discharge occurs in regions 4, 5, 11, 13, 14 and 16, while the total discharge in regions 6, 7, 8, 9, 10, 15 and 17 remain unaffected and the discharge in areas 1, 2, 3, 12 and 18 decreases significantly. The decrease of discharge in some groundwater systems can be explained by the fact that some soils in their recharge areas will be artificially drained, resulting in a reduced recharge. Also, these regions are located relatively far away from the zones where, an increase in recharge will be effected; these zones are mainly situated in the west, upper part of the study area, i.e. the Campine Plateau.

Similar to the pre-development scenarios it also appears that the discharge intensity does not always increase if the total discharge increases. Especially in region 16, there is a strong reduction of 15% in the discharge intensity, while the total discharge increases with almost 4%.

The results in Table 4 show that there are moderate changes in discharge flux and size of recharge and discharge areas, smaller than in the case of the pre-

Table 3
Recharge and discharge characteristics for the pre-development situation and percentage differences with the present situation. The table is ordered according to the change, from present to pre-development situation, in volume of the total discharge, defined as the average discharge times the discharge area

Region	Recharge area		Discharge area		Average discharge		Δ Total discharge	Average flow time	
	km^2	%	km^2	%	mm/d	%	%	years	%
16	9.6	128.6	3.1	181.8	3.3	− 10.8	146.7	174	19.0
1	6.7	31.4	2.2	46.7	3.2	− 8.6	36.8	67	-1.0
15	10.7	27.4	2.6	13.0	4.1	13.9	30.0	152	15.1
4	3.6	28.6	1.7	21.4	2.4	4.3	25.0	245	13.3
17	13.5	15.4	5.7	9.6	3.4	9.7	20.7	138	15.5
8	17.3	7.5	3.9	8.3	4.4	7.3	14.8	120	5.3
5	11.0	13.4	2.4	20.0	4.5	− 6.3	11.4	219	15.0
18	30.0	8.7	12.9	3.2	2.8	7.7	10.8	172	11.5
10	38.5	13.6	7.3	2.8	5.0	6.4	10.0	249	13.1
9	9.2	0.0	2.2	4.8	4.1	5.1	9.8	156	5.5
13	31.1	17.8	6.0	3.4	4.9	4.3	8.0	269	12.8
6	25.9	1.6	5.3	1.9	4.7	2.2	4.6	223	7.2
7	7.7	− 3.8	1.9	0.0	4.0	2.6	3.7	143	2.1
12	9.2	7.0	1.7	6.2	5.2	− 1.9	3.2	254	11.7
2	2.1	− 12.5	1.8	0.0	1.7	0.0	*0.0*	24	− 0.8
3	5.6	− 3.4	1.2	− 7.7	4.6	4.5	**− 4.8**	69	0.1
14	13.4	− 16.3	3.9	− 11.4	3.5	− 10.3	**− 19.4**	157	− 14.4
11	3.1	− 18.4	0.9	− 10.0	3.3	− 19.5	**− 26.7**	84	− 9.7

Table 4
Recharge and discharge characteristics for the future situation and percentage difference with the present situation. The table is ordered according to the change, from present to future situation, in volume of the total discharge, defined as the average discharge times the discharge area

Region	Recharge area		Discharge area		Average discharge		Δ Total discharge	Average flow time	
	km^2	%	km^2	%	mm/d	%	%	years	%
14	16.1	0.5	4.6	2.7	3.9	1.8	6.0	175	− 4.5
13	26.1	− 1.2	6.0	4.4	4.8	1.5	5.3	213	− 10.7
4	2.9	3.3	1.4	4.4	2.3	0.0	4.2	217	0.7
16	4.1	− 1.2	1.3	24.5	3.2	− 15.4	3.5	127	− 12.8
11	4.0	3.8	1.0	0.5	4.4	6.7	2.8	101	8.3
5	9.9	1.9	2.0	2.3	4.9	2.9	2.2	190	− 0.2
9	9.2	0.2	2.1	0.2	4.0	3.3	*0.4*	150	1.8
6	25.3	− 0.8	5.2	0.0	4.6	0.0	*0.1*	202	− 3.0
15	8.4	0.0	2.3	0.0	3.6	0.0	*0.0*	122	− 7.9
7	7.9	− 1.5	1.8	− 0.1	4.1	5.6	*− 0.3*	137	− 2.6
17	11.5	− 1.2	5.2	− 0.7	3.1	0.0	*− 0.3*	118	− 1.8
8	16.1	− 0.1	3.6	− 0.7	4.1	0.0	*− 0.4*	116	1.5
10	33.7	− 0.7	7.1	− 0.4	4.6	− 1.6	*− 0.9*	218	− 1.0
12	8.9	3.3	1.6	− 0.8	5.1	− 3.2	**− 1.2**	228	0.2
18	28.0	1.6	12.3	− 1.2	2.6	− 0.1	**− 1.5**	157	1.7
1	5.1	− 0.5	1.5	− 1.8	3.3	− 5.3	**− 2.4**	68	0.0
3	5.9	1.4	1.2	− 2.6	4.6	3.2	**− 3.7**	70	2.2
2	2.5	4.5	1.7	− 5.8	1.5	− 13.4	**− 12.3**	25	4.2

development scenario. This is explained by the fact that there are negative and positive changes in land-use with respect to the groundwater systems, which largely compensate each other. Areas where, recharge decreases with 50% are only 11.6 km^2 in size, while the areas where, the recharge increases with 25% amount to 31.3 km^2. However, the different measures do not neutralize each other everywhere, on a local scale. The change in groundwater level varies from a maximum increase of 55 cm (in a small area close to the water divide in the most eastern upstream part of the basin) to a maximum decrease of 7 cm (in the central and western part of the basin). The area where, the groundwater level declines is 160 km^2, which is larger than the area of 120 km^2 with a rise in groundwater level. It is significant to note that most of the discharge areas are located in the part of the study area where, the groundwater level declines.

The average groundwater flow times reduce in half of the areas, while the increase in flow time in the other areas is only very moderate. The total decrease in flow time is coupled to the reduction in the recharge areas, but is also affected by an increase in groundwater level gradients. The higher gradients are caused by the larger differences in recharge between parts of the study area. Hence, it follows that in total the compensating measures quantitatively balance the optimisation measures. However, due to spatial differentiation of these measures, large local changes in the hydrological conditions may occur. Also, it is noticed that sometimes unexpected changes occur with respect to either the groundwater discharge area or flux. It can therefore be expected that the ecological effects of the proposed land-use changes will vary considerably on a local scale. Although discharge area and flux change considerably, it is found that the decrease in groundwater level, due to the decreased recharge condition, is relatively small. Hence, the implied change in recharge, as a consequence of the land-use change, is to be regarded as mild.

4. Conclusions

The combined approach using hydrological models, vegetation mapping and GIS proves to be an effective tool in characterizing groundwater systems and discharge-recharge relationships. The traditional groundwater modelling tools MODFLOW, DRAIN and MODPATH are extended with SEEPAGE and WetSpass in order to be able to delineate groundwater flow systems in an accurate way. The flow systems are characterized by the location of discharge and recharge areas, discharge flux and flow times. Complementary use of vegetation information in the analysis of the modelled discharge areas has a clear benefit in defining different discharge regions. Therefore, this methodology increases our understanding of the ecohydrological conditions and relationships. As such it helps in setting up the framework for more detailed ecohydrological research about the functioning of specific systems, their conditions, sensitivities and potentials.

It is shown that the mapped phreatophytes are useful in validating the modelled groundwater discharge areas. Discrepancies between the modelled and mapped discharge areas can be an indication of errors or limitations (limited spatial or temporal resolution, improper boundary conditions, or limited data accuracy) in the hydrological model. However, it is also possible that the mapped phreatophytes do not reflect the present hydrological conditions of the site, because they lag behind the changes in land-use that have occurred in the recent past. Fragmentation of the landscape is another cause, due to which the relationship between the hydrological condition of the landscape and the ecological expression is disturbed. Explaining these discrepancies will require further detailed research into the local ecological and hydrological relationships as well as in the causes of recent changes. These discrepancies are therefore most interesting in revealing the functional relationship between the vegetation occurrence and the hydrological conditions.

Ecohydrological differentiation of regional groundwater discharge areas is further investigated by using hydrological and ecological parameters in a cluster analysis. The different clusters can be explained as a result of their geomorphological position in the landscape and especially their position with respect to the groundwater systems. It is concluded that plotting the alkalinity indicator versus the seepage flux is a very useful tool in discriminating different recharge–discharge groundwater systems. This graph reveals in a simple way major ecohydrological differences in a catchment which are due to regional groundwater and recharge–discharge groundwater systems. Proper handling of the distributed data is a necessity for the multidisciplinary analysis of the recharge–discharge areas. GIS plays an integrative role in this process. Its functions increase the comparison and analysis possibilities, while it also serves as an ideal platform from which the different models can be managed.

The effects of the land-use changes on the recharge–discharge areas are evaluated by using the combined approach. The results show the most sensitive recharge–discharge systems. When comparing the scenarios for implementing the future land-use changes it seems that, on a catchment level, the proposed compensation measures are sufficient in compensating the optimisation measures. However, it is clear that on a local scale there are positive and negative effects. More complicating is that for some of the discharge areas a decrease in the discharge flux is accompanied by an increase in the discharge area or an increase in the discharge flux is accompanied by a decrease in the discharge area. Such effects of the land-use changes are of particular importance for the ecological conditions of the area. Groundwater system modelling is a necessity to evaluate the intricate changes in location, size and fluxes of the discharge areas. It is concluded that the applied methodology for identifying discharge–recharge areas proves to be helpful for organizing an effective land-use planning with regard to conserving ecologically valuable areas.

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