General Project Data

Project title:	PRESYS-GQ: Demonstration of a Groundwater Quality Prediction System for Impact Assessment of Landuse Development on Sustainable Drinking Water Production LIFE96ENV/NL/230
Project location:	Pumping Station Roosteren
Region/country:	Limburg Province, The Netherlands

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Duration: 1-6-1997 - 1-6-2001 (48 months)

Total costs: 425,053.04 Ecu
Contribution by LIFE: 212,526.51 Ecu

Organisational Structure

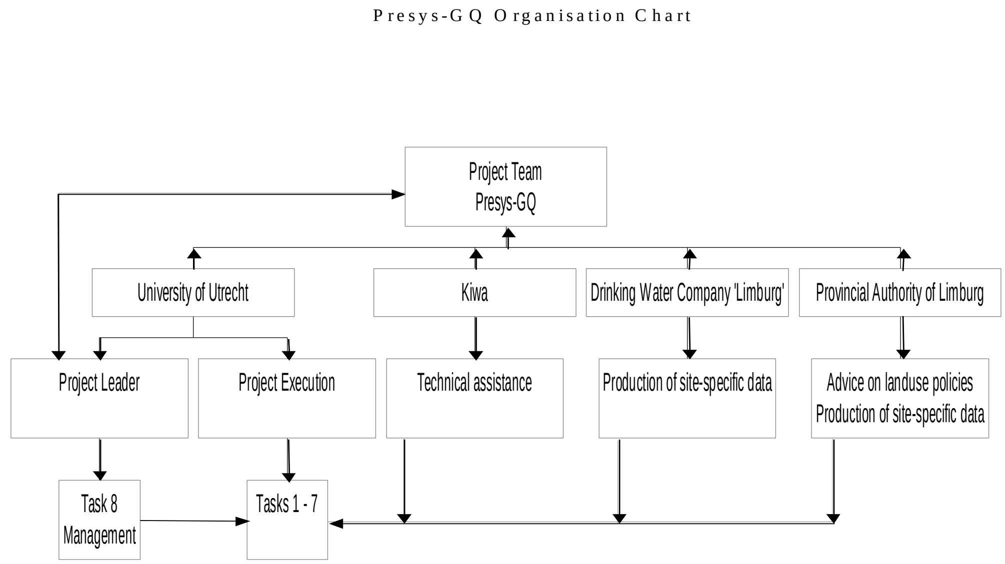

Figure 1: Organisation chart PRESYS-GQ Project.

Participants of the project:	**Tasks:**
- University of Utrecht	all main tasks;
- Kiwa	technical assistance, development of software modules;
- Drinking Water Company Limburg	production of site-specific data;
- Provincial Authority Limburg	advice on landuse policies, production of site-specific data.

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1. Introduction

1.1. Background

This report forms part of the PRESYS-GQ project, which is focussed on the development of a groundwater quality prediction system. The project is being carried out by Utrecht University. Other project participants are Drinking Water Company Limburg (WML), Provincial Authorities of Limburg Province and Kiwa Onderzoek en Advies.

In the European Union groundwater quality is deteriorating thus threatening the drinking water supply of tens of millions of people. One of the reasons groundwater contamination is still continuing, is the fact that local authorities (provincial and municipal) acting as land use planners, lack insight in the relation between different types of land use and their effects on groundwater quality. Therefore, local authorities generally disregard the need for sustainable (non-polluting) forms of land use in areas where groundwater contamination may lead to severe problems in drinking water wells.
On the other hand, drinking water companies generally lack insight in the future quality development of their primary source, i.e. groundwater. When a groundwater contamination is detected in water samples from monitoring or production wells, often rather ad-hoc decisions are made to invest either in purification facilities or in reallocation of wells, both of which are very costly. However, the long-term efficiency of these investments is unclear due to inadequate insight in future groundwater quality development.
In the light of the above there is an obvious need for a groundwater quality prediction system which can be used by the above mentioned actors relevant for the drinking water supply and which can facilitate an integrated decision making. This system should be accessible for experts as well as non-experts.
The prediction system will consist of an existing groundwater modelling package, which will be integrated with several new package modules. These new package modules will enable simulation of chemical processes in groundwater and soil, relevant to the production of drinking water. In this way, effects of different landuse policies on groundwater quality can be demonstrated. Simulation results will be presented by means of state-of-the-art computer visualisation techniques.
To demonstrate the feasibility of the prediction system a case study will be worked out for an area from the Province of Limburg, the Netherlands. Nonetheless, the prediction system will be designed for general purpose and will be applicable throughout the Community.

1.2. Objectives and project phases

General objective of the PRESYS-GQ Project is the development of a groundwater quality prediction system which can be used by actors relevant for the drinking water supply and which can facilitate an integrated decision making. This system should be accessible for experts as well as non-experts.
The project consists of three phases. The relation between phases and tasks is described in the following paragraph.

A. Standard Model Construction
   - tasks 1, 2, 3
   - task 6 partly
B. Advanced model Construction
   - tasks 4, 5
   - task 6 partly
C. Dissemination
   - task 7
   - task 6 partly

In phase A the following tasks are distinguished:

1. Construction of a groundwater flow model (MODFLOW)
2. Construction of a conservative transport model for chloride (MT3D-Cl)
3. Standard non-conservative transport model (MT3D-decay)

This report pertains to the results of the aforementioned task 1.: Construction of a groundwater flow model.

1.3. Description of task 1

Aim:
Construction of a groundwater flow model of the selected case-area.
Method:
Groundwater modelling software code MODFLOW.
Activities:
0.Selection of a representative case-area.
1.Collection of site-specific data as input for MODFLOW.
2.Simulation of groundwater levels.
3.Calibration of model by comparing simulated water levels with observed water levels in monitoring wells.
4.Calculation of streamlines and delineation of the groundwater recharge area.
5.Technical report T1.

1.4. Report structure

Chapter 1 of this report contains general information about the PRESYS-GQ project.
In Chapter 2 hydro-geological characteristics of the area of interest are discussed and the way these characteristics are schematised into the groundwater model. Chapter 3 describes results of sensitivity analyses and calibration. Maps can be found in Part 2 of this document.

2. Description of the Study Area

2.1. Site selection

Selection of an appropriate site for a case study has been carried out in close collaboration with all participants of the PRESYS-GQ project. Criteria have been formulated in order to enable an explicit trade off among advantages and disadvantages related to the selection of a case-study. The considered criteria are stated in the following paragraph:

Criteria applied to the selection of location of the case study:

1. *Sufficient data availability*

A prerequisite for a satisfying simulation of geo-hydrochemical characteristics of the study area consists of sufficient availability of observed groundwater levels, chemical composition of sub-soil and groundwater.

2. *Existence of a chemically reactive sub-soil.*

Simulation of chemical interaction between groundwater and subsoil components forms a part of the activities that will be carried out within the PRESYS-GQ project. Such a kind of simulation can only be carried out meaningfully when chemical components of the sub soil indeed can be expected to influence chemical groundwater composition significantly. With respect to the subsoil, occurrence of significant quantities of organic matter and/or reactive clay sediments forms thus a precondition for successful simulation of changes in groundwater composition caused by sub-soil characteristics (Griffioen et al., 1997).

3. *Representative geological conditions*

General modeling results of the case study should be maximally applicable to other groundwater extraction sites of drinking water companies in Europe. Prevailing geological conditions of these extraction sites consist of the occurrence of sand and clay sediments. Occurrence of calcareous geological formations is with respect to this aspect less desirable.

4. *Availability of information on landuse*

Groundwater quality is often strongly related to landuse. Availability of studies and other forms of information related to this aspect are therefore an important advantage in the analysis of groundwater quality development. Travel times of groundwater from infiltration in the sub-soil system to arrival at a well screen often comprises typically several decades, which implies that information on landuse should be known over an equal period of time.

5. *Existence of a (potential) groundwater quality problem*

Obviously, potential groundwater quality problems should exist at the considered drinking water supply well.

6. *Relevance of the case-study to WML Drinking Water Company*

It is considered desirable that results of the case study which is to be carried out will be directly useful to Drinking Water Company Limburg (WML). Thus, results of the study will not only be applicable in a general, methodological and instrumental sense to groundwater quality issues in drinking water supply, but can also directly contribute to a better understanding of (potential) groundwater quality problems at a specific site.

A number of possible sites for the case study have been evaluated with respect to the aforementioned criteria. Finally, a production well named ‘Roosteren’ has been selected for a site-specific study on groundwater quality. Although this specific well does not fully satisfy all mentioned criteria, in relation to other possible sites it complies best with the objectives of this project.

Figure 2: Location of the study area

2.2. Production well 'Roosteren'

The production well 'Roosteren' is situated in 'Limburg Province', in the south of the Netherlands. (see figure 2). Pumping station 'Roosteren' is operational since 1985, when production started at a rate of 6 MM3/a (Kragt & Juhász, 1992). The production site consists of a number of different production wells, all situated at a few hundreds of meters east from the river Meuse. The wells are located within the winter bed of the River Meuse, at three sides enclosed by the shores of the meandering River Meuse. The wells are located at relatively elevated parts of the area. It is estimated that possible inundation of the well locations may occur once in 50 years, due to high river levels. Drinking Water Company Limburg intends to increase extraction in the near future to an annual volume of 9 MM3, which implies that this site will become one of the largest production wells managed by WML. A number of other groundwater wells exists in the area, as is illustrated in Map 1: Production Wells in the Model Area.

2.3. Delineation of the model area and boundary conditions

Since regional groundwater flow is westbound oriented, the delineation of the model area comprises a small part west of 'Roosteren' and a much larger part eastwards (see Map 1). Due to the relatively steep hydraulic gradient and large transmissivities of aquifer 1 in the nabourhood of P.S. Roosteren, it is not likely that the influence area of the well will extend far westwards from the well. This expectation is confirmed in WML report 92.51.01(Kragt & Juhász, 1992), which comprises a numerical groundwater modelling study of the area of interest. In this study a simulation has been carried out for a discharge rate of 9 MM3/a at P.S. Roosteren, which resulted in virtually no drawdown west from the River Meuse. The groundwater protection zone, as defined by the Provincial Authority of Limburg, also indicates that the caption zone of production well 'Roosteren' is located in SE direction (see Map 2: Groundwater Protection Zone of P.S. Roosteren). The longer sides of the model rectangle are therefore NW – SE oriented, defined in such manner that the southwest boundary of the model area coincides with the Feldbiss fault. The Feldbiss fault forms an obstruction to groundwater flow, which particularly can be seen in average observed piezometric heads as presented in Map 11: Average Observed Heads 1985, Aquifer 2. Since furthermore regional flow direction is oriented parallel to the Feldbiss fault, the SW boundary of the model has been defined as a no-flow boundary. The remaining three sides of the model area have been defined fixed-head type of boundaries. The northwestern boundary of the model coincides partly with the River Meuse.
As far as the extent of the model area is concerned, model boundaries have been determined in order to ascertain that the caption zone of the well will completely remain within the boundaries of the model. This implies that parts of the model area are located in Germany and Belgium. At this stage of the groundwater simulations, no geo-hydrological data have been collected for these parts of the model area. If simulation results should indicate that the aforementioned parts of the model area play a significant role in the hydrological system, additional data will be collected in Germany and/or Belgium.

2.4. Geology

Sources of data
Data have been collected from TNO Groundwater maps (Homan, 1974, 1977) and a local study carried out by the Geological Survey RGD at Roosteren – Koeweide (Anonymus, RGD, 1976).

Data availability
Availability of borehole-descriptions is limited, especially for the eastern part of the model area. Transmissivity expectancy values of Aquifer 1 have been based on TNO transmissivity maps. Its point values have been estimated by analyses of 48 borehole descriptions and three pumping test analyses. Total thickness of the underlying aquitard is known at eight points in the model area, where boreholes penetrate into aquifer 2. Transmissivity values of aquifer 2 are not available.
The vertical extension of Aquifer 2 is very poorly known throughout the complete model area.

Description
Tectonic activity, erosion and sedimentation have caused the present geological characteristics of the case area. The principal geological delineation in the area is formed by the Feldbiss fault (see Map 1:Production Wells in the Model Area).
The model area is situated NE and parallel to the Feldbiss fault and forms part of the Roerdalslenk. Geomorphologically the area consists of eroded hills, varying in elevation between +20 and +100 m

NAP. The prevailing hill slope is SE – NW oriented. Run-off is conveyed into the river Meuse by a number of streams. The river Meuse itself is meandering towards the north, its natural hydraulic gradient tempered by a number of barrages. There are no barrages located in the section of the River Meuse which forms part of the model area.
The area is influenced by tectonic movements during the Pleistocene, when an upheaval of the Ardennes region in present-day Belgium and a gradual lowering of the Rhine and Meuse deltas resulted in a number of fissures, generally SE –NW oriented. These tectonic movements resulted in an increase of hydraulic gradients in the Pleistocene Meuse, evoking re-erosion of previously deposited river sediments in some areas. These processes have thus resulted in a very heterogeneous sub-soils, with many alterations between gravel, sand, loam and clay (Stuurman et al., 1996).
The uppermost layer consists of Holocene clay and loamy river sediments, varying in thickness from 0 to 10 m. A layer of high hydraulic conductivity is located directly under the clay-cover and is composed of coarse sands and gravel, in which locally clay layers occur, characterised by the Veghel, Sterksel and Kreftenheye Formations (Pleistocene). Screens of P.S. 'Roosteren' are located in this layer. Thickness of the aquifer varies from 10 – 40m, gradually diminishing in southeast direction. This layer is characterised by high to very high transmissivities in the upper part of the aquifer near P.S. Roosteren, due to the large fractions of coarse sand and gravel. Sediments of these formations were predominantly deposited by rivers in the period from the maximum extent of the Saalian glaciation in the Netherlands until the Early Holocene.
Below the aforementioned Formations, sediments generally consist of fine and loamy sands, locally intersected by clay lenses, belonging to the Kedichem Formation, formed during early and mid Pleistocene.
Underneath the Kedichem Formation is located a rather heterogeneous layer of fine and sometimes coarse sands, formed during Late Pliocene and Early Pleistocene, known as Schinveld Sands. Under this layer Brunssum Clays are located, dating from Pliocene. Schinveld sands and Brunssum clays form part of the Kiezoolite Formations.
Thickness of this layer, forming part of Brunssum and Schinveld Formations amounts 80 m. in the south, increasing to 150 m. in the north of the Roerdalslenk.
A second aquifer is located below the aforementioned aquitard, composed of a number of coarse to medium coarse sands and gravel, locally intersected by clay sediments (Waubach sands and gravel). The latter three formations all belong to the Kiezoolite Formation. Thickness varies from approximately 50 – 100 m. Due to scarcity of sufficiently profound boreholes; an accurate vertical proliferation of the latter two Formations is not available. Below the above described layers that belong to the Kiezoolite formation is located a layer of low hydraulic conductivity whichs belongs to the Breda Formation.

Model schematisation
The geological structure of the area is schematised into two aquifers, divided by an aquitard. Aquifer 1 accounts for the Veghel, Sterksel and Kreftenheye Formations. The underlying aquitard corresponds to the Brunssum and Schinveld Formations, whereas aquifer 2, located beneath this aquitard corresponds to the Waubach and Pey Sands. (see Figure 3). The Holocene clay cover in the area has not been translated in the model. Hydrological confining capacity of this layer is assumed to be modest since it is not everywhere present in the model area and many parts of it are unsaturated.

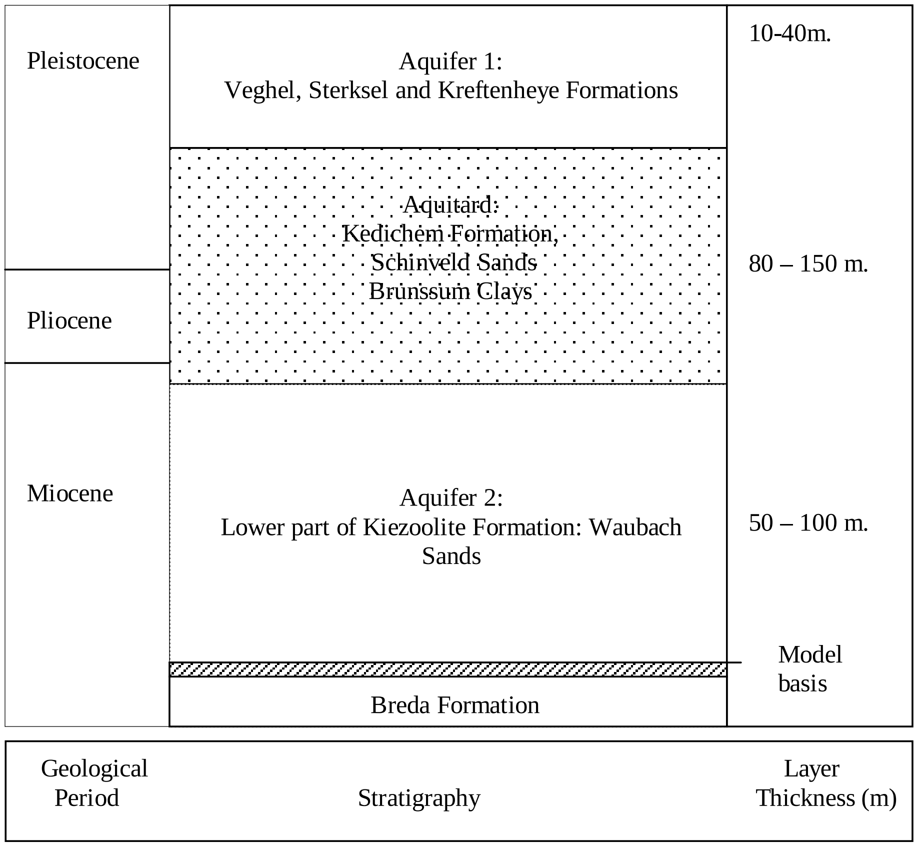

Figure 3 Hydro-geological schematisation

Aquifer 1
TNO estimated transmissivity point-data of aquifer 1 have been used for an inverse distance interpolation and thus transformed to a continuous stratigraphic entity for the model area. Estimations of transmissivity values have been based on distributions of granular size. Transmissivity values vary between 150 and 5100 m2/d

Aquitard
Hydraulic resistance of the Brunssum and Schinveld Formations (aquitard) has been estimated through elaboration of a thickness map for this aquitard, based on eight borehole descriptions. Average hydraulic conductivity is estimated at 0.002 m/d. Thickness is estimated at 70 to 80 m. Resulting hydraulic resistance of the aquitard amounts to 35000 to 40000 d.

Aquifer 2
Transmissivity of aquifer 2 is estimated at 3000 m2/d.

Model basis
Basis of the model is formed by the top of the Breda Formation.

2.5. Landuse and soils

Sources of data
Digital landuse and soil maps has been supplied by DLO Staringcenter at Wageningen and Provincial Authorities of Limburg. Some data preparation concerning water table classes has been carried out by IWACO BV, Den Bosch.

Data availability
Data availability on landuse, soils and groundwater classes is limited to the Dutch part of the model area, which covers about 60% of the total model area.

Description
Landuse within the model area is presented in Map 3,Map 4 andMap 5. Soils of the area have been grouped into four classes and are presented in Map 6. The region which is located at a maximal distance of about 3 km from the River Meuse is characterised by clay soils, with relatively high groundwater levels (see Map 7: Groundwater Classes). As no further subdivision has been made within the group of clay soils, the pronounced heterogeneity of the clay covered area is somewhat hidden, but can be recognised through the vivid pattern of polygons, of which each represents a different (sub) soil type. In the shape of some polygons present or ancient riverbeds can be recognised.
The northeastern part of the model area consists of sandy soils, with generally deeper groundwater levels than at clay soils. An exception in the sand-dominated area is formed by the valley of the Pepinus stream, with mainly clay soils and high groundwater levels. The southeastern part of the model area is dominated by loess soils, on high grounds with deep groundwater levels. Some typical data on landuse and soils are stated in the tables below:

Sand	Clay	Loess
23%	50%	26%

Table 1: Percentage of area within the Dutch part of the model area per soil type

Arable land	Meadows	Other
40%	19%	41%

Table 2 : Percentage of area within the Dutch part of the model area per landuse type

	Sand	Clay	Loess
Arable land	50%	50%	50%
Meadows	25%	27%	16%

Table 3: Landuse per soil type within the Dutch part of the model area

Model schematisation
Description of landuse and soils is incorporated in this report in order to provide a general description of the case area. No soil data heve been used with respect to the current model schematisation.Data purchased from the National Office of Statistical Data (CBS) on landuse been used in order to calculate potential evapotranspitration (see 2.6).

2.6. Precipitation and evaporation

Sources of data
KNMI (Royal Dutch Meteorological Institute).

Data availability
Five meteorological stations are located in the nabourhood of the model area (see Map 8: Location of River Gauge and Meteo Stations).
From two of these stations, both data on precipitation and Penman evaporation are available. From the other three stations no evaporation data are available.

Description
Mean long-term (1961-1990) annual precipitation of the nearest two major meteorological stations, Venlo and Beek amounts to respectively 758 and 762 mm/a. Although these values may suggest a relatively homogeneous rainfall distribution in this part of Limburg Province, *annual* rainfall data of all five stations show occasionally relative annual differences of more than 15% of the five station's annual average (see Figure 5). In general, extreme values do not exceed 10% of the five stations' annual mean value. Although some systematic differences among annual sums of precipitation seem distinguishable, they are not very pronounced.

Spatial distribution of annual potential evaporation is less variable than precipitation. Figure 6 shows total annual potential evaporation at meteo stations Beek and Venlo. From 1950 – 1986 potential evaporation has been calculated with the Penman formula, up from 1987 the Makkink formula for reference evaporation has been applied by the Royal Dutch Meteorological Institute (KNMI). These 'Makkink' values have been transformed into Penman values by application of season-dependent correction factors as provided by TNO (TNO, 1988). Differences in thus indirectly calculated 'Penman' values between the two stations seem to be greater than between directly calculated Penman values. Figure 7 illustrates this phenomenon, which is not very surprising since correction factors are empirically determined averages at a national scale.

Model schematisation
Annual precipitation of all five stations has been averaged. Given the limited accuracy of which other conditions and processes that are relevant to net recharge can be quantified, as yet it has not been considered useful to apply a spatial differentiation of annual precipitation values for calculation of net annual recharge.
In order to calculate recharge into the aquifer 1, potential evapotranspiration has been calculated as a function of landuse. Actual evapotranspiration is estimated to equal potential evapotranspiration. As important periods with a prolonged evaporation deficit are rare in 1985, water storage capacity of soils in the model area are relatively high and furthermore many farmers compensate periods of drought with supplementary irrigation from local boreholes this assumption seems to be justified for the current purposes of this study. In 1985, the cumulative evapotranspiration deficit does not exceed 40 mm; available soil water is estimated to exceed this quantity in most cases in the model area. Potential evapotranspiration data have been received from WML, in which landuse data from the National Office of Statistical Data CBS have been used to calculate weighted seasonal crop factors, which have been multiplied with Penman evaporation values at a decade (appr.10 days) interval. The first series of simulations has been carried out for 1985.Expectancy value of net recharge is therefore according to the described approach defined at 240 mm/a.

Figure 4: Annual precipitation

Figure 5: Precipitation: relative annual differences from annual mean

Figure 6: Annual Penman evaporation

Figure 7: Penman evaporation, relative differences from annual mean values

2.7. Surface Waters

Surface waters are differentiated into three groups:

- Streams of smaller size than the River Meuse that do not infiltrate;
- Secundary drainage system from which as yet no data are available;
- River Meuse and Juliana Canal, which may either drain or infiltrate.

2.7.1. Streams and secondary drains

Sources of data
Data on discharges and stages have been supplied by the regional waterboard 'Waterschap Roer en Overmaas'.

Data availability
The drainage system of the model area consists of a number of streams and rivulets of which some have their origin in Germany. Discharges are measured at seven places in and around the model area (see Map 9). Data availability and frequency of observations is irregular and varies per station. As yet, no information has been collected from remote areas of the model area, which form part of German and Belgium territory.
The entire drainage system is conveying its water driven by gravitation into the River Meuse. Average discharges of some the major streams are presented in Figure 8.

Description
Measured discharges do not cover the complete model area and part of the measured quantities originates from outside the model area. However, indicative discharge calculations show that important quantities of water are being transported by the drainage system. Average annual discharge rate of the Geleenbeek at Roosteren in 1985 was about 3 m3/s, which corresponds to a total annual quantity of water of approximately 95 Mm3. If measured quantities at Jabeek and Munster and an estimated contribution of the Sachelerbach outside the model area are subtracted, a rough estimate of surface water that originates from within the model area and is transported by drains amounts to a minimum of 20 – 25 MM3/a.

Model schematisation
Streams in the model area have been schematised according to the drainage package of MODFLOW (McDonald & Harbaugh, 1988). With this package, drainage is simulated, but no infiltration of surface waters from drains into the subsoil is possible. Streams in the model area have been schematised according to the drainage package since no important infiltration of streams in the model area is expected. If these rivulets would be schematised according to the MODFLOW river package, quantities of possibly local infiltrating water can not be controlled easily within the model structure and risk therefore to exceed realistic values. Especially during initial calibration, when calculated piezometric heads are still erroneous, this phenomenon is to be avoided.
Since availability of stream stage data is very poor, a rough estimate of these values has been made by relating these levels to surface elevation. Secondary drainage canals and ditches have been simulated without detailed information of stages and conductivity values. Due to scarcity of surface elevation data, accuracy of the schematisation of the drainage system is considered very poor. Typical resistance values have been estimated between 1 and 9 days, analogue to the WML report by Kragt & Juhász, 1992.

2.7.2. River Meuse and Juliana Canal

Sources of data
Data on discharges and stages have been supplied by Rijkswaterstaat Maastricht.

Data availability
Daily averages of discharges and stages measured at river stations Heel, Stevensweert, Maaseik and Grevenbicht are available (see Map 8).

Description
Within the model area The Meuse is meanders downstream to the north. Its average depth is estimated at 3 m. East from the River Meuse and parallel to its general flow direction is located the Juliana canal, with canal stages that are significantly highre than surrounding grund surface behind its dikes. The Juliana Canal is constructed in order to facilitate traffic of ships towards he north. The canal bed is lined. The River Meuse is characterised by a pluvial regime, showing relatively low discharges from May until October and high discharge during winter (see Figure 11). Minimal and maximal extreme river stages at Roosteren show differences of about 8 m. During extreme high waters the flood plain area around P.S. Roosteren becomes inundated. Average annual discharge at Borgharen, located in the southern part of Limburg Province, is about 215 m3/s, which corresponding to an average annual volume of over 6700 MM3.

Model schematisation
The River Meuse has been schematised in the model by application of the river package of the MODFLOW code (McDonald & Harbaugh, 1988). This package allows both infiltration and drainage by river cells. Average annual river stages (1985) have been allocated to river cells at locations that correspond with the River Meuse in the model area. Stages in between river stations have been calculated by application of linear interpolation of known river stages at Grevenbicht, Maaseik, Stevensweert and Heel. Since the bed of the Juliana Canal is lined, the canal has not been schematised in the model.

Figure 8: Streams: average discharges

Figure 9: River Meuse – extreme stages at Maaseik

Figure 10: River Meuse: stages at Roosteren at 30% and 70% exceedance probability

Figure 11: River Meuse: discharges at Borgharen at 30% and 70% exceedance probability

2.8. Piezometric heads

Sources of data
Measured piezometric heads have been supplied by IGG-TNO and by WML.

Data availability
The major part of available piezometric data have been measured at sites in the west part of the model area; in the south east part of the model area data availability is poor. Typically, piezometric data have been measured at a 14 days interval.

Description
The first aquifer in the area is considered freatic, since the overlying clay cover is not present in large sections of the model area. Available piezometric heads in this aquifer are measured in about 40 observation boreholes, mainly concentrated in the western part of the model area (see Map 10). Generally, the saturated zone starts at 0 –5 m. below surface. Water in this aquifer flows towards the River Meuse, partly conveyed by its contributaries Roer and Geleenbeek. Annual averages of observed piezometric heads show considerable local discontinuities, presumably to be contributed to local occurrence of clay sediments within aquifer 1. However, regional flow patterns are clearly distinguishable throughout the model area. Especially in the eastern part of the model area, steep piezometric gradients can be observed.
In the nabourhood of P.S. Roosteren, piezometric gradients vary from 1 to 3 m/km (Lit WML). Average difference in piezometric heads in 1985 between the extreme NW en SE boundaries of the model area is 25 – 30 m, on average approximately 1.6 m/km

The second aquifer is confined, with local piezometric heads that amount to +7 m. above those of Aquifer 1. Observation wells in the aquifer are scarcely available and therefore no accurate piezometric surface could be constructed. Average difference in piezometric heads in 1985 between the extreme NW en SE boundaries of the model area is 15 - 20 m., on average approximately 1 m/km.
For both aquifers regional groundwater flow direction is NW.

Model schematisation
Annual averages for 1985 have been calculated and allocated to corresponding model layers. Piezometric heads for fixed head boundary cells have been calculated by application of inverse distance interpolation of point data. WML data on piezometric heads have not been used since they have been measured in relation to ground surface elevation, which at this stage could not be accurately transformed to NAP reference values.

2.9. Grid

According to the initial phase of the modelling study at present, resulting in a regional flow model, a regular grid configuration of 500m * 500m cells has been defined, consisting of 34 rows and 20 columns. The model area consists thus of a rectangle of 10 by 17 km, representing an area of 170 km².
An image of the grid is presented in Map 1: Production Wells in the Model Area.
When initial calibration is completed, refinements of the grid will be implemented.

3. Modeling Results

3.1. Sensitivity analyses

In order to determine sensitivity of piezometric heads and water balance terms to model input variables, a number of sensitivity runs have been carried out, before beginning calibration of the model. For a number of input variables of the model, an estimated ‘expectancy interval’ has been determined, from which it is considered likely that ‘true’ values are located between its outer limits. Quantification of the expectancy intervals has been based on previous studies, literature, data availability, data-variability and best professional judgement. For each maximal and minimal extreme value of the expectancy range, a sensitivity run of the model has been carried out, while values of the other variables were kept in the centre of their respective expectancy interval. The calculated average difference between piezometric heads in both cases indicates thus the model-wide sensitivity of piezometric head to a model-input variable.
Naturally, chosen intervals of input values are closely related to the resulting sensitivity which should therefore not be viewed as very accurately determined values.
At this stage of the project, sensitivity has been related to piezometric head and water balance terms; in the course of the project sensitivity will be related to the very objectives for which the model was constructed: prediction of groundwater quality.

Variables that have been evaluated in sensitivity analyses and magnitude of their respective expectation intervals are stated in the following table and are graphically presented in Figure 12 and Figure 13.

Variable	**Expectancy**	**Maximum**	**Minimum**
Transmissivity Aquifer 1 (m2/d)	Variable	+10%	-10%
Resistance Aquitard (d)	Variable	+20%	-20%
Transmissivity Aquifer 2 (m2/d)	3000	+100%	-100%
Net recharge (mm/a)	240	+20%	-20%
Drain stage (m)	Variable	+3 m	-3m
Drain resistance (d)	5 d	9 d	1 d
River resistance (d)	5 d	9 d	1 d
Boundary piezometric heads (m)			
NW	Variable	+1 m.	-1 m.
NE	Variable	+2 m.	-2 m.
SE	Variable	+4 m.	-4 m.

Table 4: Variation of model input values in sensitivity analyses

Figure 12: Sensitivity analyses, variation of input values 1 (m. and d.)

Figure 13: Sensitivity analyses, variation of input values 2 (%)

3.2. Sensitivity of piezometric head

In Figure 14, average absolute differences of calculated piezometric heads with observed heads are presented. The figure clearly indicates that average piezometric head is most sensitive to fixed head boundary values of both aquifers. Naturally, this phenomenon is strongly related to the large range that exists between minimal and maximal values of the chosen expectancy interval. Improvement of model results should therefore focus on these variables, by purchasing additional measured piezometric heads near model boundaries. Variation of drain stages has also a strong impact on heads; it is expected that more accurate information on drain stage levels could considerably improve model results.

Relative insensitivity of piezometric head to aquitard resistance and transmissivity values of Aquifer 2 is caused by the great thickness of the aquitard; even changes of 20% of resistance values keep resistance values high and therefore fluxes modest in relation to lateral fluxes in Aquifer 2.

Simulated heads in Aquifer 2 are more sensitive to changes of boundary heads than those in Aquifer 1. Since recharge and drainage partly tend to compensate changes of boundary head values in Aquifer 1, no such compensating mechanisms are present in Aquifer 2.

Changes of transmissivity in Aquifer 2 do affect piezometric heads in that aquifer but have a stronger impact on simulated heads in Aquifer 1. Since fluxes from Aquifer 2 to Aquifer 1 are mainly controlled by resistance values of the aquitard, changes of transmissivity in aquifer 2 do change the fluxes somewhat, but the magnitude of the fluxes is small in comparison to transmissivity values of aquifer 2. These relatively unimportant changes of outgoing fluxes from aquifer 2 do have a much stronger impact on heads in Aquifer 1, which is characterised by relatively low transmissivity values in the eastern part of the model area. This implies that a change of flux in Aquifer 1 leads to a much greater change in piezometric gradient (and head) than the same change of flux does in Aquifer 2.

3.3. Sensitivity of water balance terms

A graphical presentation of water balance terms of stationary sensitivity runs is presented in Figure 15. Total volumes of water vary between about 60 and 80 MM3/a. Extracted volumes by wells are constant in all runs, since well discharge was kept constant in all simulations. Precipitation budget is constant in all runs, except for the two runs with respectively maximal and minimal expectancy values for precipitation. All other water balance terms vary as a function of simulated piezometric head. On average boundary fluxes and recharge account each for about half of the water source, whereas infiltrated water from the River Meuse makes out about 2% of incoming water. Summed volumes of boundary fluxes show considerable differences among many runs, caused by large expectancy intervals of boundary heads.

Figure 15 illustrates clearly that drain fluxes make out a much smaller water budget than estimated on a basis of measured discharges in some streams in the model area (see 2.7.1). The minimal estimated annual volume of drainage water according to paragraph 2.7.1 was 20 – 25MM3 whereas this quantity in a model run with input values at expectancy values does not exceed 2 MM3. Expectancy intervals for drainage levels will be therefore increased for initial calibration of the model. Clearly, additional information on the drainage system could improve model results.

It can be concluded that within the current expectancy intervals model performance is very sensitive to allocated piezometric heads at the fixed head boundaries of the model. The area around P.S. Roosteren is strongly influenced by the River Meuse and piezometric conditions of the north western boundary of the model. Additional information on these conditions will reduce the size of the expectancy interval of the relevant variables and thus strongly improve accuracy of results. Model results also can become considerably more accurate if additional information on the secondary drainage system will be purchased.

Figure 14: Sensitivity of average simulated piezometric head to model input

Figure 15: Sensitivity of water balance terms to model input

3.4. Calibration of the model

Calibration of the model was carried out through stationary simulations of groundwater flow in 1985. The year 1985 has been selected because it is the first year that P.S. Roosteren has been operational and furthermore because 1985 is with respect to meteorology largely an average year. The calibration has thus been carried out for average hydrological conditions. In the course of the project, refinement of the calibration will be carried out, not only with respect to the methods that will be applied, but also with respect to collection of additional data on model variables such as observed piezometric heads will be purchased. An evaluation of results of the various methods will be carried out for project task Nr. 2., when simulation of chloride transport will be implemented and model calculations will concern a longer period than only 1985. Results of the first calibration of the model will be used for further evaluation of the hydrological characteristics of the model area and for identification of the principal limiting factors for a satisfying model performance. Whether the model will meet the required accuracy for prediction of groundwater quality development can only definitively be determined by analyses and validation of these very predictions, and not by indirect criteria for model performance such as correspondence between observed and simulated piezometric heads.

Results of sensitivity analyses have already indicated that within the chosen expectancy intervals of many model variables, a large range of simulated piezometric heads is possible. Considering these results, it is desirable that in the near future additional data will be purchased, particularly with respect to piezometric boundary conditions and with respect to the drainage system. Initial calibration was carried out in order to evaluate hydrological conditions of the model area.
Results of sensitivity analyses have demonstrated that hydrological characteristics of the model area are dominated by an aquitard with high resistance values, resulting in little interaction between the two aquifers, that are located respectively above and under the aquitard. However, some interaction has been perceived through the results of the sensitivity analyses. Since the model is constructed in order to predict groundwater quality developments, even a relatively modest interference with respect to fluxes between both aquifers may be of importance for predicting groundwater quality.
Drainage capacity of the secondary drainage system was enlarged as compared to sensitivity analyses in order to enable a closer correspondence between observed and simulated discharge rates of the drainage system.

Calibration has been carried out by application of an automated procedure, which has been developed within the framework of the PRESYS-GQ project. With respect to calibration techniques, hydrologists are divided: some strongly believe in automated calibration procedures, while others prefer to calibrate groundwater models manually. An advantage of application of automated calibration procedures lies in the application of formalised and explicit decision rules, which makes the product of a calibration session better reproducible. Decision rules for automated calibration techniques can be as complex as is necessary for a specific purpose, involve statistical or other functions and still remain practical and efficient. A practicable and objective comparison of calibration techniques is hardly possible if calibration is carried out manually.
Within the framework of task 1 of the PRESYS-GQ project, a simple automated calibration procedure has been designed, which will be refined in the course of the project. The decision rules that have been applied consist of three principles:

- Minimal absolute difference between simulated and observed piezometric head throughout the model area.
- Minimal difference between expectancy values and calibrated values of input variables
- Model input values are to remain within the chosen expectancy intervals of each variable.

Average values of observed piezometric heads in 1985 have been interpolated in order to construct a continuous surface of piezometric head. Calibration has been carried out on a cell-by-cell basis, where for each cell input values have been modified according to the aforementioned three principles, without application of any weight factor. Starting from all variables set in the middle of expectancy intervals, input values were modified in small steps in order to reduce differences between observed and simulated heads. The process was halted when further modification of input values only resulted in negligeable additional improvement of model results.

Average differences between calculated and observed piezometric heads are tabulated in Table 5: Results of model simulations, both for the model with all input values set at expectancy values and for the calibrated model.
Further improvement of model results was not possible with current cell size, schematisation and limits of estimated expectancy intervals of input values.

Run	Aquifer	E1	AE1	E2	AE2	DE	DEA
Expectancy	**1**	0.30	1.57	0.29	0.76	0	0
Expectancy	**2**	*	*	0.79	1.55	0	0
Calibrated	**1**	0.02	0.73	-0.40	0.56	0.002	0.2
Calibrated	**2**	*	*	-0.02	1.51	0.03	0.2

* Due to limited availability of pointdata no continuous piezometric surface has been constructed for aquifer 2.

Table 5: Results of model simulations, differences between simulated and observed piezometric heads.

Legend:
E1: average difference simulated – average observed piezometric point data (m)
AE1: average absolute difference simulated – average observed piezometric point data (m)
E2: average difference simulated – interpolated average observed piezometric data (all cells) (m)
AE2: average absolute difference simulated – interpolated average observed piezometric data (all cells) (m)
DE: average difference from model input values expressed as a fraction of the expectancy intervals (-)
DEA average absolute difference from model input values expressed as a fraction of the expectancy intervals (-)

Map 13 and Map 14 show spatial distribution of errors. Reduction of the cell size of the model may improve results, as calculated heads show that local irregular gradients are hard to simulate with the current cell size.

Map 15 shows the calculated caption zone of P.S. Roosteren. The delineation of the caption zone corresponds approximately to the groundwater protection zone as defined by provincial authorities and presented in Map 2.

3.5. Conclusions

A groundwater model for P.S. Roosteren has been constructed. Sensitivity analyses indicate that additional information on particularly boundary heads and drainage conditions is most needed. Results of the initial calibration indicate that P.S. Roosteren is located in an area with a highly heterogeneous subsoil and many local discontinuities of the regional piezometric gradient. Differences between simulated and observed piezometric heads are such that further refinement of the model in both horizontal and vertical direction will be needed. Additional data on observed piezometric heads and of the drainage system will be purchased.

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Part 2: Maps

Map 1: Production Wells in the Model Area

Map 2: Groundwater Protection Zone of P.S. Roosteren

Map 3: Landuse – Urban Areas and Surface Water

Map 4: Landuse - Arable Land, Meadows and Urban Zones

Map 5: Landuse – Forests and Natural Vegetation

Map 6: Soil Classes

Map 7: Groundwater Classes

Map 8: Location of River Gauge and Meteo Stations

Map 9: Location of Stream Gauge Stations

Map 10: Average Observed Heads 1985, Aquifer 1

Map 11: Average Observed Heads 1985, Aquifer 2

Map 12 Transmissivity Estimates for Aquifer 1 by TNO

Map 13: Differences Simulated – Observed Piezometric Heads, 1985 Aquifer 1

Map 14: Differences Simulated – Observed Piezometric Heads, 1985 Aquifer 2

Map 15: Streamlines and Caption Area of P.S. Roosteren

Appendix 1 Time Table