

The effects of human interventions on groundwater recharge

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Abstract Water tables in The Netherlands have fallen due to human interventions in the water regime. This has caused hydrological degradation, particularly over the last 50 years. Factors responsible for this hydrological degradation include: increased agricultural crop production, changes in land use, increased drainage, lowering of the drainage base, and increased groundwater abstraction. It is unknown, however, whether, and if so to what extent, these factors have changed the groundwater recharge rate. Therefore a study was carried out in three different regions in The Netherlands to quantify groundwater recharge using a regional hydrological model. The physically-based model SIMGRO, in which the unsaturated zone, the saturated zone and surface water are integrated, was used to predict the groundwater recharge. The calculations show that the natural recharge increases when water tables are deep. Variations in meteorological conditions over the last 50 years have a pronounced effect on the natural recharge, and the effect is greater than the changes caused by any of the human influences.

Key words drainage; evapotranspiration; groundwater; hydrological degradation; recharge; The Netherlands

INTRODUCTION

The Netherlands is a lowland delta, formed by the rivers Rhine and Meuse. More than half of the country is presently situated below sea level (the “lower” part) as a result of a rise in sea level accompanied with land subsidence induced by drainage. The rest of the country is just slightly higher (<100 m) than sea level (the “higher” part). In most parts of the country the water table is shallow (between 0.3 and 2.5 m below the soil surface) and a dense network of water courses is needed to drain the land, but also to supply water to agricultural areas in dry summer periods.

Over the last 50 years much attention has been given to improving agricultural production, resulting in higher water demands. The increased population needs more drinking water, which is mainly abstracted from groundwater. This, and other factors, have caused changes in groundwater recharge and water tables to fall. Lower water tables have adversely affected conditions in nature conservation areas (Runhaar *et al.*, 1996). Numerous factors are responsible for this hydrological degradation: increased agricultural crop production; changes in land use; increased drainage (installation of subsurface drains); lowering of surface water levels and increased groundwater abstraction. Variations in the water regime are also caused by differences in meteorological conditions (wet and dry) over a number of years. For these factors it is important to use one modelling approach that describes the important components of the hydrological system. The model SIMGRO (SIMulation of GROundwater flow and

surface water levels) meets this requirement. It takes into account the flow of water in the saturated zone, the unsaturated zone and the surface water in an integrated manner (Querner, 1997). Therefore it is suitable for use in estimating the effect of all factors causing a fall in groundwater levels.

The objective of this paper is to describe the effects of human interventions in the water regime. The effects will be shown as differences in the natural groundwater recharge. The natural groundwater recharge is the flow of water from the unsaturated zone to the saturated zone and depends mainly on rainfall, land use, soil characteristics and depth of the water table.

SCENARIO APPROACH

A scenario study was set up to quantify the effects of human interventions and various scenarios were defined to represent the man-induced changes over the last 50 years. The change in the natural groundwater recharge was used as an indicator of the hydrological degradation. Results are presented for regions with similar groundwater conditions as defined by water table fluctuation classes (Table 1). The seasonal fluctuation of groundwater is defined in The Netherlands in terms of depth below the soil surface of the "average highest" and "average lowest" groundwater levels. The average highest or lowest level within a hydrological year at a location are obtained by taking the three highest or lowest groundwater levels measured or simulated every fourteen days. In general, the lowest levels occur in mid summer and the highest at the end of winter.

The present situation is the reference for the calculations. The scenarios are intended to simulate the situation about 50 years ago. These scenarios can also be used to explore hydrological conditions in the near future. The scenarios represent the changes due to the increase in groundwater abstraction (public water supply), changes in evapotranspiration caused by higher agricultural production levels, and changes in water management (surface water level and water supply). Five meteorological years with more or less average conditions were selected for the simulations. The average rainfall was 774 mm year⁻¹ and the average potential evapotranspiration for grass was 541 mm year⁻¹.

Table 1 The classification of Dutch water tables as seasonal fluctuations of the depth below soil surface defined in terms of "average highest" and "average lowest" groundwater levels (Van der Sluis & De Guijter 1985).

Groundwater level	Water table fluctuation class (m below soil surface):					
	III	IV	V	VI	VII	VIII
General description	shallow	intermediate	deep			
Average highest	<0.4	>0.4	<0.4	0.4–0.8	0.8–1.4	>1.4
Average lowest	0.8–1.2	0.8–1.2	>1.2	>1.2	>1.2	>1.2

COMBINED SURFACE AND GROUNDWATER FLOW MODEL SIMGRO

The SIMGRO model simulates regional groundwater flow in relation to drainage, water supply, sprinkler irrigation, subsurface irrigation and water level control. SIMGRO is physically-based and can therefore be used in situations with changing

hydrological conditions. A detailed description of the model is given elsewhere (Querner, 1997).

Groundwater flow

To model regional groundwater flow, as in SIMGRO, the system has to be schematized geographically, both horizontally and vertically. The horizontal schematization allows input of different land uses and soils per subregion, in order to model spatial differences in evapotranspiration and moisture content in the unsaturated zone. For the saturated zone various subsurface layers are considered (Fig. 1). A time step of one day is generally used, because meteorological data is often available on a daily basis.

SIMGRO uses the finite element method as a basis to describe the regional saturated groundwater flow. The groundwater levels and fluxes are calculated per nodal point. The unsaturated zone is split in to two reservoirs, one for the root zone and one for the subsoil (Fig. 1). If the equilibrium moisture storage in the root zone is exceeded, the excess water will percolate to the saturated zone. If the moisture storage is less than the equilibrium moisture storage, then the result will be an upward flow from the saturated zone. The height of the phreatic surface is calculated from the water balance of the subsoil, using a storage coefficient, which is dependent on the depth of the groundwater level below soil surface (see Querner, 1997). The unsaturated zone is modelled one-dimensionally per subregion and land use. It is robust in terms of numerical stability and for regional studies does not require too much input data.

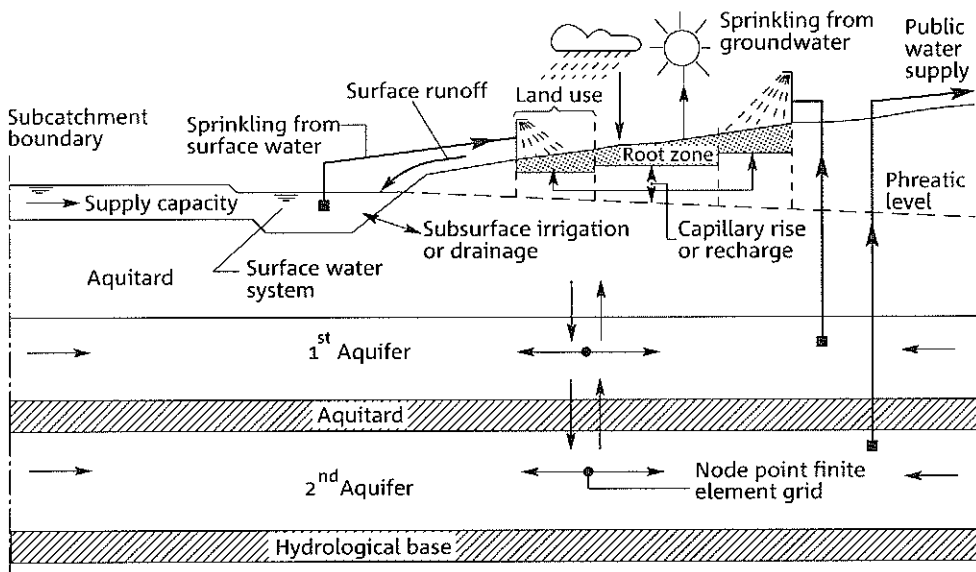


Fig. 1 Schematization of water management in the SIMGRO model. The main feature is the integration of the saturated zone, unsaturated zone and surface water systems within a subregion (Querner, 1997).

Evapotranspiration is a function of the crop and moisture content in the root zone. The measured values for net precipitation, potential evapotranspiration for a reference crop (grass) and woodland are input data for the model. The potential evapotranspiration for other crops or vegetation types are derived in the model from the values for the reference crop by conversions with known crop factors (Feddes, 1987).

Surface water flow and drainage

In The Netherlands the surface water system is often a dense network of water courses. It is not feasible to explicitly account for all these water courses in a regional computer simulation model. The surface water levels in the smaller water courses are important for estimating the amount of drainage or subsurface irrigation, and the water flow in the major water courses are important for the flow routing. Therefore, the surface water system is modelled as a network of reservoirs. The outflow from one reservoir is the incoming flow to the next reservoir, and surface water levels depend on the amount of storage and discharge from a reservoir.

The often dense network of water courses, related to size and density, is important for the interaction between surface water and groundwater. In the model, four drainage subsystems are used to simulate the drainage. The interaction between surface water and groundwater is calculated for each subsystem using a drainage resistance and the difference in level between groundwater and surface water (Ernst, 1978).

ANALYSIS OF HUMAN INTERVENTIONS BY SIMGRO

Study areas

The drought analysis was carried out in three different regions of the Netherlands, ranging in size from 8000 to 32 000 ha (Fig. 2): Westerwolde (325 km²) in the northern region of The Netherlands; Poelsbeek and Bolscherbeek (67 km²) in the east; and Kromme Rijn (300 km²) in the central region. These three regions were selected because a calibrated SIMGRO model was available for them; they all have typical sandy soils and they represent the major landscapes and geo-hydrological conditions in the higher parts of The Netherlands.

Schematization

For the SIMGRO model the groundwater system needs to be schematized by means of a finite element network. The schematization of the Kromme Rijn area is shown in Fig. 3 as an example and the network comprises 2185 nodes spaced about 500 m apart. The study area was subdivided into 143 subregions (Fig. 3) using the different soil properties and the layout of subcatchments (level for modelling the unsaturated zone as shown in Fig. 1). The study area consists of sandy soils. Land use is predominantly agricultural: about 48% is pasture, 6% is fruit farming, 3% is arable land (mainly silage maize), 21% is woodland and 13% residential (Querner *et al.*, 1994).

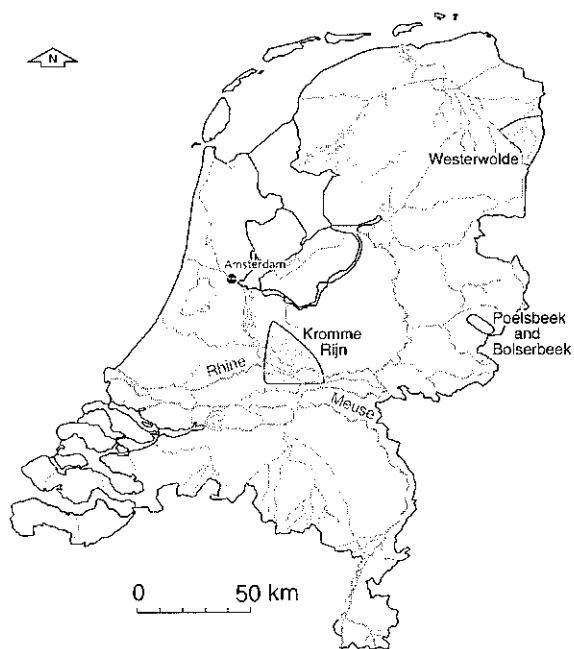


Fig. 2 The three areas in The Netherlands used to estimate the effect of human interventions.

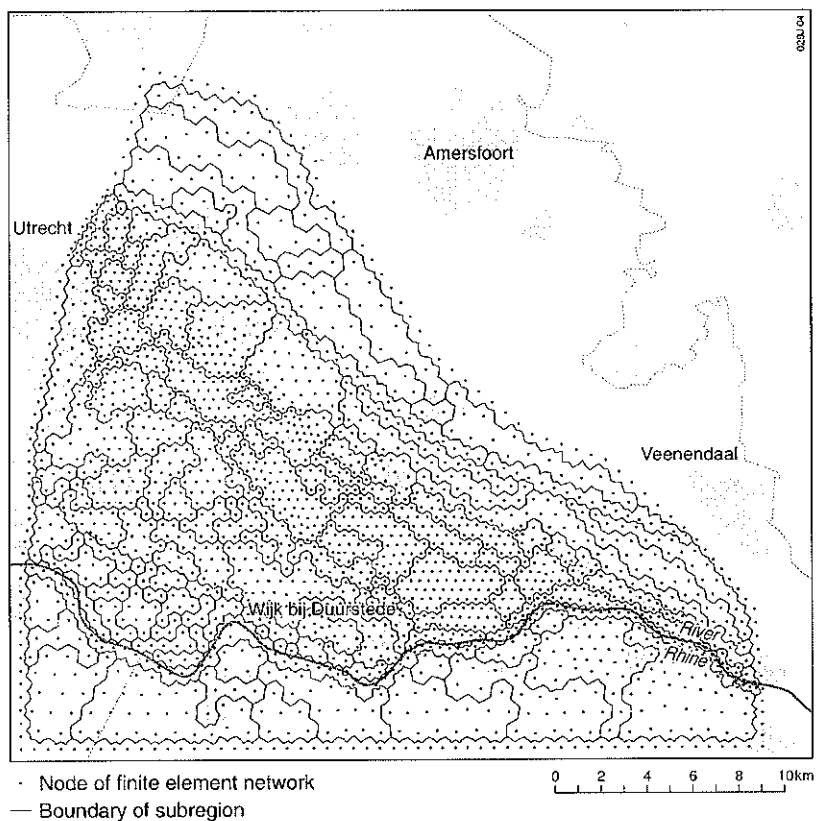


Fig. 3 The schematization of the Kromme Rijn area, showing the finite element network and the subregions. The hydrological processes modelled in a subregion are given in Fig. 1.

Groundwater recharge in the present situation

The groundwater recharge—the water flowing from the unsaturated zone to the saturated zone—has been calculated for the dominant land-use types present in the study areas. Within a year this natural recharge changes, and for shallow groundwater levels it can become negative (upward capillary flux) during the summer. Figure 4 shows an example of the recharge calculated for a water table class IV. In winter time the recharge varies between 10 and 20 mm per 10 days, with peaks as high as 40 mm. In dry periods the recharge becomes negative, which means that an upward capillary flux occurs. This situation is only possible if the groundwater level is not too deep. During such dry periods the reduction in upward flux due to the lowering of the water table can be observed (Fig. 4, May to September 1975). For the winter period 1973/1974, average recharge is 1.7 mm day⁻¹; in the summer of 1974 it is 0.2 mm day⁻¹; in the winter of 1974/1975 it is 2.7 mm day⁻¹; and in the summer of 1975 it is -0.2 mm day⁻¹. Over long periods (several years) the natural discharge is equal to the amount of precipitation minus the actual evapotranspiration. Over such long periods, changes in soil water can be neglected.

Table 2 gives the average natural groundwater recharge for the three study areas. The natural recharge was calculated for the period of five years with more or less average conditions as described in the Scenario Approach section. The range in the results within each of the three study areas is given as well. Table 2 shows that for all land-use types the groundwater recharge increases as the depth of the groundwater level increases. For groundwater classes III to VII, the increase in recharge is gradual and under grassland the recharge increases from 238 mm year⁻¹ to 282 mm year⁻¹. The increase in class VIII is significantly more. For deep water tables (classes VII and VIII from Table 1) the actual evapotranspiration is much lower than the potential, particularly in summer. This lowering is caused by the soil moisture deficit in the root zone and the fact that the upward capillary flux cannot reach the root zone. The result of the lower actual evapotranspiration is an increase in natural recharge. For shallow groundwater levels the actual evapotranspiration rate is about equal to the potential rate and a possible soil moisture deficit is compensated by an upward capillary flux.

Changes in groundwater recharge due to man-induced changes

The purpose of the study was to quantify the important man-induced changes in the Netherlands, which have taken place mainly over the last 50 years. The scenarios represent the situation during the 1950s. The modelling exercises covered in this paper are:

- stopping all groundwater abstraction (public and industrial water supply);
- lowering potential evapotranspiration (70 mm) as derived from the agricultural production levels during the 1950s (the actual reduction is calculated by the model depending on the moisture conditions);
- surface water management to restore conditions characteristic of the 1950s (surface water levels raised by 0.30 m; drainage conditions reduced);
- no surface water supply to agriculture;
- natural variation in meteorological conditions (years 1951–1960 = 765 mm year⁻¹; and 1961–1970 = 887; 1971–1980 = 735; 1981–1990 = 783; all in mm year⁻¹).

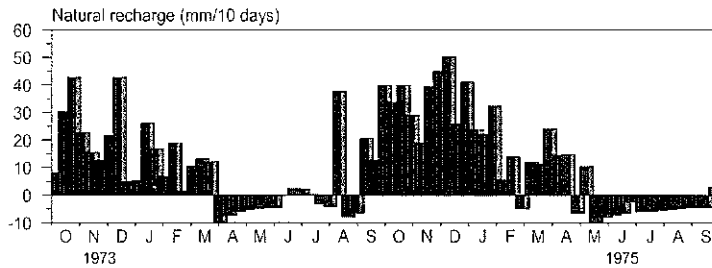


Fig. 4 Natural groundwater recharge for the period October 1973 to October 1975 calculated for water table class IV.

Table 2 The average natural groundwater recharge (mm year^{-1}) for the three study areas differentiated by land use and water table fluctuation classes (average rainfall of 774 mm year^{-1} and potential evapotranspiration for grass of 541 mm year^{-1}).

Water table class	Pasture	Arable	Pine	Deciduous	Range (+/-)
III	238	219	145	265	20
IV	248	238	145	267	15
V	254	234	—	—	*
VI	256	248	150	270	15
VII	282	270	158	279	30
VIII	336	338	217	333	50

* not enough data available.

The impact of sprinkler irrigation, changes in land use and urbanization are not presented. These effects are often very local or involve a wide range of possible changes. The scenarios have been defined for the topics above, based on data from national surveys. The scenarios, therefore, represent average changes, but regionally these changes may be different. The natural variation in meteorological conditions over longer periods gives us an indication as to how variations between dry and wet periods (10 years) relate to the effects of man-induced changes.

Table 3 contains a summary of the results. Because the variation between the results for the water table fluctuating classes III to VIII was limited, only the results for classes IV and VII are presented. The results for the reference situation are given as absolute figures and for the scenarios as their deviation from the reference situation. Table 3 gives the minimum and maximum values calculated for the three study areas. The following conclusions on the effect of man-induced changes on the groundwater recharge can be drawn from Table 3:

- The effects of meteorological conditions (different weather years) on groundwater recharge is greater than any of the man-induced changes (variation from -31 to 119 mm year^{-1}).
- In the 1950s, agricultural production was lower than at present and the assumed potential evapotranspiration was 70 mm lower (scenario 2). Table 3 shows a greater recharge of between 24 and 66 mm year^{-1} in this situation.
- Some effects of water management were identified (up to 37 mm year^{-1}). The change in recharge is more pronounced for the deeper groundwater levels because the upward capillary flux is reduced (see also Table 2).
- The changes in water supply and groundwater abstractions have little effect on recharge at a regional scale. Locally, near a pumping well, bigger changes could occur.

Table 3 The effects of human interventions and natural factors on groundwater recharge for water table classes IV and VII in the three study areas. The values printed in italics are for the reference situation, the others are shown as their deviation from the reference situation. A negative value for the recharge indicates a decrease.

Description	Groundwater recharge:	
	Min. (mm year ⁻¹)	Max. (mm year ⁻¹)
Reference situation (1990)*	<i>211</i>	<i>288</i>
Stop permanent groundwater abstractions	-10	0
Reduced potential evapotranspiration (70 mm)	24	66
Surface water management of the 1950s**	-37	-5
No surface water supply for agriculture	3	5
Weather years: 1951–1960 (moderate dry)	4	14
1961–1970 (wet)	94	119
1971–1980 (dry)	-31	-16
1981–1990 (moderate dry)	10	30

* Average meteorological conditions.

**Surface water levels raised by 0.30 m; drainage conditions reduced.

CONCLUSIONS

The analyses were carried out for shallow groundwater levels, i.e. at between 0.3 and 2.5 m below the soil surface. Under such conditions there is quite a variation in natural groundwater recharge. For shallow and intermediate groundwater levels the difference is small, but for deeper groundwater levels the recharge is much greater due to the reduced evapotranspiration. This reduced evapotranspiration is a result of the deficit in soil moisture in the root zone and a negligible upward capillary flux.

The influence of meteorological conditions on natural recharge has been substantial over the last 50 years. In the 1960s, with very wet years, the recharge was much higher than in the 1980s. The change in recharge also has a pronounced effect on the groundwater levels. The variation in recharge caused by weather conditions is much greater than any of the man-induced changes.

The analyses have been carried out for shallow groundwater conditions in the Netherlands and for different landscapes. The differences in the results between the three landscapes were not great. The results, therefore, will be applicable to similar meteorological and groundwater conditions in other parts of the world.

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