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Monitoring and the FLONET/TRANS model as tools to characterize the nitrate distribution and transport in the Noor catchment (the Netherlands)

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Abstract. Intensive human activities, such as agricultural practices, groundwater abstraction or land use changes, have had a negative impact on the state of the natural environment in The Netherlands. The increased inputs of fertilisers and animal manure after 1950 have boosted crop production to a high level, but have also contributed to increased nitrogen emissions from agriculture to groundwater, surface waters and atmosphere. Since 1991, a comprehensive hydrological and hydrogeological research project has been started in the Noor (chalk) catchment situated on the Dutch-Belgian boundary due to situation has become critical in this region. The investigation covers analysis of the hydrogeological system of the Noor catchment, including the relationship between recharge, groundwater heads, springflow, streamflow and chemical composition of water. The monitoring shows that groundwater under the plateau is heavily polluted (often NO_3^- concentrations > 100 $mg.l^{-1}$). Springs also have high NO_3^- contents (mean: 64 $mg.l^{-1}$) because they are fed by this groundwater. Groundwater under the wet valley is less polluted (mean: 27 $mg.l^{-1}$) due to denitrification and being old, unpolluted water. Water in the Noor brook and its tributaries is coming from the polluted springs and from seepage areas in the wet valley that drain the less polluted groundwater there. The nitrate concentrations of the Noor brook and its tributaries (mean: 42-46 $mg.l^{-1}$) reflects the characteristics of diluted spring water. The modelling with FLONET/TRANS confirms that the NO_3^- contents in the Noor catchment in the late 1990's can be explained with the historical NO_3^- input and the groundwater flow pattern. Scenario studies indicate that a reduction of 75 % of the NO_3^- input is required to start a decline NO_3^- concentrations in the water system.

Key words: Nitrate, Water Quality, Monitoring, Modelling, FLONET/TRANS, the Netherlands

Introduction

The study area is situated in the southeastern part of the Netherlands (Limburg province) and the Northeast of Belgium, in the centre of the triangle Maastricht - Aachen - Liege (Fig. 1). Because of the hydrogeological properties of the Noor chalk catchment area, the surface water in the Noor brook is predominantly controlled by the groundwater system (Van Lanen & Dijksma, 1999). The land use, mainly agriculture, causes several problems (especially deterioration of the water quality by nitrates). The physical properties of nitrates and hydrogeological characteristics of the study area dictate the groundwater pollution according to the spatial patterns of the groundwater flow. Because the surface water flow is predominantly fed by groundwater flow, the increased NO_3^- concentrations in the groundwater system affect also the surface water quality subsequently. Generally, the contamination affects the natural conditions (environment, nature reserve) as well as human health (deterioration of drinking water of some remote farms with own water supply) and well being.

The Sub-department of Water Resources of the Wageningen University started a research study in 1991, also called the „Zuid-Limburg project". The investigations cover analysis of the hydrogeological system of the Noor catchment, including the relationship between recharge, groundwater heads, springflow and streamflow and chemical composition of water. In the context of this project, the database with monitoring data has been used to investigate water flow and nitrate transport through the

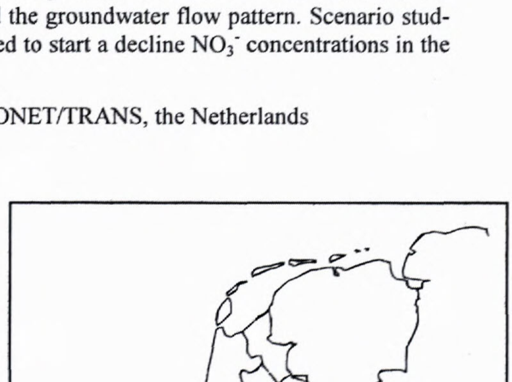

Fig. 1 Situation Map

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groundwater system towards the groundwater-fed Noor stream. Subsequently, these data and hydrogeological information were used to develop a model using FLONET/TRANS. With the model the groundwater flow pattern, the current NO_3^- distribution and possible NO_3^- developments in the coming decades were explored.

The main objectives of the paper are twofold:

- characterisation of the nitrate distribution in the Noor catchment using basic statistical procedure;
- analysis of the current situation and prediction of future nitrate patterns with application of three nitrate load reduction scenarios of 25, 50 and 75 % using the FLONET/TRANS simulation modelling package.

Natural conditions of the study area

The Noor brook catchment covers an area of 1056 ha. According to the Koppen's classification, the study area is classified as moderately rainy and humid throughout all seasons. The average rainfall equals about 750 $mm.yr^{-1}$, whereas the average potential evapotranspiration is 575 $mm.yr^{-1}$. The region is situated on the Chalk (Margraten) Plateau. Most of the valleys are dry and only the downstream parts of the deeply incised valleys carry water (van Lanen et al., 1995). Over the last ten years the discharge varied at the outlet between 0,25 and 0,90 $mm.d^{-1}$.

The investigation area together with the surrounding plateaus belongs to the marginal part of the Ardennes and strongly coincides to this geological setting (Nota - van de Weerd, 1978; Demoulin, 1995). The oldest geological unit consists of consolidated Palaeozoic rocks, which form the impermeable base of the investigated hydrogeological domain. It is overlain by Upper Cretaceous and Quaternary sediments, which constitute a multi-aquifer system. Except in the north, topographic and groundwater divides of the Noor catchment are assumed to coincide.

The Upper Carboniferous unit is generally characterised by consolidated sandstones and shales. Due to both, extensive erosion and hiatuses, the Permian, Triassic, Jurassic and Lower Cretaceous sediments are missing (van Lanen et al., 1995). Upper Cretaceous sediments discordantly overlie the Palaeozoic rocks. The Aachen and Vaals Formations represent the lower part. The Aachen Formation mostly consists of sandy sediments. The Vaals Formation is represented by clayey and silty sediments interbedded with sandstone layers. The upper part of the Cretaceous sedimentation cycle is characterised by deposition of carbonates and is divided into two units: the Gulpen and Maastricht Formations. In the Tertiary the sedimentation changed from carbonates, via marine clays and sands into fluviatile deposits due to a regression of the sea. The deposition of sands and gravel by the Maas River took place in the Early Pleistocene. In the Late Pleistocene, a loess (eolic sediment) layer covered the area. During the Middle and Late Tertiary and Pleistocene strong weathering and erosion removed all sediments in this area up to the Gulpen Formation. This chalk deposit is covered by unconsolidated regolith (Eindhoven Formation). During the Pleistocene and Holocene the drainage pattern developed and the deposition of the valley fillings (Singraven Formation) occurred on the top of the Cretaceous sediments (van Lanen et al., 1995). In a cross-section through the catchment perpendicular to the Noor brook, the following typical physio-geographic units can be distinguished: plateau, foothill, transition area and wet valley. The first two units do not have surface water.

The hydrogeological parameters of the main studied geological units are shown in Tab. 1. Overall permeability of the Vaals formation is rather low (10^{-3} $m.d^{-1}$). Nevertheless, water transmissivity of the Vaals formation become higher due to the presence of several 0,1-0,2 m thick fractured sandstone layers with permeability of 20-50 $m.d^{-1}$. Due to the low effective porosity of the Gulpen Formation, reaching up to 5-10% only, the primary (intergranular) permeability of the chalk is low (0,5 $m.d^{-1}$). Overall permeability can be increased in the areas with well-developed karstic phenomena and can reach 10 $m.d^{-1}$. Regolith is a mixture of clay, flints and Maas deposits derived from denudation and erosion of Cretaceous, Tertiary and Quaternary sediments. The vertical permeability of regolith (Eindhoven Formation) reaches from 0,5 to 5 $m.d^{-1}$. The Singraven Formation comprises of valley fillings consisting of the fine-grained sediments interbedded with gravel and peat layers. Its permeability differs strongly from place to place and varies between 10^{-3} to 10^{-1} $m.d^{-1}$ (van Lanen et al., 1995; Schunselaar – van der Hoeven, 1993; Nota – van de Weerd, 1978).

Methods of data processing and modeling

Since 1991 the Sub-department of Water Resources of the Wageningen Agricultural University has started a research in the Noor catchment by establishing a monitoring network. Data has been collated on recharge, groundwater heads, springflow, streamflow and chemical composition of water. The hydrogeological and hydrochemical database consists of data from 63 piezometers (located in 5 cross-sections), 4 springs, 3 dug wells and 12 surface water monitoring locations (Noor brook and its tributaries). The chemical analyses have taken place in the *conventional laboratory* of the Sub-department of Soil Science and Geology of the Wageningen University. Since 1994 a special device, a set of integrated, *selective ions (Hydrion-10, HYDRION B.V., Wageningen)* has also been used to analyse chemical components. The water sampling is carried out regularly during the year. The frequency of the sampling varies for different locations. It depends on the temporal variability and the demand for detailed hydrochemical research and interpretation.

The calculation of the basic statistical moments (mean, median, standard deviation, minimum, maximum) has been used to describe the current distribution of nitrate in the Noor catchment. The data was also clustered according to several criteria, and statistical moments are described separately for the springs, piezometers, wells, Noor brook and its tributaries. The statistical analysis was developed separately for the samples analysed in the con-

Tab. 1 Hydrogeological parameters of the investigated formations

Formation	Total thickness	Overall permeability
Singraven Formation	1 to 5 m	10^{-3} to 10^{-1} m.d^{-1}
Eindhoven Formation	regolith - 1 to 5 m	regolith – 0,5 to 5 m.d^{-1}, loess - 10 and 10^{-2} m.d^{-1}
Gulpen Formation	30-35 m	0,5 and 10 m.d^{-1}
Vaals Formation	40 and 50 m	low - 10^{-3} m.d^{-1} sandstone layers 20 and 50 m.d^{-1}.
Upper Carboniferous; Namurien	>50 m	very low - < 10^{-6} m.d^{-1} consolidated sandstones and shales

ventional laboratory and samples analysed with the Hydrion-10. For selected monitored locations a trend analysis was performed using regression techniques.

The FLONET/TRANS model has been used as a tool to simulate groundwater flow and nitrate transport. FLONET/TRANS has been designed to approximate natural, three dimensional (3D) groundwater systems in either the two-dimensional (2D) horizontal plane or vertical cross-section. It suits especially all hydrogeological domains with significant vertical variation in physical properties or with significant vertical flow gradients. This software package is a combination of two numerical finite element models: a steady state saturated groundwater flow model and a transient advective-dispersive contaminant transport model. The model solves flow equations using the dual formulation (Frind & Matanga, 1985), which formulates the flow equations in terms of hydraulic potential and stream function:

$$\frac{\delta}{\delta x}\left(K_{xx}\frac{\delta\phi}{\delta_x}\right)+\frac{\delta}{\delta y}\left(K_{yy}\frac{\delta\phi}{\delta y}\right)=0$$

$$\frac{\delta}{\delta x}\left(\frac{1}{K_{yy}}\frac{\delta\psi}{\delta x}\right)+\frac{\delta}{\delta y}\left(\frac{1}{K_{xx}}\frac{\delta\psi}{\delta y}\right)=0$$

where:

- x horizontal co-ordinate [m]
- y vertical co-ordinate [m]
- K_{xx} hydraulic conductivity in the x direction [m.s^{-1}]
- K_{yy} hydraulic conductivity in the y direction [m.s^{-1}]
- ϕ hydraulic head [m]
- ψ stream function [m^2.s^{-1}].

In advective-dispersive contaminant transport FLONET /TRANS solves the 2D equation with linear retardation and first-order decay:

$$\frac{\delta}{\delta x_1}\left[\frac{D_{ij}}{R}\frac{\delta c}{\delta x_j}\right]-\frac{\delta}{\delta x_i}\left(\frac{v_i}{R}c\right)-\lambda c=\frac{\delta c}{\delta t}$$

where:

- x, y spatial co-ordinates [m]
- v_i average linear flow velocity [m.s^{-1}]
- D_{ij} hydrodynamic dispersion coefficient [m^2.s^{-1}]
- R retardation [-]
- λ linear decay rate [s^{-1}]
- t time [s]
- c concentration [mg.dm^{-3}].

Groundwater flow velocities are derived from the stream function solution of the flow equation (Guiger et al., 1996):

$$v_x=\frac{q}{\theta};\qquad v_y=\frac{q_y}{\theta}$$

where:

- θ effective porosity [-]
- q groundwater flux [m.s^{-1}]

The program assumes several conditions: a) steady 2D groundwater flow; b) fully saturated conditions; c) constant density pore water; d) contaminant in the dissolved phase; e) contaminant dilution with a temperature equal to that of the pore water. The program supports the following boundary conditions (Tab. 2).

The model was applied for different values of the recharge (dry, normal and wet period) and results of this sensitivity analysis are given.

Results and discussion

Statistical analysis

The general characteristics of all samples analysed both in the conventional laboratory and with Hydrion-10 are given in Tab. 3, Graph 1 and 2. The nitrate concentration in the Noor catchment is characterised by a very high variation from 0,5 to 147,6 mg.l^{-1} of NO_3^-. The observed mean value 41,1 (42,0 Hydrion-10) mg.l^{-1} is very closed to the drinking water standard of 50 mg.l^{-1} NO_3^- in the European Union.

The measured NO_3^- concentrations in the conventional laboratory and with the Hydrion-10 reasonably agree. The median value measured with the Hydrion-10 is little bit higher than the one derived from the conventional laboratory analysis (45,3 versus 42,1 mg.l^{-1}). With the Hydrion-10 more low concentrations (23% < 7 mg.l^{-1}) are measured than with the conventional laboratory methods (17% < 7 mg.l^{-1}). According to the Hydrion-10, 56% of the samples is below the drinking water standard, whereas the conventional method results in 68%. Both methods have 4% of the samples above 98 mg.l^{-1}.

The nitrate concentrations of the *Noor brook* show a different pattern (Tab. 4). The mean nitrate content is 45,7 mg.l^{-1} (52,6 mg.l^{-1} Hydrion-10) which is a little bit more than the catchment mean concentration. The variation is very high with a minimum value of 26,3 mg.l^{-1} and a maximum concentration of 60,6 mg.l^{-1}. The statistical

Tab. 2 Flow and transport boundary conditions available in FLONET/TRANS (Guiger et al., 1996)

Boundary type	Groundwater flow	Contaminant transport
First Dirichlet	$\phi = \varphi_0$ Fixed head boundary (e.g. river or lake, or at a distant exit boundary)	$c = c_0$ Fixed concentration boundary (e.g. a large, well-mixed source)
Second Neumann	$q_n = q_0 = K\frac{\delta\phi}{\delta n}$ Specified flux boundary (e.g. recharge across water table, inflow or outflow boundary or no-flow boundary q = 0)	$\frac{\delta c}{\delta n} = 0$ Zero-concentration gradient (e.g. no outflow or impermeable boundary)
Third Cauchy	not available	$\frac{q_0 c_0}{\theta} = vc - D\frac{\delta c}{\delta x_i}$ Dispersive flux boundary (e.g. source with known influx q_0 and concentration c_0)

Tab. 3 Basic statistical parameters of nitrate concentration (mg.l^{-1}) in the Noor valley

Measure technique	Mean	Median	Standard Deviation	Minimum	Maximum	Number of samples
Conv. laboratory	41,1	42,1	27,0	0,5	147,6	479
Hydrion-10	42,0	45,3	30,2	1	140,8	917

Tab. 4 Statistical moments of the nitrate concentrations (mg.l^{-1}) in selected groups of water samples

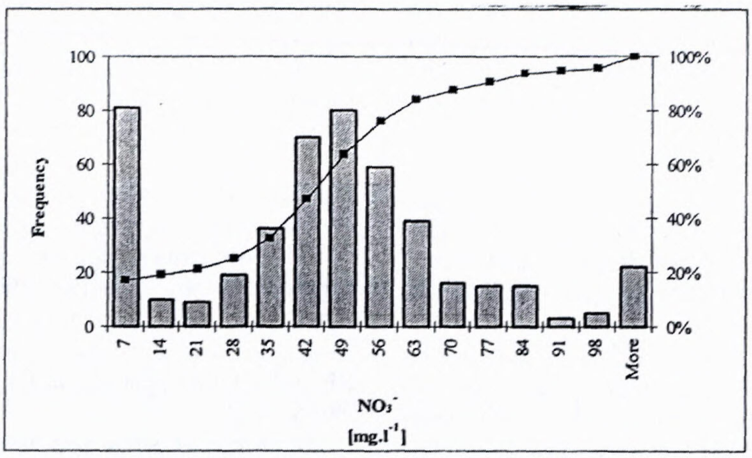
	Mean	Median	Standard Deviation	Minimum	Maximum	Number of samples
Conventional laboratory						
all groundwater	41,2	36,9	37,6	0,5	152,5	252
all surface water	43,9	43,5	8,4	24,5	70,7	227
Noor brook	45,7	45,5	7,7	26,3	60,6	102
Piezometers	26,5	12,6	33,5	0,5	138,3	173
Springs	64,0	65,7	10,3	45,2	82,5	51
Tributaries	42,4	40,9	8,7	24,5	70,7	125
Wells	90,4	95,2	30,9	0,5	152,5	28
Hydrion-10						
All groundwater	38,5	34,8	36,1	1	140,8	604
All surface water	48,7	48,5	9,8	23,3	80,4	313
Noor brook	52,6	52,9	8,6	23,3	80,4	137
Piezometers	27,0	11,7	31,2	1	140,6	461
Springs	66,2	68,6	10,9	38,4	89,7	93
Tributaries	45,6	43,8	9,7	26,0	76,6	176
Wells	92,9	96,6	30,8	1	140,8	50

moments of the *Noor tributaries* are very similar to those of the main stream with mean values of 42,4 mg.l^{-1} (45,6 mg.l^{-1} Hydrion-10). The variation is slightly higher from 24,5 mg.l^{-1} to 70,7 mg.l^{-1} (Tab. 4).

The sampled *springs* occur on the foothill, where the chemical composition of the groundwater is determined by mixing of groundwater following shallow and deep flowpaths. This results in quite high variation of nitrate concentrations, from 45,2 to 82,5 mg.l^{-1} (38,4 to 89,8 mg.l^{-1} measured by Hydrion-10) - Tab. 4. Moreover, it is very characteristic for the objects situated on the foothill and on the plateau, that the population of low concentrations is missing due to the intensive agricultural activities in this part of the valley, from which the groundwater flows to the spring outlets and because of denitrification.

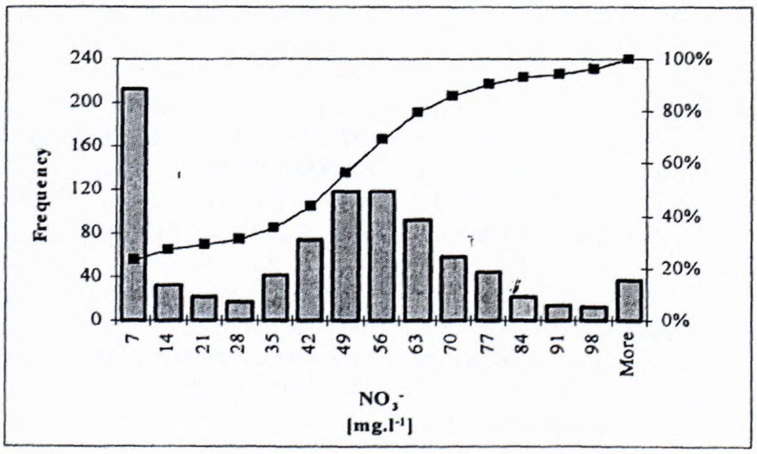
The nitrate concentrations of groundwater sampled from the *piezometers* that mainly occur in the wet valley are the lowest from the selected groups. The mean nitrate contents reach values of 26,5 mg.l^{-1} (27,0 mg.l^{-1} Hydrion-10). The long groundwater travel time from the plateau

NO_3^- class	Frequency	Cumulative %	NO_3^- class	Frequency	Cumulative %
0-7	81	17%	49-56	49	79%
7-14	10	19%	56-63	28	85%
14-21	9	21%	63-70	23	89%
21-28	19	25%	70-77	13	92%
28-35	45	34%	77-84	11	94%
35-42	75	50%	84-91	2	95%
42-49	89	68%	91-98	5	96%
			>98	20	100%



Graph 1 Statistical characteristics of the nitrates (mg.l^{-1}) for all samples in the Noor catchment (analysed in the conventional laboratory)

NO_3^- class	Frequency	Cumulative %	NO_3^- class	Frequency	Cumulative %
0-7	213	23%	49-56	118	69%
7-14	33	27%	56-63	92	79%
14-21	21	29%	63-70	59	86%
21-28	17	31%	70-77	45	91%
28-35	41	35%	77-84	22	93%
35-42	74	44%	84-91	14	95%
42-49	118	56%	91-98	13	96%
			>98	37	100%



Graph 2 Statistical characteristics of the nitrates for all samples in the Noor catchment (analysed with Hydrion-10)

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towards the riparian area is a possible reason for the lower NO_3^- concentrations. It means that the water has been infiltrated before the NO_3^- input became high (before 1950's). Moreover denitrification processes are assumed to take place in the aquifer. The very low nitrate load in the middle of the valley (nature reserve area is not being used for agricultural purposes) probably contributes also this fact (van Lanen et al., 1995).

The number of the analysed samples from the monitored *dug wells* is too small to give a reliable description and interpretation of the current situation on nitrate pollution (Tab. 4). However, the mean concentration of nitrates is very high , i.e. 90,4 mg.l^{-1} (92,2 mg.l^{-1} Hydrion-10) of NO_3^-. This confirms the fact the nitrate pollution in the Noor catchment is caused by human activities, because the wells are very close to the dwellings or agricultural fields situated on the plateau and foothill, which are characterised by high loads of nutrients.

In the northern part of the valley generally higher mean concentrations of nitrates were observed than in the southern one (Kordík, 1998) probably due to higher loads of nutrients in the northern valley (e.g. different land use, agriculture practices).

The evolution of nitrate concentration in time is controlled by the long-term variation in groundwater recharge. Another important factor is the nitrate input, which is controlled by the intensity of agricultural activities and type of farming. Linear trend analysis shows generally an increasing trend in nitrate concentration for most of the monitored locations (Kordík, 1998).

Figure 2 presents the trend analyses for the *Sint Brigida spring* (Br1), the *dug well* (OW5) with extremely high nitrate contents since 1996, the *Noor brook* (profile NE) and the *piezometers* (B3a and WP96). In many piezometers the nitrate content has increased rapidly during the last decade up to values of 100 mg.l^{-1}. The *deep piezometer* (WP 96), which is situated on the northern plateau, is characterised by a negative trend. This trend might be caused by implementation of the nitrate policy into the practice. However, in most monitoring locations the nitrate concentrations exceed the drinking water standard of 50 mg.l^{-1} in the European Union.

Simulation modelling

Simulation of nitrate transport

Nitrate as a stable form of dissolved nitrogen, is very mobile in groundwater (e.g. Freeze and Cherry, 1979). Generally, the nitrate migration in groundwater systems depends mostly on groundwater flow, its direction and velocity (under aerobic conditions). Groundwater flow direction and velocity depend on the geological framework and recharge conditions. Therefore a model was proposed for different recharge conditions based on hydrological characteristics such as precipitation, reference evapotranspiration, soil moisture characteristics and crop factors (for different types of land use structure and vegetation). Groundwater recharge has been calculated by the soil water balance model NUT_NEE for the period 1960-1995. According to the simulated annual groundwater recharge values, three types of steady-state groundwater system conditions have been defined (Kessels, 1997): dry, average and wet. They reflect the different recharge conditions from practically zero in the wet valley to 0,001123 m.d^{-1} on grassland during wet conditions. In this study the hydrodynamic model developed by Kessels (1997) was used. He used the FLONET/TRANS software package to develop the model. The basic hydrogeological properties (hydraulic conductivity in the x, y-direction; effective porosity) have been derived from field research and some were further calibrated by the MODFLOW model (van Lanen et al., 1995).

In principle, the results of the groundwater flow simulation are the following. The groundwater flow velocities are highest in the chalk sediments (Gulpen Formation) and regolith formation, mainly in the transition area (Fig. 3). Generally, the groundwater flow velocities are increasing towards the valley. Low velocities are observed towards the water divides. In the less permeable clayey silts of the Vaals Formation a decrease of groundwater velocities occurs. The groundwater flow path starts at the plateau or in the transition area and terminates usually in the valley centre (van Lanen et al., 1995; Kessels, 1997).

The transport parameters have been defined according to published physical properties of nitrate (Domenico - Schwartz, 1997; Freeze - Cherry, 1979): namely contaminant and source decay rate λ, $\beta = 0$ d^{-1} because of stability and low retardation of nitrates; diffusion coefficient D = 0,00001 $m^2.d^{-1}$; longitudinal dispersivity α_L = 10 m and transverse dispersivity α_T = 0,1 m. Zero-flux boundaries of the flow model (impermeable base and hydrologic water divides) have been interpreted in the transport model as zero-concentration gradient ones. The upper boundary coinciding with the groundwater table has been approached as a dispersive flux one. So, this is the only boundary, where nitrates are entering the multi-aquifer system. The average value of the NO_3^- input at the groundwater table is higher in the northern part of the catchment (115,7 mg.l^{-1}) than in the southern one (83,4 mg.l^{-1}). The nitrate-input concentrations are lowest within the valley centre (55,0 mg.l^{-1}). The initial input nitrate concentration for all recharge situations was assumed to be 20 mg.l^{-1} NO_3^-. The recharge values depend on the different earlier-defined three hydrological situations (model under the average conditions has developed Klonowski, 1997).

The nitrate migration has been simulated for the last about 50 years (Kordík, 1998). The simulated nitrate distribution for the three recharge conditions is given in Fig. 4 for the early 1950's (600 days) and the late 1990's (18000 days). Nitrates, after migration through the unsaturated zone (long travel time – up to 10 years), are reaching the groundwater table and start moving according the groundwater flow pattern. In the early stage (600 days), the higher concentration (about 25 mg.l^{-1}) occurs at the foothill and in the transition area (especially in the regolith formation, in which the groundwater velocities

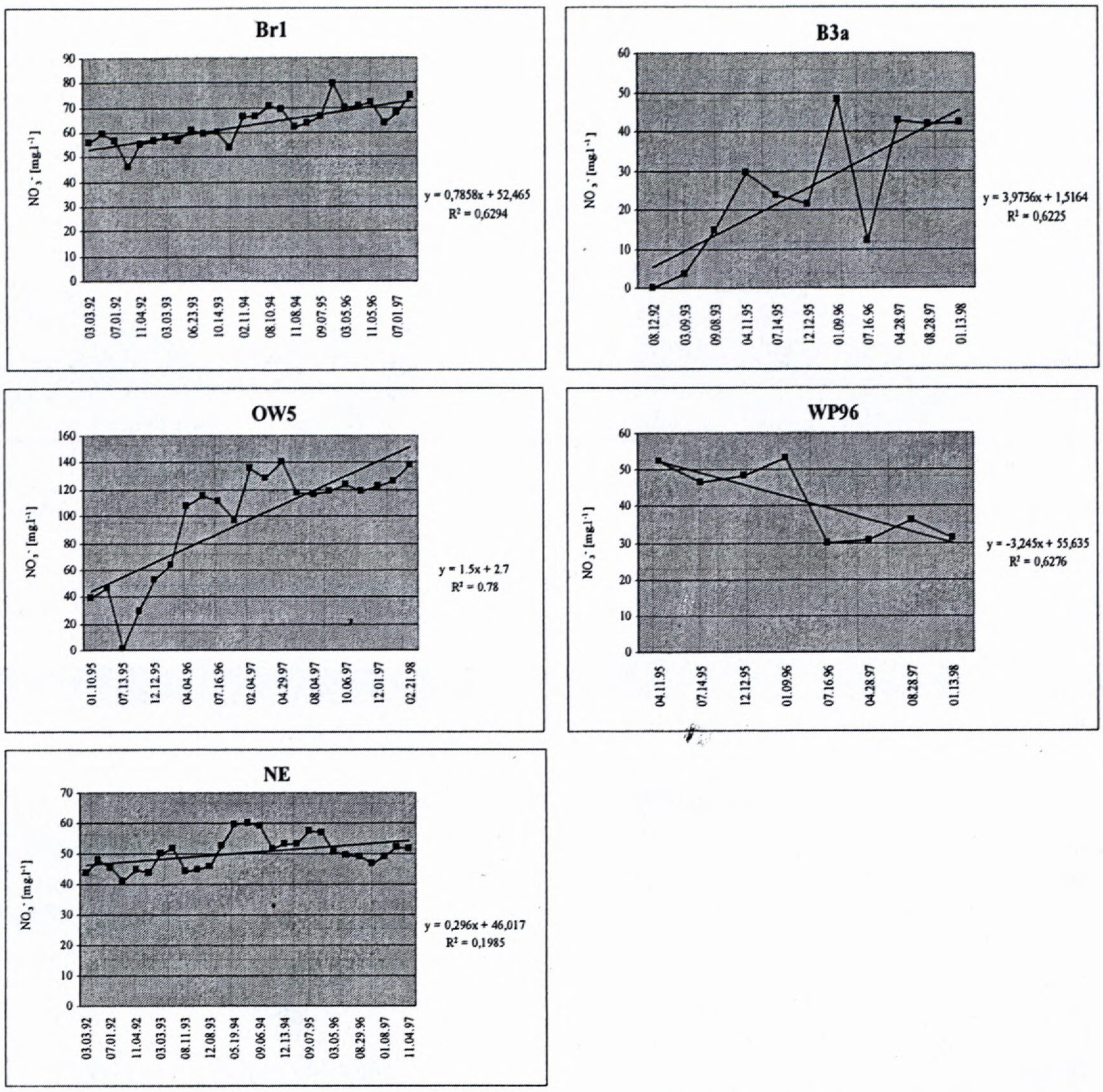

Fig. 2 Trend analysis of nitrates for some selected monitoring locations (Br1-spring Sint Brigida; OW5-dug well; NE-Noor brook; B3a-piezometer; WP96-deep piezometer)

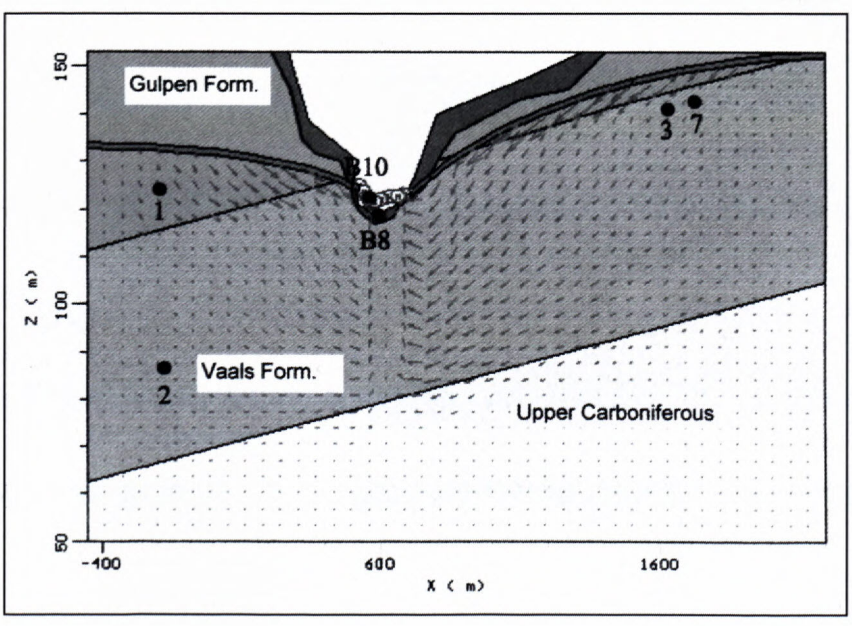

Fig. 3 Simulated groundwater velocities using FLONET/TRANS (Kessels, 1997)

are the highest and the fastest contamination of groundwater by nitrates is expected). On the plateau, the migration of the nitrate plume is going more slowly. After 600 days, the nitrates do still not affect the deeper parts of the aquifer.

Almost the same migration patterns prevail in the following years (e.g. late 1990's), although the polluted zone expands. The nitrate concentration in the transition area would have reached the drinking water standard of 50 $mg.l^{-1}$ after about 25 years under wet conditions, after 33

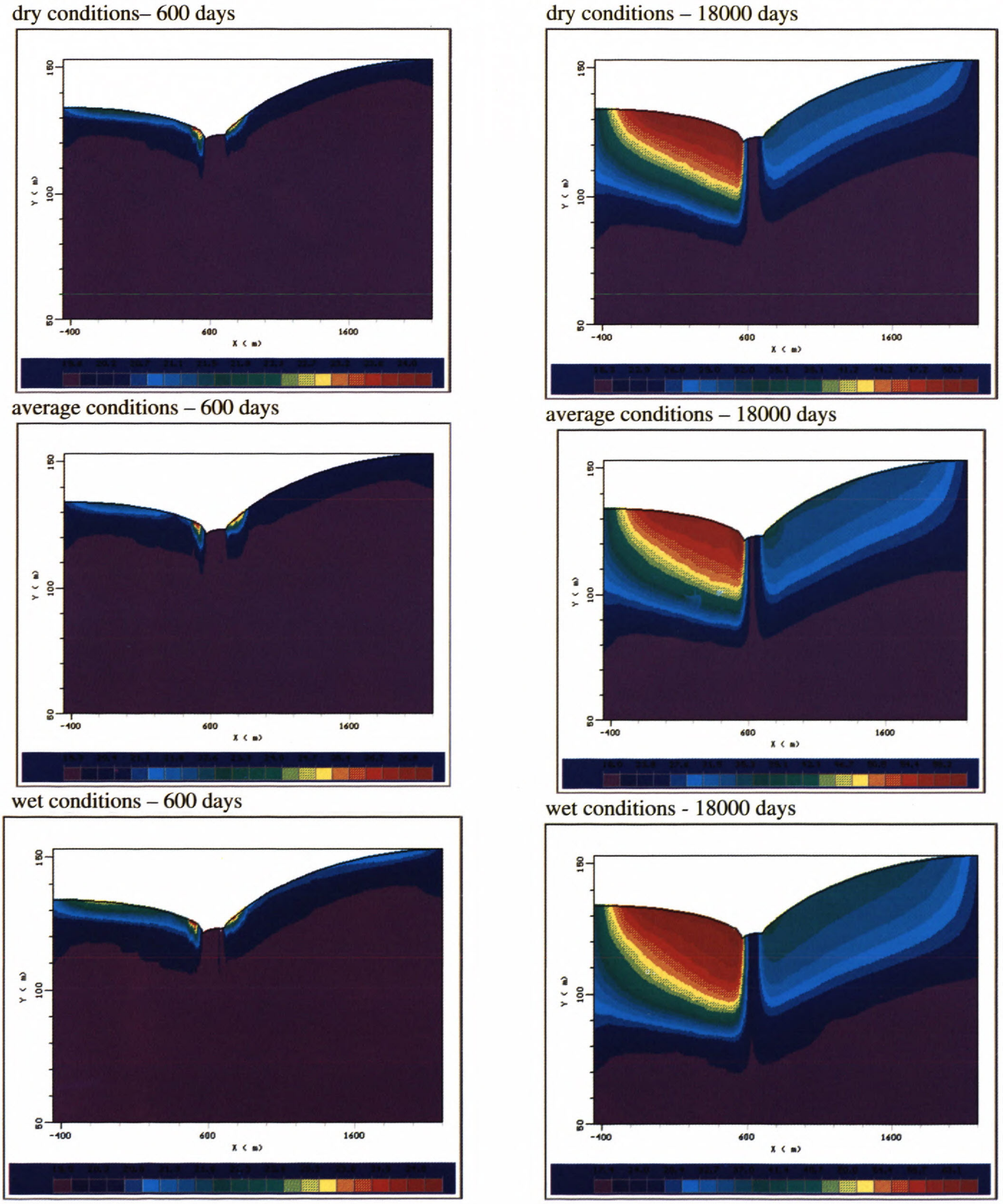

Fig. 4 Distribution of nitrates simulated by FLONET/TRANS after 600 and 18000 days for three different recharge conditions

years under average conditions and after 50 years under dry conditions. It means that in the Noor catchment the nitrate contamination is two times faster under wet conditions than under dry circumstances. After about half a century, almost the whole multi-aquifer system is affected by nitrate pollution, which corresponds with current observations in the Noor catchment. The contamination appears even at the end of the longest flowpaths in the valley filling sediments. The nitrate migration, according to the spatial groundwater flow patterns, shows a zone of stagnant groundwater at the bottom of the aquifer (Fig. 4). It does not take an active role in groundwater flow and is characterised by low nitrate concentrations.

The breakthrough curves of selected points (piezometers B8, B10 and hypothetical points 1, 2, 7; Fig. 3) confirm the migration patterns (Fig. 5). The points 1 and 7 are located under the northern and southern plateau about 10 m below the simulated groundwater table. The point 2 is situated deeper in the Vaals Formation, where lower concentrations of NO_3^- were expected. The quickest response to the contamination is shown in *piezometer B8.* It is situated in the transition area, in which groundwater follows short and shallow flow paths. Relatively high values of nitrates are already observed in the first year of simulation. The concentrations reach very high values at the end of the simulation period (late 1990's), i.e. about 50-65 $mg.l^{-1}$ depending on the hydrological conditions. Initially, *location 1* shows a relatively slow response to the contamination. After about 3 years of simulation the values start increasing and running almost parallel to the curve of B8. It reaches also high concentrations of nitrates at the end of the simulation (about 47-60 $mg.l^{-1}$). The response on *location 7* is similar to location 1, but the final value is the lowest (about 30 $mg.l^{-1}$). A very slow response to the contamination was simulated in the piezometer B10 and location 2. The *piezometer B10* is situated within the valley centre, at the end of the longest groundwater flowpath. Not earlier than about 20–25 years, the concentration is suddenly increasing and reaches a final concentration of 30–40 $mg.l^{-1}$ for B10 and 22-40 $mg.l^{-1}$ for *location 2.* The breakthrough curve of location 2 confirms the fact, that the nitrate pollution can reach even deeper zone of the hydrogeological structure.

Exploration of future nitrate pollution

Based on the previous simulation, a model to explore future nitrate concentration and distribution has been defined. The model describes three different scenarios of nitrate input reduction, i.e. reduction by 25%, 50% and 75 %. No significant differences in precipitation and evapotranspiration are assumed to occur in the near future. Therefore the groundwater recharge has not been adapted. The simulations were carried out for dry, average and wet recharge conditions. The calibrated transport parameters, the hydrogeological properties and the flow boundary conditions of the multi-aquifer system have remained unchanged as well. The initial nitrate concentrations have been derived from the previous model by means of six polygons with a characteristic average concentration of NO_3^- inside the polygons following the groundwater table, the water divides and some nitrate iso-concentration lines, i.e. 20, 30, 40 and 50 $mg.l^{-1}$. The lowest initial concentration of 20 $mg.l^{-1}$ of NO_3 remains the same and is assigned to the Upper Carboniferous impermeable base or stagnant zone of the aquifer, respectively. All simulations have been carried out for a time period of 36000 days (about 98,5 years; Kordík, 1998).

The results of the ***25% nitrate reduction scenario*** show high, steadily growing nitrate concentrations. The nitrate concentrations for the different locations (Fig. 3) are shown in the Fig. 5. Already after a very short time the concentration in *piezometer B8* reaches a very high value of more than 50 $mg.l^{-1}$ for all simulated conditions, which is a response to the already existing nitrate contamination under the plateau. Afterwards, the nitrate concentration is slightly increasing with concentrations of 57-70 $mg.l^{-1}$ at the end of the simulation (late 2090's). The curve of the *location 1* is almost parallel with the curve of piezometer B8 and the final concentrations reach values of 60-70 $mg.l^{-1}$ depending on the recharge conditions. The curve of *piezometer B10* starts with the lowest concentrations of 35–47 $mg.l^{-1}$. After reaching a local maximum and a local minimum, the concentration is increasing steadily to final values of 52-60 $mg.l^{-1}$. The curve of *location 3* has a stable or slightly decreasing character with the final concentration of 31 $mg.l^{-1}$. Generally, a reduction of NO_3 by 25% is not sufficient to reduce future NO_3 concentration in the Noor catchment. The nitrate input after 25% reduction (i.e. 62,5 $mg.l^{-1}$) is still higher in most places than the concentration by the end of the 1990's. The decreasing concentration at location 3 is not clear. Incorrect simulation of the nitrate concentrations might occur because of not precise and limited assignment of polygons to define the initial concentration or because the Peclet and Courant accuracy criteria has not been met.

50 % reduction scenario (Fig. 6): under the northern plateau the concentration does not undergo significant changes in time and under the southern part of the valley the concentrations slightly decline. The curves of the *locations 1, B10 and B8* show no significant changes in concentrations after passing either a local maximum or minimum and they are characterised by values of 43-51 $mg.l^{-1}$ at the end of the simulation depending on the recharge conditions. The simulation shows that even a reduction of the nitrate load by 50 % will not significantly reduce the nitrate concentration in the groundwater system of the Noor catchment for all simulated recharge conditions. A completely different situation occurs at *location 3,* where the concentration of nitrates significantly declines in time with a final concentration of about 25 $mg.l^{-1}$. The earlier-mentioned problems of modelling with the FLONET/TRANS software package are the reason for this.

The ***reduction scenario of 75 %*** (Fig. 6) shows a gradual decrease of the nitrate concentration in time for all recharge conditions and for all locations. The final concentrations of nitrates at the end of simulation (late 2090's) are very similar in the *locations 1, B8 and B10*

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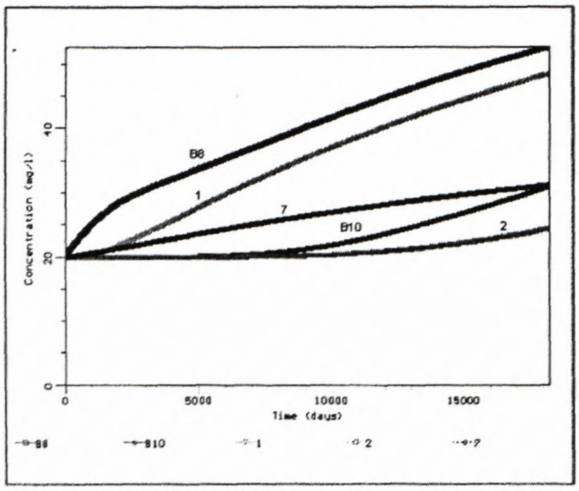
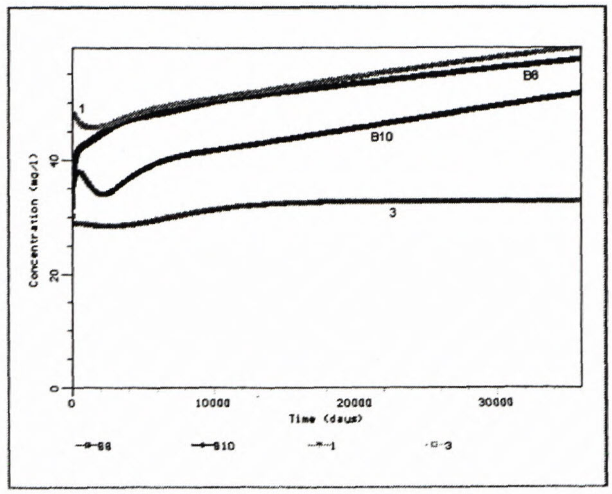
Last 50 years

dry conditions

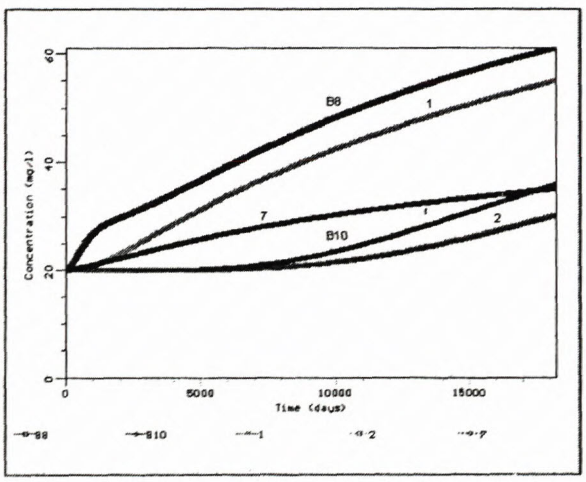


25% reduction scenario

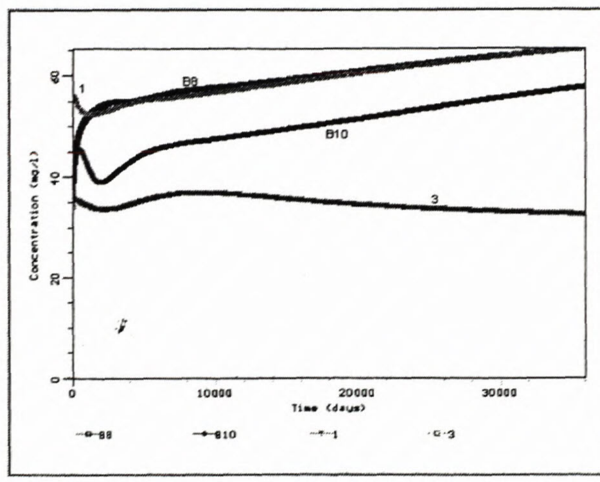
dry conditions



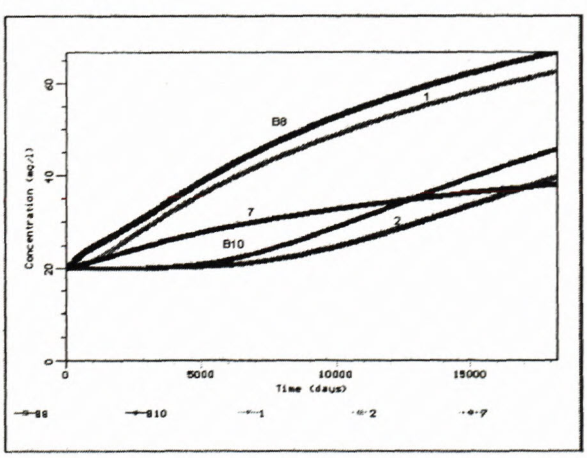
average conditions



average conditions



wet conditions



wet conditions

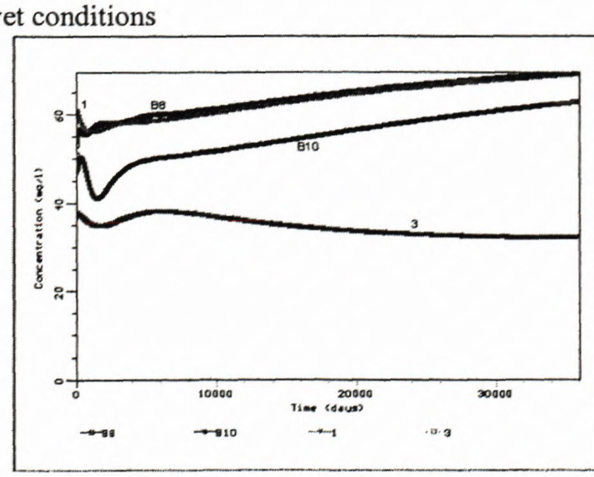
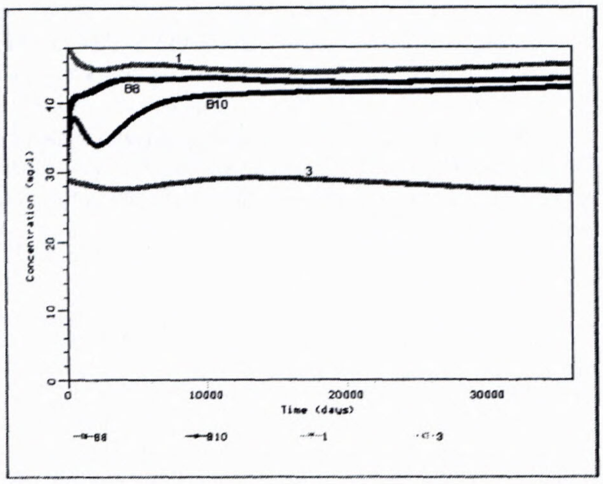


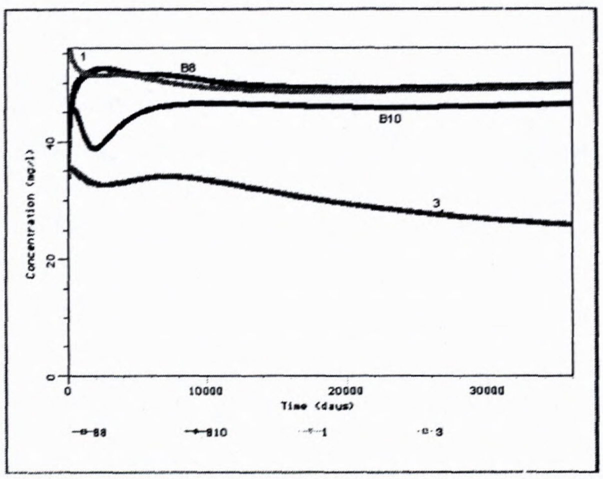
Fig. 5 Simulated breakthrough curves of NO_3^- for some points (simulated for the last 50 years and for a reduction scenario of 25 %)

50% reduction scenario

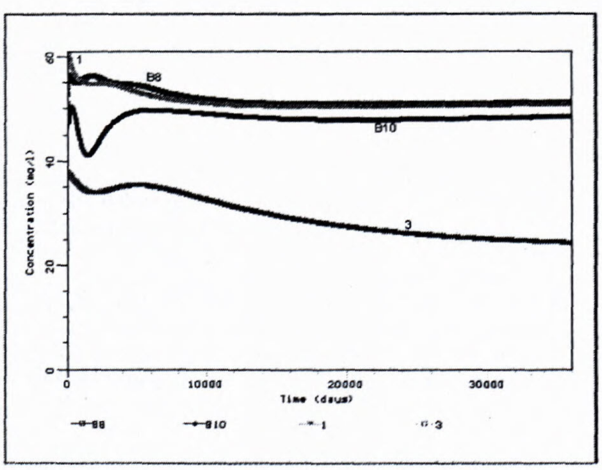
dry conditions



average conditions

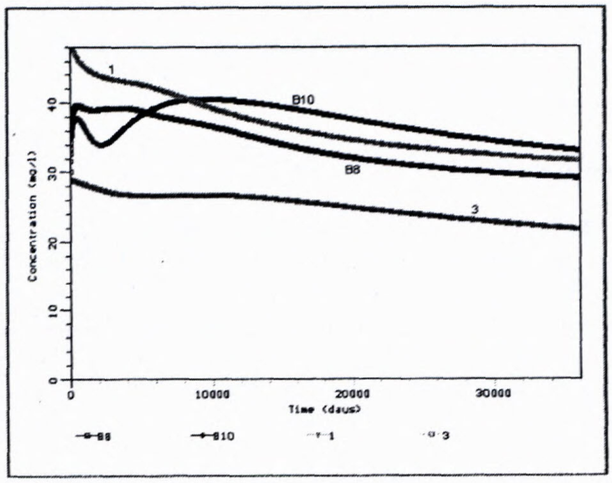


wet conditions

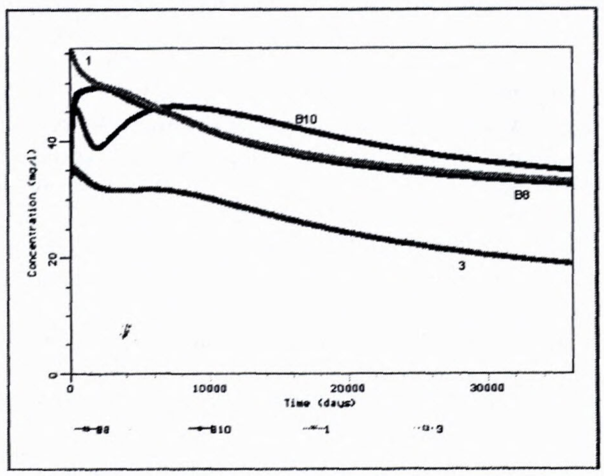


75% reduction scenario

dry conditions



average conditions



wet conditions

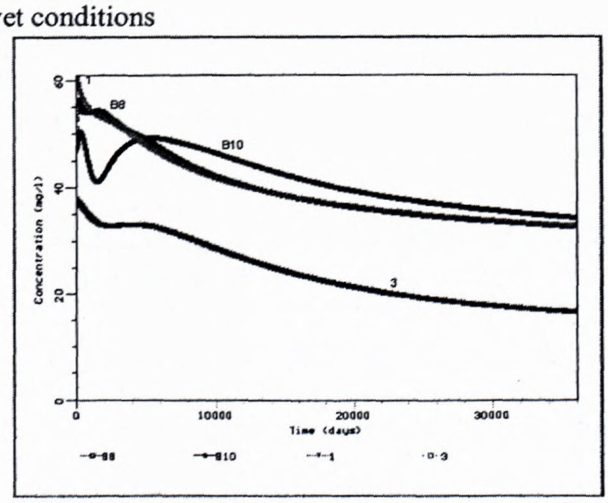


Fig. 6 Simulated breakthrough curves of NO_3 for some points (reduction scenarios of 50 and 75 %)

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(about 29-38 mg.l^{-1}). The final concentrations at location 1 are lower (19-24 mg.l^{-1}). The breakthrough curves show, that a reduction of the nitrate input by 75% is required to decrease the NO_3^- concentration below the drinking water standard (50 mg.l^{-1}) and to improve the overall environmental situation in the Noor catchment.

Conclusions

The investigated region belongs to the most fertile part of the Netherlands and about 97 % of the Noor catchment is used for agricultural purposes. The deterioration of the environment (especially decreasing of water quality) by nitrates is a very urgent problem. The nitrate concentration in the Noor valley is characterised by a very high variation from 0,5 to 147,6 mg.l^{-1}. The mean values of about 42 mg.l^{-1} are very close to the drinking water standard of 50 mg.l^{-1}. The *dug wells* under the plateau have the highest NO_3 concentration (often > 100 mg.l^{-1}). The *piezometers* that mostly occur in the centre of the valley have substantially lower concentrations (mean 26,5 mg.l^{-1}) due to old, unpolluted groundwater, denitrification, and low NO_3^- input in the wet valley. The *springs* (64,0 mg.l^{-1}), which are predominantly fed by polluted groundwater from the plateaus have clearly higher values than the *Noor brook and its tributaries* (42,4-45,7 mg.l^{-1}). Inflow from groundwater low in nitrate (denitrification, old groundwater) dilute spring water, so that water in the Noor and its tributaries is lower in nitrate than the springs. The trend analysis shows generally an increasing trend in the nitrate concentration for almost all monitored locations.

The *FLONET/TRANS* model has been used as a tool for the simulation of groundwater flow and nitrate transport. The model was applied to different recharge conditions (dry, normal and wet period) to analyse the current situation and to explore the future nitrate distribution in the valley for three nitrate load reduction scenarios of 25, 50 and 75 %.

Nitrates, after migration through the unsaturated zone, reach the groundwater table and start moving according to the groundwater flow pattern. In the early stage of simulation (early 1950's) high concentration of about 25 mg.l^{-1} occurs in the regolith formation, in which the groundwater velocities are highest. Under the plateau, the migration of the nitrate plume is going more slowly. The concentration in the transition area would reach 50 mg.l^{-1} (drinking water standard) after 25 years under wet conditions, after 33 years under average conditions and after 50 years under dry recharge conditions. It means that the groundwater system exceeds the pollution limit two times faster under wet conditions than under dry circumstances. At the end of simulation (late 1990's) almost the whole multiaquifer system is affected by nitrate pollution.

The results of the ***25 % nitrate reduction scenario*** show high, steadily growing nitrate concentrations due to still higher nitrate inputs than the concentration in the late 1990's. The results of the ***50 % reduction scenario*** indicate that under the northern plateau the concentration would not undergo significant changes in time and under the southern part of the valley the nitrate content would slightly decline. The breakthrough curves show that a ***reduction of the nitrate input by 75 %*** is needed to decrease the NO_3^- concentration below the drinking water standard (50 mg.l^{-1}) and to improve the overall situation of the environment in the Noor catchment.

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References

Demoulin (Ed.), 1995. Physical Geography of the Ardennes. Department of Geography and Quaternary, University of Liege (Belgium) (in French).

Domenico, P.A. & Schwartz, F.W., 1997: Physical and Chemical Hydrogeology. 2nd Edition, New York, Chicester, Brisbane, Toronto, Singapore: John Wiley & Sons, Inc.

Freeze, R.A. & Cherry, J.A., 1979: Hydrogeology. Engelewood Cliffs, New Jersey: Prentice-Hall.

Frind, E.O. & Matanga, G.B., 1985: The dual formulation of flow for contaminant transport modelling. Review of theory and accuracy aspects. Water Resources Res., 21-2, 159-169.

Guiger, N. – Molson, J. – Franz, T. & Frind, E., 1996: FLONET/TRANS User Guide Version 2.2. Ontario: Waterloo Hydrogeologic Software, Waterloo Centre for Groundwater Research.

Kessels, J.C.H.M., 1997: Groundwater heads in some cross-sections in the Noor catchment. Modelling with the FLONET/TRANS software package. MSc. thesis, Department of Water Resources, Wageningen University (in Dutch).

Klonowski, M., 1997: Waterflow and migration of nitrate in the chalk catchment of the Noor brook and impact on the Noorbeemden Nature Reserve. Internship Report of European Course in Environmental Management. Wageningen University.

Kordík, J., 1998: Waterflow and nitrate transport in the Belgian-Dutch chalk region. Exploration of consequences to the environment for the Noor brook catchment. Internship Report of European Course in Environmental Management. Wageningen University. 81 p.

Lanen, H.A.J. van – Weerd, B. van de – Dijksma, R., van Dam, H.J. & Bier, G., 1995: Hydrogeology of the Noor catchment and the impact of groundwater abstraction from the western boundary of the Margraten Plateau. Department of Water Resources, Wageningen University.

Lanen, H.A.J. van & Dijksma, R.,1999: Water flow and nitrate transport to a groundwater-fed stream in the Belgian-Dutch chalk region. Wageningen: Hydrological Processes 13: 295-307.

Nota, D.J.G. & Weerd, B. van de, 1978: A hydrogeological study in the basin of the Gulp creek - 1. Groundwater characteristics. Department of Water Resources, Wageningen University.

Schunselaar, S.S. & Hoeven, K.M.L.J. van der, 1993: Valley fillings a source for hydrogeology. The 3D distribution of the valley fillings and the hydraulic properties in the upstream part of the Noorbeemden Nature Reserve and its impact on groundwater flow. Department of Water Resources, Wageningen University (in Dutch).