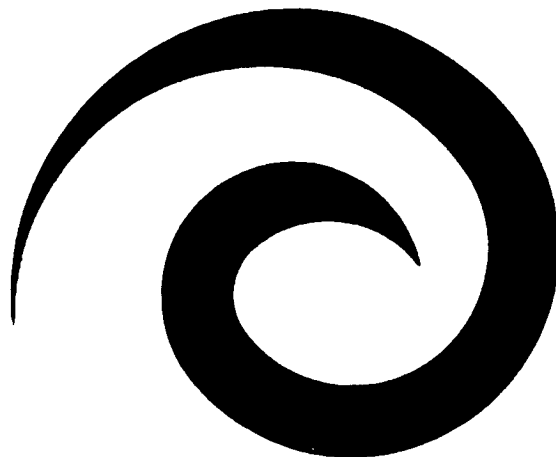


# Water



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VOLUME 1

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## PREPRINTS OF PAPERS



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# Characterization of a regional groundwater discharge area by combined analysis of hydrochemistry, remote sensing and groundwater modelling

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**Summary** A multi-layer regional groundwater flow model for simulation of quantitative groundwater discharge has been developed and applied to the wetland nature reserve Walenbos, (Belgium). The model predicts groundwater seepage, infiltration zones, fluxes, and travel times. The different vegetation types and chemical characteristics of the seepage water in the nature reserve compared very well with the different local and regional groundwater systems predicted by the model and served as validation for the model. In addition, Landsat TM remote sensing analyses were used to validate the distribution of recharge and discharge areas. All analyses were integrated in a GIS resulting in an efficient multi-disciplinary method for a more fundamental understanding of groundwater wetland flow systems.

## 1 INTRODUCTION AND GEOGRAPHICAL SETTING

Regional groundwater flow studies have traditionally been a field of study for hydrogeologists. Apart from the basic conditional geological description, most authors analyze regional groundwater systems by studying topography, land and soil features, hydrochemistry, environmental isotopes, piezometric patterns or groundwater numerical model results. Those aspects were listed by Freeze and Cherry (1) as different ways of mapping discharge and recharge areas. Simultaneous studies of those aspects is often limited due to the tendency for monothematic specialisations, lack of data and a platform of integration. With Geographical Information Systems (GIS) an appropriate environment for analysis and comparison of thematic data is now available.

In this article a multi-thematic approach to the analyses of groundwater discharge areas is followed. It is shown and advocated that a multi-thematic GIS-integrated approach results in a better, more holistic understanding of the groundwater flow systems.

The approach is applied to the surroundings of the forest nature reserve, Walenbos, located about 30 km east of Brussels, Belgium, with a size of 12 by 16 km (Figure 1). The topography is characterized by a series of SW-NE undulating Pliocene hills that are between 50 and 100 m high and consist of glauconite rich sand with often a hard pan at the top. Walenbos lies in the valley of the River 'Brede Motte'. Within the valley a slightly elevated ridge divides Walenbos in an eastern and a western sub-basin.

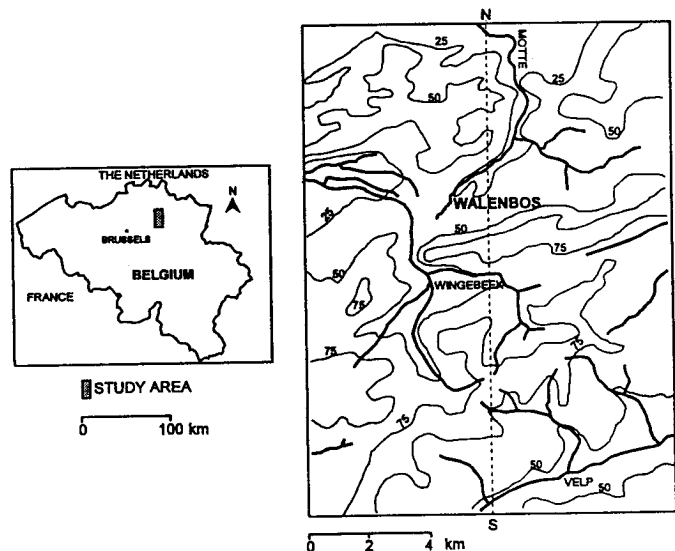


Figure 1: Geographical setting

## 2 DESCRIPTION OF A MULTI-LAYER GROUNDWATER DISCHARGE MODEL

A steady state quasi three-dimensional groundwater model was developed. In case of a three-layer system the flow situation can be described as follows:

(a) Horizontal flow in a phreatic aquifer

$$\frac{\partial}{\partial x} [K(h-z) \frac{\partial h}{\partial x}] + \frac{\partial}{\partial y} [K(h-z) \frac{\partial h}{\partial y}] + c(g-h) + N - P = Q \quad (1)$$

where

- $K$  = hydraulic conductivity of the aquifer [ $L T^{-1}$ ],
- $h$  = position of water table [L],
- $z$  = elevation of base of aquifer [L],
- $c$  = hydraulic resistance of semi-confining layer [ $T^{-1}$ ],
- $g$  = piezometric level of the semi-confined aquifer [L],
- $N$  = effective precipitation [ $L T^{-1}$ ],
- $P$  = pumping rate [ $L^3 T^{-1} L^{-2}$ ], and
- $Q$  = groundwater seepage [ $L^3 T^{-1} L^{-2}$ ].

(b) Vertical flow through an aquitard

(c) Horizontal flow in a semi-confined aquifer

$$\frac{\partial}{\partial x} (T \frac{\partial g}{\partial x}) + \frac{\partial}{\partial y} (T \frac{\partial g}{\partial y}) + c(h-g) - P = 0 \quad (2)$$

where  $T$  = transmissivity [ $L^2 T^{-1}$ ].

Since no groundwater discharge exists in infiltration areas, these can be identified from equation (1) as the areas where the groundwater table is deeper than 0.5 m below the ground level. The latter accounts for the unsaturated zone. Consequently, the other areas in the study region are discharge areas, with the groundwater table equal to the ground level minus 0.5 m. The groundwater discharge flux in discharge areas can be calculated from equation (1).

Additionally, a flow tracing module was developed. The procedure calculates, starting from each grid cell, a three-dimensional flow line. Horizontal flow velocity components are calculated from the slope of the piezometric level. The vertical flow velocity is interpolated linearly with depth in the top and bottom aquifers and is assumed constant in the aquitard, as illustrated in Figure 2.

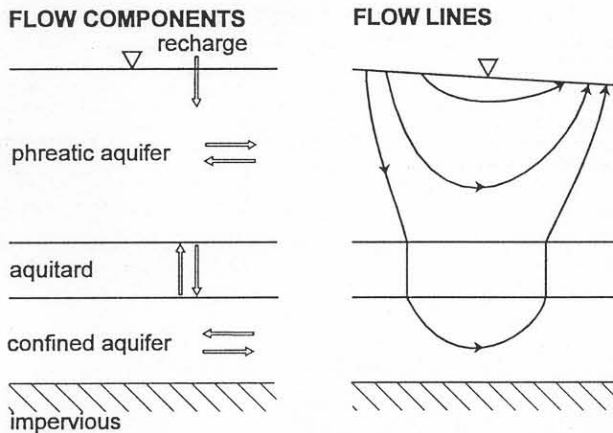


Figure 2: Sketch of velocity components and flow lines

The multi-layer model and a simplified one-layer version were integrated into the GIS GRASS at respectively a file transfer and a GRASS library level (Batelaan et. al. (2)).

The model has been applied to Walenbos. The hydrogeological situation was schematized by:

- (a) a top phreatic aquifer consisting mainly of a Pliocene, glauconite rich sand of 4 to 95 m thickness (Figure 3) with a hydraulic conductivity of 11 m/day (Bronders (3));
- (b) a semi-confining 30 m thick layer, mainly consisting of plastic clay and sandy clay with a hydraulic resistance of 0.007 day<sup>-1</sup>;
- (c) a lower semi-confined aquifer with an impervious base consisting of 15 m coarse sands. Pumping tests have yielded an average hydraulic conductivity of 7 m/day (Bronders (3)).

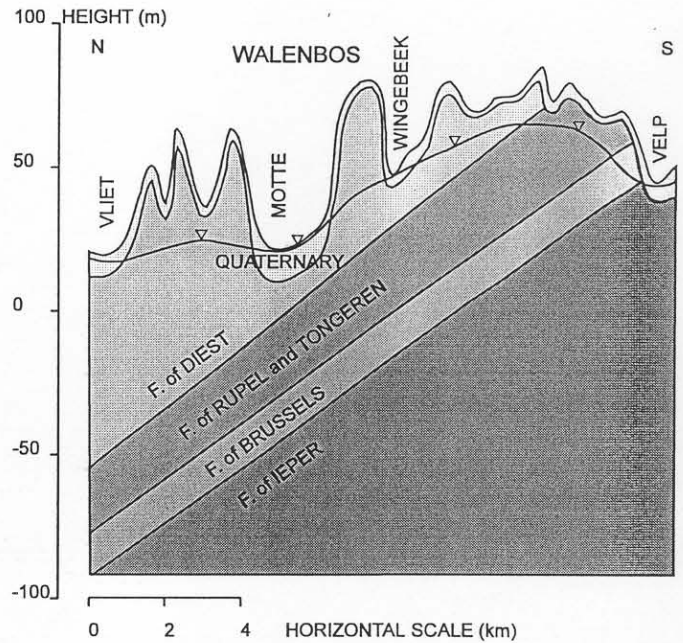


Figure 3: Hydrogeological N-S profile through the study area

For this schematization the equations were solved with a finite difference scheme using a five point discretisation and a red-black ordering for the Gauss-Seidel iterative solution procedure (Hackbusch (4)). The area was discretized in a grid with a resolution of 50 by 50 m. Figure 4 shows the calculated groundwater discharge areas. Within the Walenbos two important basins with groundwater discharge appear. Using the flow tracing module the contributing areas and the flow times to Walenbos can be calculated (Figure 5).

From these results it can be concluded that the contributing area is almost three times as large as would be deduced from topography only. It takes up to about 100 years for water in the unconfined aquifer to reach Walenbos. Infiltrated water at the northern and southern boundary of the contributing area and at the water divide in the south-eastern part of the study area flows through the confined aquifer and has therefore transfer times of several hundred years.

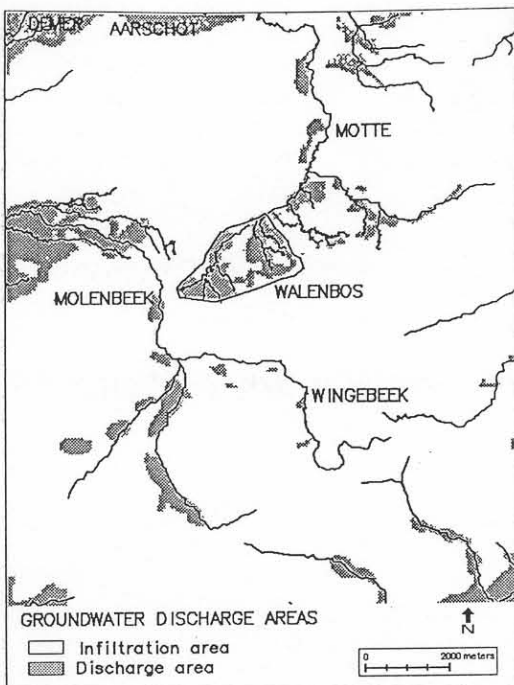


Figure 4: Calculated groundwater discharge areas, overlain by riversystem

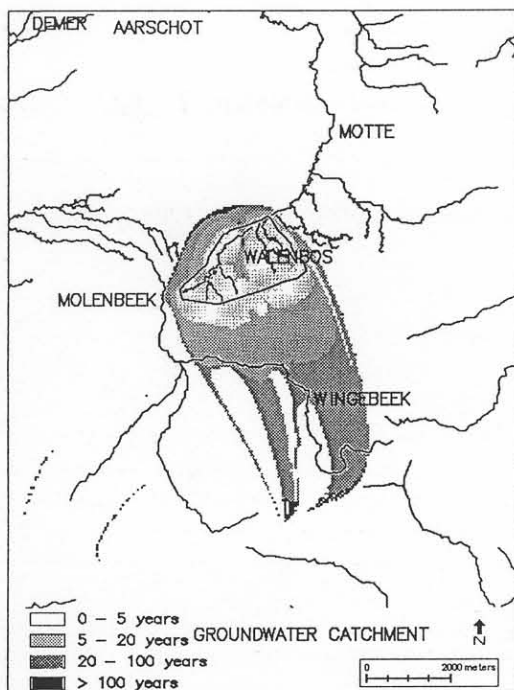


Figure 5: Contributing area of Walenbos and flow times

### 3 VEGETATION AND PIEZOMETRY

In the last century large parts of Walenbos were used as meadows. Today the nature reserve consists of a 350 ha of forest and only 20 ha of meadows and open areas. Due to the wet soil, intensive agriculture and wood production with fast growing trees such as Canadian popular, Japanese larch, etc. could only succeed by maintaining a labour intensive drainage system. In the last few decades the area is left to spontaneous development.

For the last 4 years eco-hydrological monitoring takes place. Groundwater levels are registered in more than 110 piezometers. Measured upward groundwater pressure differences in a double piezometer are used to map groundwater discharge patterns (Figure 6d). Measured small seasonal groundwater level differences indicate an upward groundwater flux big enough to compensate summer evapotranspiration (Figure 6c). Out of the 70 different mapped plant species and 15 mosses several are indicators of groundwater discharge (phreatophytes) (De Becker (5)). The oldest forest parts with species such as beach and oak are situated along the south side on the colluvial at the foot of the valley wall. Just north of this zone appear oligotrophic and mesotrophic alder carr with a species rich shrub, herb and moss layer, dominated by extensive peatmoss (*Sphagnum div. spp.*) carpets and many phreatophytes. In this zone high groundwater discharge in the remains of the drainage system is found. This drainage system is often blocked by colony forming iron-oxidizing bacteria (*Gallionella ferruginea*) which are binding the iron from the groundwater. Further northwards in the valley eutrophic alder forests are found due to stagnant and ion-rich water. On the dryer spots appears alder-bird cherry forest.

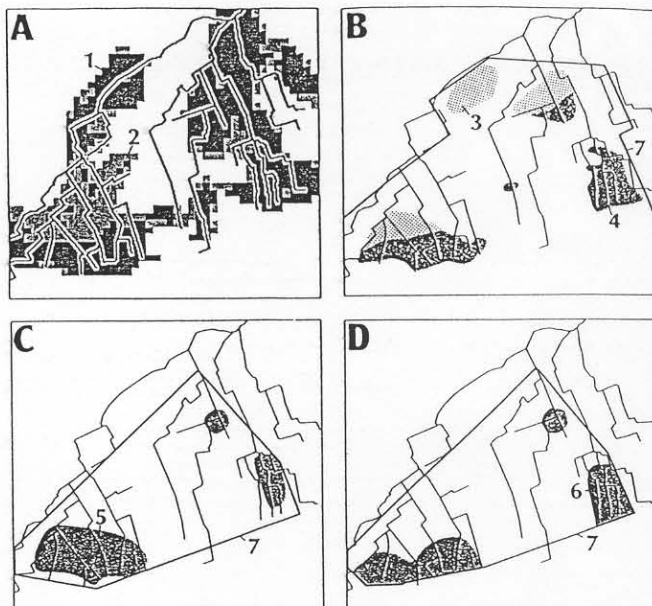


Figure 6a: Simulated groundwater discharge in Walenbos (1: high discharge, 2: low discharge)

Figure 6b: Mapped discharge dependent vegetation (3: basic type, 4: acid type)

Figure 6c: Part of Walenbos with waterlevel changes smaller than 40 cm (5)

Figure 6d: Areas with groundwater pressure differences indicative of groundwater discharge (6), boundary of area of field measurements (7)

Figure 6b presents some results of the vegetation mappings. From comparison of the groundwater model results (Figure 6a) with vegetation mappings and groundwater level measurements (Figure 6b, c, d) it can be concluded that the vegetation and piezometric patterns give a good identification of the groundwater discharge system.

#### 4 HYDROCHEMICAL ANALYSES

During January/February (1/93) and May/July 1993 (5/93) two series of water samples for chemical analyses were taken, distributed over the nature reserve. The results of the analyses of the two series are similar so that only the last series (5/93) will be discussed. In this series 125 samples were taken in the piezometric network of the nature reserve. Twenty-one percent of the samples having an absolute electrical neutrality greater than 5 % were excluded. 99 samples were retained. Table 1 lists the 15 parameters for which each sample was analyzed.

Table 1: Analyzed parameters of samples of 5/93

Kations	Anions
NH <sub>4</sub> <sup>+</sup>	HCO <sub>3</sub> <sup>-</sup>
Na <sup>+</sup>	H <sub>2</sub> PO <sub>4</sub> <sup>-</sup>
K <sup>+</sup>	NO <sub>3</sub> <sup>-</sup>
Ca <sup>2+</sup>	SO <sub>4</sub> <sup>2-</sup>
Mg <sup>2+</sup>	Cl <sup>-</sup>
Fe <sup>2+</sup>	
pH (field)	
pH (lab)	
EC-electrical conductivity (field)	
EC-electrical conductivity (lab)	

Several single parameter iso-concentration figures revealed a first picture of the spatial distribution of different water types. Due to the number of samples it was decided to perform a cluster analysis. The cluster analysis used 13 parameters, excluding pH (lab) and EC (lab) and was based on a hierarchical fusion technique in combination with Ward's minimum variance linking method. On the basis of the dendrogram, four clusters could be identified (De Becker (5)). Table 2 gives the minimum, maximum, average and standard deviation of the different parameters in the clusters. Figure 7 gives the spatial distribution of the clusters over Walenbos.

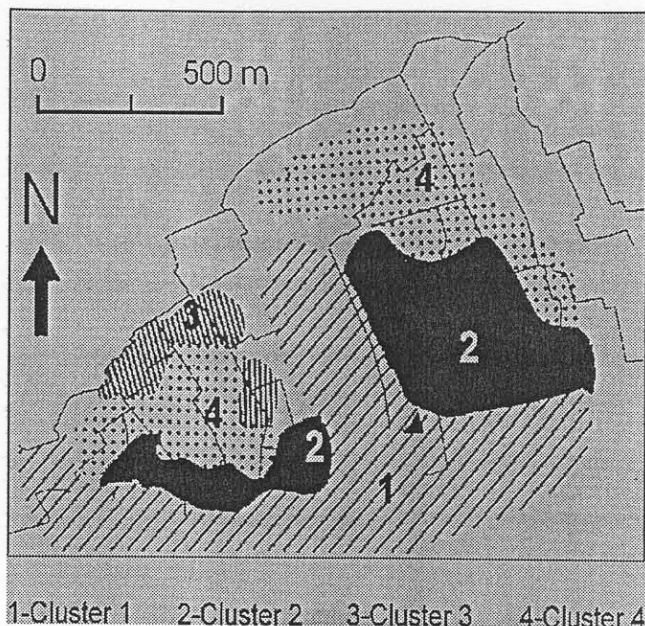


Figure 7: Spatial distribution of clusters of 5/93

From a principal component analysis of the chemical parameters it can be concluded that electrical conductivity, Ca<sup>2+</sup>, Mg<sup>2+</sup>, SO<sub>4</sub><sup>2-</sup> and HCO<sub>3</sub><sup>-</sup> are highly correlated and are the most influential parameters in the data set. These parameters explain almost 60 % of the total variance in the series. Table 2, Piper, Maucha and Stiff diagrams explain the chemical characteristics in relation to the spatial distribution of the clusters (Figure 7). Out of all clusters, cluster 1 shows the lowest pH, HCO<sub>3</sub><sup>-</sup> and Ca<sup>2+</sup> and the highest values for Na<sup>2+</sup>, Cl<sup>-</sup>, Fe<sup>2+</sup>, NO<sub>3</sub><sup>-</sup>, K<sup>+</sup>, NH<sub>4</sub><sup>+</sup> and H<sub>2</sub>PO<sub>4</sub><sup>-</sup>. This cluster is clearly outstanding in chemical characteristics. It could be described as metatrophic water and precipitation quality. Possibly, effects of human activity such as sewage water discharge and nitrification are noticeable in some of the relatively high concentrations of the ions. High Fe<sup>2+</sup> concentration can be explained by the glauconite mineral which is abundant in the top aquifer. Samples of this cluster are located at the foot of the hills south of Walenbos, in the active southern discharge zones and on the ridge between the two sub-basins in Walenbos. Cluster 2 has a quality in-between cluster 1 and 4. It is located in a narrow band, north of cluster 1 in the active discharge zone. In winter its size is minimum due to the enlargement of cluster 1 to the north. Cluster 3 is chemically similar to cluster 2, also in-between the quality of cluster 1 and 4. An outstanding feature of this cluster is its high SO<sub>4</sub><sup>2-</sup> concentration. Due to the small number of samples belonging to this cluster interpretation is difficult. The cluster appears only in a belt at the northern rim of the western sub-basin of Walenbos (Figure 7). Cluster 4 is in quality opposite to cluster 1. It has a high concentration of Ca<sup>2+</sup> and HCO<sub>3</sub><sup>-</sup> and is the most alkaline cluster. It can be described as a lithotrophic type of water. It is located in the lowest parts of the sub-basins.

Table 2: Statistics of clusters of samples of 5/93

cluster1 16 sampl.	condf μS/cm	pH f	HCO <sub>3</sub> <sup>-</sup> [ppm]	H <sub>2</sub> PO <sub>4</sub> [ppm]	NO <sub>3</sub> [ppm]	NH <sub>4</sub> <sup>+</sup> [ppm]	SO <sub>4</sub> <sup>2-</sup> [ppm]	Cl [ppm]	Na <sup>+</sup> [ppm]	K <sup>+</sup> [ppm]	Ca <sup>2+</sup> [ppm]	Mg <sup>2+</sup> [ppm]	Fe <sup>2+</sup> [ppm]
min.	118	4.7	1.5	0.016	0.022	0.006	13	22	9.2	0.3	6	1.5	0.12
max.	1154	6.4	71.0	1.347	37.621	6.955	359	77	33.0	6.3	145	18.0	39.00
aver.	386	5.5	20.9	0.176	5.401	0.537	77	47	16.9	3.2	32	6.0	9.09
std.dev.	60	0.1	4.9	0.087	2.913	0.429	20	4	1.7	0.4	8	1.1	3.18
cluster2 35 sampl.													
min.	218	5.7	39.0	0.016	0.022	0.006	7	16	8.4	0.8	19	1.8	0.07
max.	549	6.6	135.0	0.940	3.320	0.927	96	63	20.0	4.0	66	9.4	29.60
ave.	334	6.2	79.9	0.083	0.190	0.100	31	33	11.6	2.4	34	4.7	8.75
std.dev.	15	0.0	3.7	0.028	0.094	0.028	4	2	0.6	0.1	2	0.3	1.27
cluster3 9 sampl.													
min.	494	6.2	140.0	0.031	0.022	0.006	93	16	8.4	1.2	74	8.3	0.15
max.	1202	7.0	355.0	0.188	1.018	0.374	319	37	15.0	3.4	200	19.0	23.10
ave.	805	6.7	225.0	0.059	0.413	0.140	182	28	11.4	2.1	121	13.7	8.46
std.dev.	72	0.1	20.8	0.018	0.142	0.045	26	2	0.7	0.2	12	1.2	2.37
cluster4 39 sampl.													
min.	255	6.3	93.0	0.016	0.022	0.006	4	9	4.8	0.7	27	3.1	0.01
max.	1325	7.5	625.0	0.626	2.611	1.932	185	31	17.0	5.7	230	18.0	14.40
ave.	452	6.9	222.6	0.114	0.380	0.173	28	15	8.2	2.3	67	7.7	3.38
std.dev.	31	0.1	16.5	0.022	0.092	0.058	5	1	0.3	0.2	6	0.6	0.55

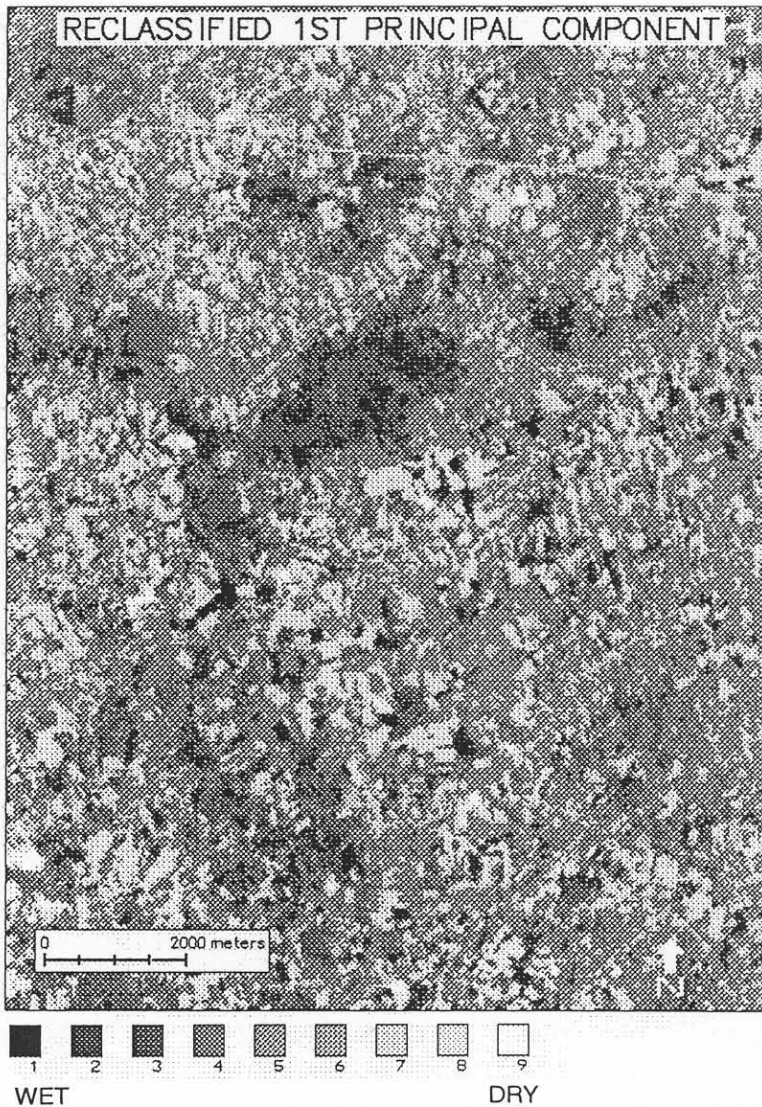


Figure 8: Reclassified first principal component of TM 1, 2, 3, 4, 5 and 7 for the entire study area

## 5 REMOTE SENSING

In order to investigate the possibility of using remote sensing for identification of groundwater discharge patterns, an analysis of a Landsat Thematic Mapper (TM) image of 20th September 1986 was performed. From different methods applied, such as Normalized Difference Vegetation Index (NDVI), single band ratios, Principal Components Analysis (PCA) and tasseled cap, PCA appeared to be an efficient data reduction method and will therefore be discussed here. PCA uses six TM bands, excluding the thermal band. The first component explains almost 70 % of the variance, while the first and second components together explain more than 94 % of the variance. TM 1, 2, 3, 5 and 7 give a high positive contribution to the first component. TM 4 is lower and negatively correlated to the first component. Analyses of the histogram of the first component reveals that it consists of three normal distributions. Bobba et. al. (6) suggested in an analysis of Landsat Multi Spectral Scanner band 5 and 7 and their ratio, that the three normal distributions in the histogram could indicate discharge, transition and recharge areas. Therefore, the first component was reclassified in nine different groups (Figure 8) making use of the eccentricity of the distributions.

A field investigation indicated that the nine groups could be related to areas ranging from open water, marshes, densely vegetated areas, meadows, urban areas to dry elevated exposed soils. From Figure 8 Walenbos appears as a very wet area. Also several other groundwater discharge areas can be identified.

## 6 INTEGRATION OF RESULTS AND CONCLUSIONS

Integrating the different aspects of groundwater discharge characteristics offers new insights into the relationships between groundwater and the environment.

The remote sensing analyses results in a regional picture of the groundwater discharge situation. Comparing the wettest areas of the reclassified principal component 1 with the groundwater discharge areas results in a coincidence of only 16.1 %, because many non-groundwater discharge areas are classified as wet areas in the remote sensing analyses. Therefore, remote sensing can at present only be used as a regional indicator of groundwater discharge areas.

The vegetation mappings together with the chemical analyses clearly give a more precise and detailed description of the quantity and quality of the discharge system. The vegetation in the area of cluster 1 (Figure 7), at the foot of the hill south of Walenbos, is dominated by oligotrophic alder forest. Chemically, this area indicates groundwater discharge of acid water with low alkalinity, high iron content and small contemporary pollutions. This quality, the high discharge, as simulated by the model, and

the sensitivity of this cluster with respect to the seasonal differences of recharge, indicate that this area is dominated by discharge from the unconfined aquifer with relative short flow times. The most important formation of this aquifer, the Diest Formation, contains abundant glauconite which causes the high iron content of the discharge water.

In the lowest part of the valley, cluster 4 defines a less acid, more alkaline type with high  $\text{HCO}_3^-$ ,  $\text{Ca}^{2+}$  and low  $\text{Fe}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{Na}^+$  and  $\text{SO}_4^{2-}$  concentrations. Clearly, this water is of lithotrophic origin. The fine sandstone Formation of Brussels, in which this semi-confined aquifer is situated, is known to have some calciumcarbonate in its matrix. Hence, the groundwater flow system belonging to the area of this cluster is determined by long flow lines, discharging in the lowest parts of the valley and lithologically determined qualities. The quality of the water and the fact that the discharged groundwater is stagnant in this zone causes the vegetation to be meso- or eutrotrophic, i.e. mainly alder forests.

This study shows that when the results of the different approaches are combined, a more detailed and complete understanding of the groundwater system is obtained and how this interferes with the landscape and its ecological features.

## 7 ACKNOWLEDGMENT

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## 8 REFERENCES

1. FREEZE, R.A. and CHERRY, J.A., Groundwater, Prentice-Hall Inc., 1979.
2. BATELAAN, O., DE SMEDT, F., OTERO VALLE, M.N. and HUYBRECHTS, W., "Development and application of a groundwater model integrated in the GIS GRASS", Application of geographic information systems in hydrology and water resources management, KOVAR, K. and NACHTNEBEL, H.P., IAHS publ. 211, 1993.
3. BRONDERS, J., "Contribution to the geohydrology of Mid-Belgium by means of geostatistical analysis and a numerical model" (in Dutch), 1989, Ph.D. thesis, Free University Brussels, Belgium.
4. HACKBUSCH, W., Multi-grid methods and applications, Springer-Verlag, Berlin, 1985
5. DE BECKER, P., Chemical characteristics of the groundwater in the state nature reserve 'Het Walenbos' (in Dutch), 1993, M.Sc. thesis, Free University Brussels, Belgium.
6. BOBBA, A.G., BUKATA, R.P. and JEROME, J.H., "Digitally processed satellite data as a tool in detecting potential groundwater flow systems", 1992, *J. Hydrol.* 131, 25-62.