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A Methodology for Mapping Regional Groundwater Discharge Dependent Ecosystems

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ABSTRACT

The relation between groundwater recharge and discharge is one of the most important aspects in the protection of ecological 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 the ecological status or development. This methodology is applied to a land-use planning project in the Grote-Nete basin, Belgium. Discharge regions are delineated on basis of their simulated spatial discharge contiguity, position in the landscape and alkalinity of the plant habitat. Field mapping of phreatophytic vegetation verified the simulated discharge areas. It is shown that the discharge clusters are significantly different in discharge intensity and alkalinity. The integration of the hydrological modelling and vegetation mapping proves to be advantageous in revealing some of the ecological differences in the catchment.

1 INTRODUCTION

Main objectives of modern land planning are the protection of ecologically valuable areas and land-use in support of integrated water management. Special attention should be given to the effect of land-use changes on the hydrological cycle and the protection of groundwater systems, especially discharge and recharge areas (de Ridder, 1998). In discharge areas often groundwater discharge, seep or spring wetlands have developed (Mitsch and Gosselink, 2000). These are from ecological point of view very valuable wetlands, since they mostly have an almost permanent shallow water table, and a constant lithotrophic water quality. 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).

2 METHODOLOGY

A methodology is presented for characterizing discharge and recharge areas making use of hydrological modeling and vegetation mapping within a GIS framework. The methodology consists of the following components: (a) Groundwater flow modelling to obtain the groundwater head distribution as well as to identify groundwater discharges (location and fluxes); (b) Calibration of the groundwater model with head data and river discharge; (c) Mapping of phreatophytic vegetation for identification of shallow groundwater table conditions and for checking the groundwater modelling results; (d) Delineation of regions of discharge areas with similar topographical, hydrological and ecological characteristics, based on numerical model results and vegetation mapping; (e) Identification of recharge areas associated with a discharge region, using particle tracking; (f) Statistical grouping of different recharge-discharge systems into clusters; (g) A GIS procedural interface to embed the previous steps in a structured way and to increase the efficiency of analysis.

2.1 Groundwater modeling

In order to simulate recharge and discharge areas, the MODFLOW model code (Harbaugh and McDonald, 1996) has been modified slightly as follows. The flow in the phreatic groundwater layer is simulated in steady state using following equation:

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

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]. 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. 2, whereas in discharge areas h is known and D can be calculated as:

$$D = \nabla(T\nabla h_D) + R \pm Q \quad (2)$$

where h_D [L] 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 (Batelaan and De Smedt, 1998).

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 et al., 2001). The surface runoff is calculated from the slope, soil type, land-use and precipitation intensity ratio. The evapotranspiration is calculated from potential evapotranspiration, soil moisture storage capacity and soil cover and the groundwater recharge is estimated from the seasonal water balance. The model has been integrated with Arc/Info (Asefa et al., 1999) and ArcView (Batelaan et al., 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 and groundwater system analysis

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.

Ellenberg (1991) defined six indicator values for more than 1750 vascular plants species with respect to their habitat for Middle European locations. The wetness (F-value) and acidity (R-value) 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. Hill et al. (1999) redefined the indicators for British conditions.

A list of 23 phreatofytic plant species has been identified on basis of a literature study and regional field knowledge (Londo, 1988, Ellenberg, 1991, Hill et al., 1999). For the study area a vegetation mapping was performed, 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. Besides the point vegetation mapping the Biological Evaluation Map (BEM) (Rombouts and Delafaille, 2000, Berten and Hermans, 2000) was also used. De Baere (1997) defined for each vegetation mapping unit of the BEM an alkalinity indicator, which ranges from 1 very acidic environment (pH about 4) to 5 slightly basic (pH higher than 7) and a trophic level indicator, which ranges between 1 for a very oligotrophic environment to 5 for a very nutrient rich environment.

A next step is the delineation of wetland or discharge regions with 'similar' characteristics. Basis for the delineation is the contiguity of the simulated 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. 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.

A relative comparison of the different recharge-discharge groundwater systems is required in order to increase our knowledge on the relationship between regional groundwater and phreatophytes. Cluster analysis with groundwater flow and ecological status parameters is used to aggregate the different recharge-discharge systems into a reduced number of significantly different types of systems. Since cluster analysis requires a relatively extensive set of parameters, it is also investigated if a similar grouping of systems can be obtained with a reduced number of parameters.

3 APPLICATION AND DISCUSSION

The study area is located about 60 km north-east of Brussels and is 293 km² 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 her many tributaries, resulting in very slightly elevated interfluvies and broad swampy valleys (Wouters and Vandenberghe, 1994). The topography ranges from 14 to 65 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. The transmissivity of the aquifer system increases from about 1000 m²/d in the west of the area to about 3000 m²/d in the east of the area, groundwater extraction totals 66580 m³/d. Boundary conditions for the steady

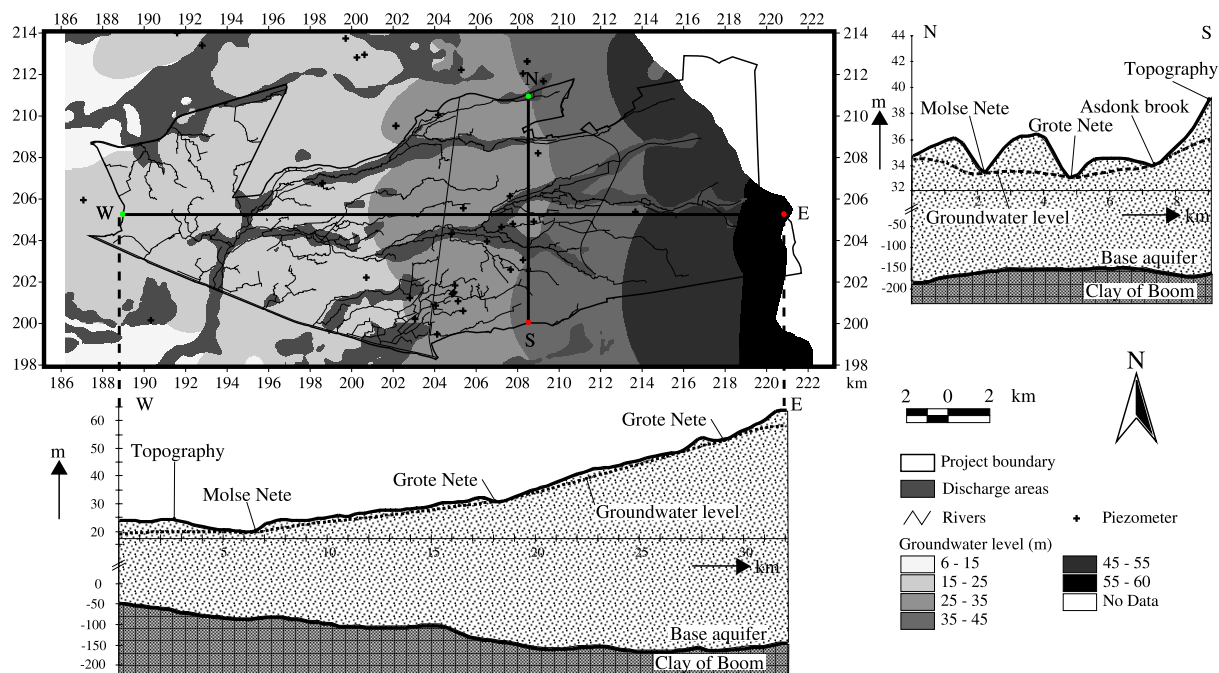


Figure 1: Simulated groundwater levels, discharge areas and north-south and west-east profiles over the groundwater system in the land planning project area Grote Nete

state groundwater model were taken from a regional flow model for Dijle, Demer and Nete basins (Batelaan et al., 1996). The WetSpas calculated 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 shallow groundwater tables and high transpiration by the vegetation. On average the recharge in the valleys is about 60 mm/y lower than in the interfluvies.

Fig. 1 shows the resulting calculated groundwater heads, discharge areas and a north-south and west-east profile of the groundwater system. Most discharge areas appear as bands of 500 m wide along the main water courses in the area. The average discharge intensity is 4 mm/d . Calibration of the model on basis of 38 piezometers (Fig. 1), results in a good agreement: a correlation coefficient of 0.99, a root mean square error of 0.45 m and a mean absolute error of 0.35 m . Analysing 10 years of river discharge data from a station downstream of the area gives an average specific discharge of 328.5 mm/y . Comparing this to the sum of the WetSpas simulated surface runoff (43.4 mm/y) and baseflow from the groundwater model, given by the coupled WetSpas simulated recharge (279.2 mm/y), results in a water balance error of less than 2%.

At 193 locations in the visited valleys of the Grote-Nete basin, 564 times phreatophytic indicators are mapped. 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, 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* at 41 locations, *Equisetum fluviatile* at 33 locations, *Scirpus sylvaticus* at 14 locations, and *Caltha palustris* at 3 locations. The mesotrophic meadows have a high abundance of the discharge indicator *Lychnis flos-cuculi* at 26 locations.

Within the study area of Grote-Nete, 79% of the mapped phreatophytic plant locations are found to lie within discharge areas as simulated by the groundwater model. Most of these locations correspond to medium or high discharge areas. The remaining 21% or 41 plant locations fall outside the simulated discharge zones. Most of these 'mismatches' can be explained as a result of scale limitations of the simulated results and uncertainty in the phreatophyte mapping. In the upper reaches of the valleys the mapped phreatophyte R-values are generally lower than in the downstream parts of the valleys, where the average R-value is about 7. This relatively high value shows that the quality of the water available for the plants is becoming clearly more alkaline in the downstream locations. On one hand, this can be explained by local groundwater discharge systems in the upper reaches, which feed plants with relatively local infiltrated water of atmospheric quality (with low R-values). On the other hand, the downstream locations are most likely linked to much larger recharge-discharge systems, resulting in a more

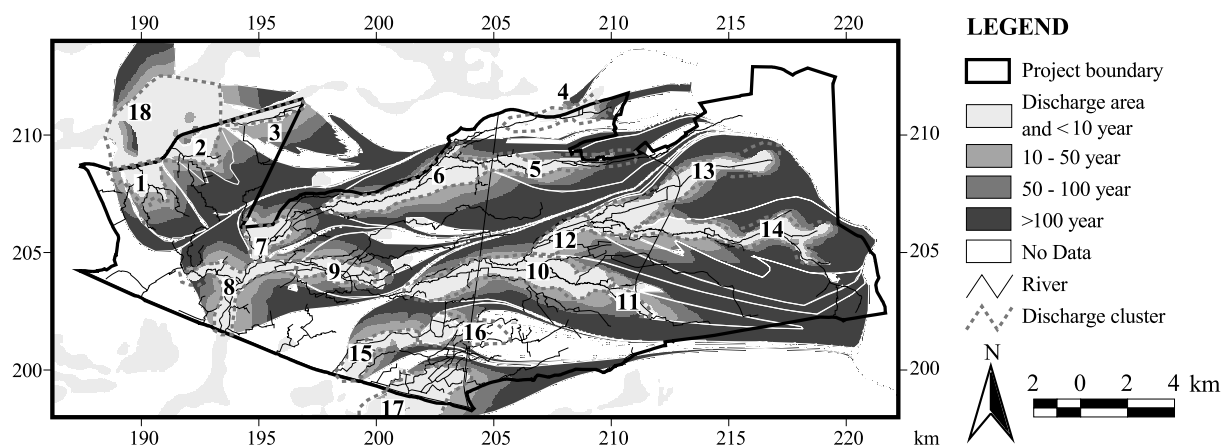


Figure 2: Simulated groundwater flow systems, indicated are the different discharge areas, their associated recharge area, and the groundwater travel times.

lithotrophic water quality (with high R-values).

Areal contiguity of discharge locations along the different water courses, landscape ecological characteristics and the branching of the river system are used as criteria to delineate 18 different discharge regions. From Fig. 2 the size and extend of calculated the recharge area, contributing to each discharge region, can be clearly distinguished. The groundwater flow time at a certain location indicates how long it will take for a water particle, that just reached the groundwater table after infiltration, to flow underground and reach one of the delineated discharge regions.

The BEM alkalinity and trophic indicators are two parameters which can help in the description of the ecohydrological properties of the different regions. Other parameters of which descriptive power can be expected, are the hydrologic parameters, average flow time from recharge to discharge area, the ratio of the recharge area over the discharge area and the discharge flux. Average values of these five parameters are calculated for the 18 groundwater flow systems and these are analysed in a standardized way by a cluster analysis (Fig. 3a) Two major different clusters can be observed, which on a lower level can each be split up in two clusters. Cluster I and II consist of discharge areas all located in headwaters or geomorphological highest locations of the study area. Cluster I can be characterized as a relatively local, but deep, flow system situated upstream and with a relative atmotrophic quality. Cluster II can be characterized as a relatively local, but shallower, flow system situated downstream and with a relative atmotrophic quality. Cluster III and IV are situated respectively in the centre and most downstream part

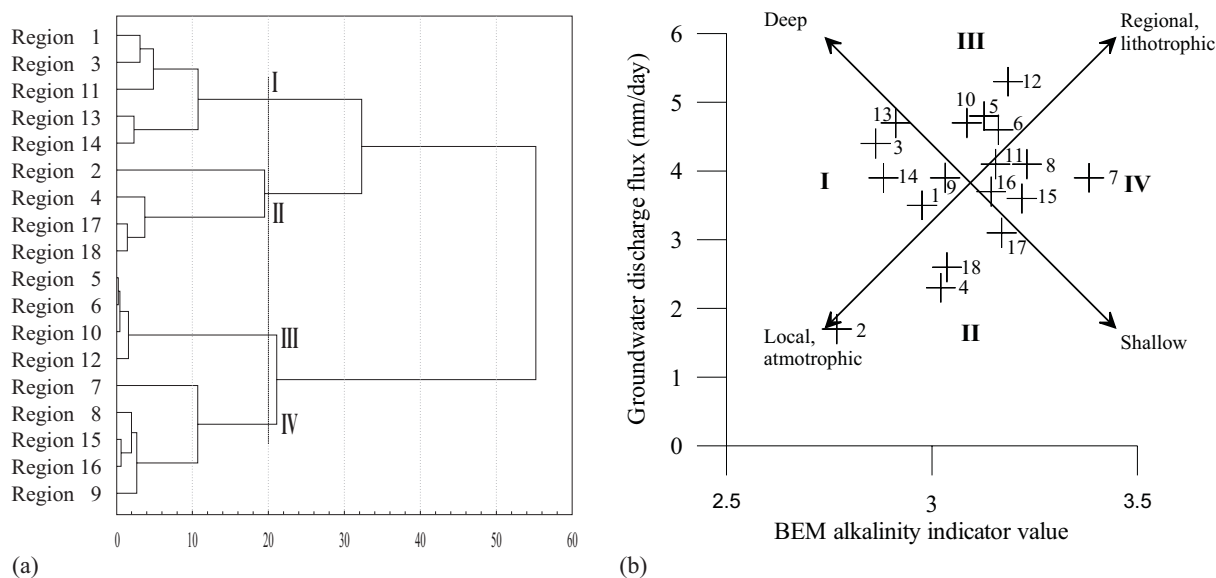


Figure 3: (a) Cluster dendrogram for the 18 groundwater flow systems, (b) Comparison of average BEM alkalinity indicator values with the groundwater discharge flux per groundwater discharge region. The clusters I (local, deep, upstream and atmotrophic), II (local, shallow, downstream and atmotrophic), III (regional, deep, central and lithotrophic) and IV (regional, shallow, downstream and lithotrophic) are indicated.

of the study area. Cluster III is a regional, deep and relatively lithotrophic groundwater system, discharging in the central part of the study area, while cluster IV is also a regional and relatively lithotrophic system, but shallower and situated more downstream.

In order to simplify the qualitative analysis of the differences between groundwater systems in relation to their ecohydrologic and hydrologic characteristics, we select the most important hydrologic parameter, i.e. the seepage flux, and the most important ecohydrologic parameter, i.e. the alkalinity indicator. The four different clusters can be identified again, as shown in Fig. 3b with some small deviations in the centre of the graph where the differences between the groundwater systems are less obvious. The delineation of the clusters in the graph is rather striking. It shows that on basis of these two parameters important significant ecohydrological differences in the recharge-discharge groundwater systems can be revealed.

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