

THE PRODUCTION AND USE OF NITRATE AND PHOSPHATE IN AGRICULTURE AND THEIR CONSEQUENCES ON REGIONAL GROUNDWATER QUALITY

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Summary

The one-dimensional quantitative model MANRUU has been developed for the purpose of physical planning on a national level to calculate the over-production of nitrogen and phosphorus in animal manure per municipality. MANRUU calculates total manure production per municipality from input data on animal-specific manure production (kg N, P₂O₅ per year), fertilizer use and the number of animals of various categories. Data on crop-specific fertilizer demand and on acreage of all crops grown are used to calculate the maximum amount of manure per municipality applicable from an environmental point of view.

The two-dimensional model WATRUU calculates mean concentrations of nitrate and ortho-phosphate in shallow groundwater for catchment areas. It uses the output of the model MANRUU and realistic assumptions on conversion processes of nitrate and phosphate. By using watersheds, an indication can be given of the flow direction and spatial effects of the polluted shallow ground-

water. The results of the calculations are displayed as maps, based on input data for 1983. Computed mean nitrate concentrations are up to 16 times in excess of the EC-standards for drinking water. Phosphate saturation down to the groundwater level is expected to occur in the soil of 145,000 ha of farming land within 25 years when no preventative measures are taken.

The model results were compared with data from a detailed study of the quality of the top groundwater layer in the entire Province of Utrecht. The comparison was found to be reliable at a confidence level of 95%.

1 Introduction

Since the foundation of the European Community one of the major developments in Dutch agriculture has been the large scale development of intensive husbandry of cattle, pigs and poultry, especially in the Pleistocene sand areas of the Eastern, Central and Southern part of the Netherlands (fig.1).

The large amounts of slurry produced by these animals cause serious problems with respect to soil and groundwater contamination, because slurry production has far exceeded the agricultural fer-

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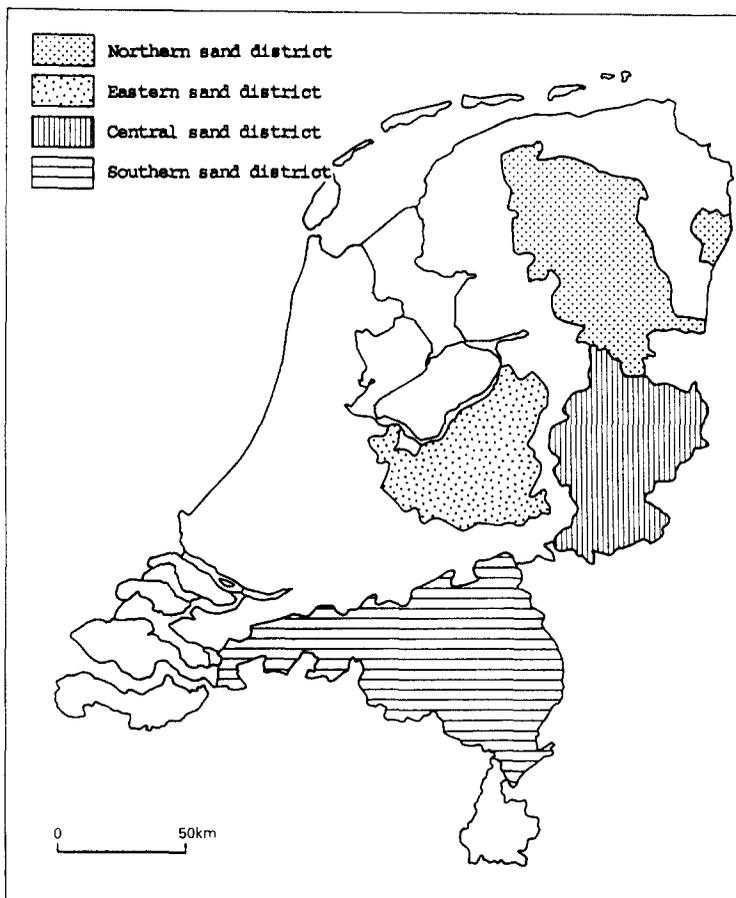


Fig. 1: Location of sand districts in the Netherlands.

tilizer demand. Up to this moment there is no other way operational to dispose of the over-production than dumping it on farming land.

On a local scale the dumping of animal manure has already led to a severe soil contamination with phosphate (VAN RIEMSDIJK et al. 1983). On a regional scale shallow groundwater is highly contaminated with nitrate, and to a lesser extent also with phosphate and potassium (DE WIT et al. 1986). Due to subsurface drainage polluted groundwater may threaten natural areas in seep-

age zones and the production of drinking water.

Therefore, the quantitative models MANRUU and WATRUU have been developed to calculate nitrate and phosphate concentrations in the groundwater toplayer of catchment areas in the regions mentioned above, for the purpose of physical planning on a national and regional scale with respect to the protection of natural areas in seepage zones and the production of drinking water.

2 The model "MANRUU": calculation of the production and application of animal manure and fertilizer

Every year, the Netherlands Central Bureau of Statistics presents figures on the numbers of animals in a great many animal-groups per municipality. Together with a standard production per animal of minerals in slurry produced by each group, the total production of animal manure (expressed as kg N, P₂O₅ or K₂O) per municipality can be calculated. The results presented in this article are based on the enumeration of 1983 (CBS 1984).

The Netherlands Institute of Agricultural Economics has made an estimation on the amount of fertilizer used in every municipality for 1979/1980 (WIJNANDS et al. 1983). In order to calculate the total amount of minerals available to fertilize the acreage of grassland and arable land in a certain municipality these figures are added to the production of animal manure.

The total fertilizer demand depends on the acreage of the various crops grown in a municipality (ha), and on the specific fertilizer demand of each crop (kg N, P₂O₅, K₂O per ha). The specific fertilizer demand can be looked at in two different ways:

- From a pure agricultural point of view, fertilizer should be applied to a level above which production rates will significantly fall and/or diseases will occur. In this sense nitrogen (for most arable crops) and potassium (grassland) are limiting factors (SLUIJSMANS et al. 1978).
- From an environmental point of view, application of macro-nutrients

should be allowed up to a level, which at normal production levels will cause only minimal damage to soil and groundwater. In this sense nitrogen (for its negative effects on drinking water quality) and phosphate (for its strong influence on eutrophication of surface water) are limiting factors on both arable land and grassland (STOM 1983, VISSERS et al. 1985).

Since this study aimed at the contamination of shallow groundwater, only the maximum amount of animal manure and fertilizer applicable from an environmental point of view will be worked out in detail.

2.1 The maximum allowed amounts of nitrogen and phosphate by manure from an environmental point of view

2.1.1 Nitrogen

In order to minimize the leaching of nitrogen to groundwater from farming land, it is important to include in the calculations all possible sources that influence the supply to and removal of nitrogen from soil. Since only inorganic compounds are subject to leaching (mainly nitrate), special attention will be given to the inorganic nitrogen balance of farming land and to conversion processes in the soil.

The relevant processes will be described hereunder with respect to their application in the model "MANRUU".

2.1.1.1 Atmospheric deposition As a result of all kinds of human activities nitrogen compounds are emitted to the atmosphere. By means of dry and wet deposition these compounds are returned to

the soil surface. Around 1980, the mean annual nitrogen deposition amounted to 46 kg N/ha (VAN AALST et al. 1983). It is assumed that about 90% of this quantity is available as fertilizer to grassland and 50% to arable land due to the length of the growing season (VISSERS et al. 1985).

2.1.1.2 Mineralization and immobilization In sandy soils without a supply of fresh organic matter the balance of immobilization and mineralization leads to a decrease in the soil organic matter content (SCHEFFER et al. 1984). Animal manure contains, apart from inorganic nitrogen, a certain amount of organic compounds. These organic compounds will mineralize in a certain period after application. In the first years this will lead to an increase of the content of soil organic matter. After continuous application of animal manure over a long time an equilibrium is reached, in the course of which mineralization of organic compounds is equal to the amount of fresh organic matter annually supplied by animal manure (VAN KEULEN et al. 1982). In MANRUU it is assumed that farming land in the Netherlands has reached this equilibrium. However, a part of the organic nitrogen will mineralize after the end of the growing season, and is not available to the crop. Based on calculations by SLUIJSMANS et al. (1978) it is in MANRUU assumed that on arable land 78% of the organic nitrogen content of animal manure is available to crops, and on grassland 94%.

2.1.1.3 Volatilization As a result of the low pH of sandy soils in the Netherlands, volatilization of ammonia from fertilizer is negligible (BUIJSMAN 1983). The high pH of animal manure however leads

to a volatilization of 20% of the amount of inorganic nitrogen applied to arable land, and of 32% of the amount of inorganic nitrogen applied to grassland (SLUIJSMANS et al. 1978).

2.1.1.4 Crop uptake The relation between available inorganic nitrogen and crop uptake is not linear. If nitrogen availability increases, crop uptake of nitrogen will increase at an ever decreasing rate (SPALACCI et al. 1979). Since the nature of the relation strongly depends on local (climatic) circumstances (VAN KEULEN et al. 1982) no general description of this relation can be given. In the model MANRUU crop uptake has been approached by "the mean uptake at a good yield" (BERNELOF-MOENS 1973).

On a regional scale biological nitrogen fixation and surface run-off are of minor importance under Dutch circumstances (STEENVOORDEN 1981).

From an environmental point of view, the maximum allowed nitrogen application level (MNL) should therefore equal crop uptake (U) plus volatilization (V) minus atmospheric deposition (D):

$$\text{MNL} = \text{U} + \text{V} - \text{D} \quad (1)$$

The above this level produced quantities of nitrogen are available for denitrification and leaching (see section 3.1).

When using animal manure some corrections must be made to incorporate the above mentioned influence of mineralization after the end of the growing season and volatilization. By taking this into account an effectivity of the nitrogen in animal manure of 79.2% on arable land and of 81% on grassland was calculated. arable land:

$$\text{MNL} = (1.263 * \text{U}) - 23 \text{ kg N/ha} \quad (2)$$

grassland:

$$\text{MNL} = (1.235 * U) - 41 \text{ kg N/ha} \quad (3)$$

2.1.2 Phosphate

Characteristic for the behaviour of phosphorus compounds in sandy soils is the extremely low mobility of inorganic (ortho)phosphate and most of the organic phosphorus compounds (inositolphosphate). Immobilization occurs under circumstances where a net supply of phosphate exists, as in most soils with agricultural land use.

In general it can be stated that in the Netherlands atmospheric deposition (0.09 kg P/ha/y; KNMI/RIV, 1982) and surface runoff are negligible. Surface runoff only occurs during wintertime on a local scale, in the event that animal manure has been landspread. About 1 kg P per ha is removed in this way (SHERWOOD 1979).

The inorganic phosphate balance of the soil can therefore be expressed as:

$$(\text{fertilizer} + \text{animal manure}) - (\text{immobilization} + \text{crop-uptake}) = \text{fixation}$$

2.1.2.1 Immobilization Animal manure consists of only 1.5% of soluble organic phosphorus compounds which are susceptible to leaching, and for about 18.5% of insoluble organic compounds that will act as inorganic phosphate (LEXMOND et al. 1982).

Inorganic phosphates, either from fertilizer or animal manure mainly consists of calcium-phosphates. In agricultural used sandy soils these phosphates will be soluted and subsequently immobilized by aluminum- and ferri-ions. When at a given phosphorus concentration in soil water no more phosphate is adsorbed, the soil layer may be considered saturated. Further amounts of phosphate

will penetrate deeper in the soil, before being adsorbed.

2.1.2.2 Crop-uptake Crops are only capable of taking up inorganic phosphates. Fertilizer phosphate is therefore completely available. In animal manure phosphorus consists of both organic and inorganic compounds. Inorganic phosphate compounds are completely available under normal circumstances in agricultural used soils. Organic compounds are converted to inorganic phosphates within a period of 20 weeks (STEENVOORDEN 1981). Given the low content of soluble organic phosphates (1.5%), in MANRUU the efficiency of phosphate in animal manure is assumed to be 100%.

Since over-dressing with phosphate will cause saturation of the soil and subsequent leaching and eutrophication of ground- and surface water, the maximum allowed phosphate application level (MPL) from an environmental point of view and assuming a sufficient phosphate availability in soil should equal crop uptake (U).

$$\text{MPL} = U \quad (4)$$

2.2 Results

An over-production of manure exists when the total amount of nitrogen or phosphorus produced in animal manure and fertilizer in a certain area (e.g. municipality) exceeds the maximum allowed application level for respectively nitrogen or phosphorus in the same area.

Fig.2 presents the results of the calculations of over-production of manure per municipality in 1983 in the Dutch sandy soil regions, based on the nitrogen-content of animal manure and fertilizer.

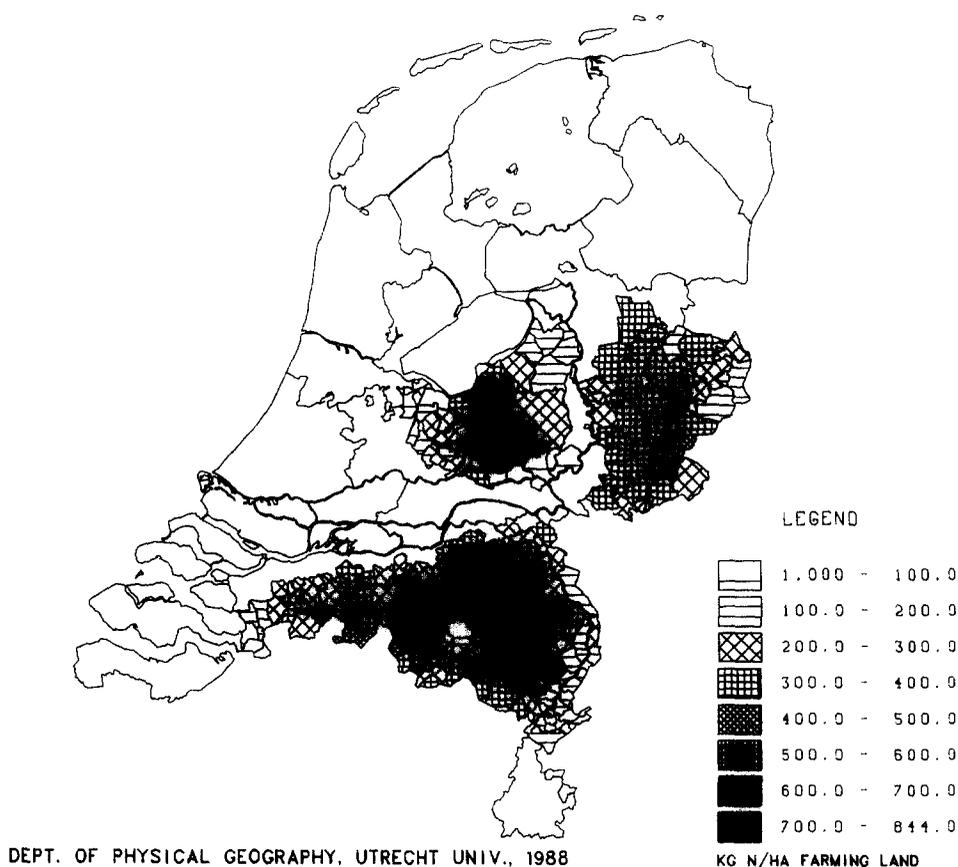


Fig. 2: Over-production of manure in Dutch sand districts, 1983, environmental approach, based on nitrogen (N).

From this figure it can be seen that in almost every municipality (234 on a total of 238) more nitrogen is produced than can be applied as a fertilizer. In fact there is only 0.20% of the total amount of farming land without an over-production of manure.

Highest mean over-productions are to be found especially in two regions: The "Geldersche Vallei"-are (central part of the Netherlands) and the "Peel"-area (eastern part of the Southern sand-district). Here, over-production mounts

up to 844 kg N per ha of farming land.

The over-production of animal manure in the Dutch sandy soil districts in 1983 totals up to 35.2 million m³, which is about 79% of the total production of animal manure in these areas. About 57% of it consists of cattle slurry. The high application levels of fertilizer on grassland (up to 400 kg N/ha) reduce the allowed application of cattle slurry on grassland to a large extent.

The regional differences of the over-production of phosphorus in animal ma-

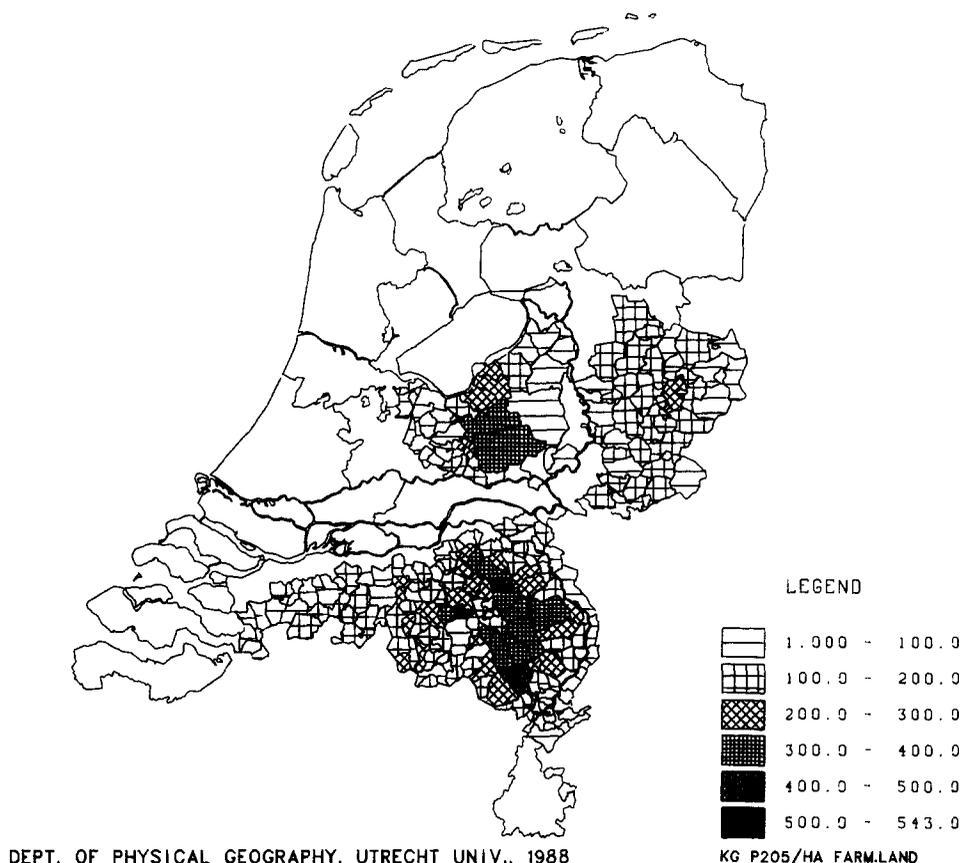


Fig. 3: Over-production of manure in Dutch sand districts, 1983, environmental approach, based on phosphorus (P_2O_5).

nure and fertilizer per municipality in 1983 shows the same pattern as the over-production of nitrogen (fig.3). Only 6 municipalities (or 0.58% of the total amount of farming land in the sandy soil districts) have no over-production. Highest values (up to 543 kg P_2O_5 /ha) occur in the Geldersche Vallei and Peel regions.

The mean over-production of phosphorus in the Dutch sandy soil districts totals up to 18.1 million m^3 , mainly consisting of pig slurry (64%). The differ-

ence with respect to nitrogen can be explained by the much lower amount of fertilizer-P applied to grassland and therefore a much higher application rate of cattle slurry.

3 The model "WATRUU": calculated groundwater contamination with nitrate and phosphate

In section 2.1 the maximum allowed application levels of nitrogen and phospho-

rus were calculated according to the environmental point of view. The above this level produced quantities are available for denitrification and leaching (N) or for fixation (and leaching) (P). Since it is assumed that the Dutch agricultural used sandy soils have reached an equilibrium with respect to the organic matter content (2.1.1), the total over-production of nitrogen may be regarded consisting of inorganic nitrogen only.

In order to deal with spatial effects of the landspreading of (animal) manure, the model WATRUU has been developed to calculate the mean nitrate and phosphate concentration of the upper groundwater in watershed areas based on the output from MANRUU (VISSERS et al. 1985).

These catchments (in area ranging from about 200 to more than 10,000 ha) must be regarded as hydrological units, in which spatial relations by ground- and surface water between an infiltration and seepage zone occur. In WATRUU a total mixing within a catchment is assumed of groundwater that infiltrates in agricultural (potentially contaminated) and in natural (potentially uncontaminated) parts.

3.1 Nitrate

As a result of mineralization and nitrification most nitrogen in sandy soils under aerobic conditions is present as nitrate (NO_3). Nitrate in soil is not subject to any adsorption or fixation processes, and will leach to the groundwater under influence of percolating rainwater. Under anaerobic conditions nitrate is subject to denitrification.

The denitrification rate is strongly dependent on the content of organic matter, the depth of the watertable, the ox-

igen content of groundwater, and the transmissivity of the substratum (DAY et al. 1978). These parameters vary widely, even on a local scale, which causes the denitrification rate in sandy soils to vary from less than 20% to about 80% of the available nitrate (RIJTEMA 1980, KOLENBRANDER 1981). The model WATRUU calculates nitrate leaching at both levels, indicating the maximum and minimum nitrate leaching respectively.

The mean nitrate concentration in the upper groundwater is calculated by dividing the total nitrogen loss by the total net annual precipitation per watershed. Taking into account the mean effective porosity of sandy deposits, the mean calculated nitrate concentration is related to the upper meter of the phreatic groundwater.

Maximum nitrate leaching will occur in infiltration areas (deep watertables, high oxygen content, low organic matter content), especially when these are built up from coarse sand formations, such as morainic ridges or terrace deposits. Minimum nitrate leaching will occur in flat, low situated fine sandy textured seepage areas (high watertables, low oxygen content, high organic matter content). This means, that the mean calculated nitrate concentration at a denitrification level of 20% refers to the infiltration area of watersheds, and the mean calculated nitrate concentration at a denitrification level of 80% to the seepage area.

3.2 Phosphate

In section 2.2.2 it was already stated, that the total over-production of phosphate will be immobilized in the soil system by adsorption and precipitation.

The adsorption capacity of the soil is determined by the contents of iron and

aluminum, and by the buffer concentration of phosphate in soil moisture. Normally the buffer concentration is about 3 mmol P/l (VAN RIEMSDIJK 1983). At this level phosphate adsorption may be regarded as a downward moving piston front (LEXMOND et al. 1982; see also VAN DE ZEE et al. 1986). The downward velocity of this front can be calculated with the following formula (LEXMOND et al. 1982):

$$\delta y = \frac{O}{B * S} * 141 \quad (5)$$

in which

δy = velocity of downward movement (cm/year)

O = over-production of phosphate (kg P₂O₅/year)

B = bulk density of soil (1400 kg/m³)

S = sorption capacity of the soil (mmolP/kg)

The sorption capacity S not only depends on the above mentioned distribution of Fe and Al in the soil profile, but also on phosphate over-productions in the past by which the maximum sorption capacity partly is used up.

Based on a detailed study by VAN RIEMSDIJK et al. (1983) this residual sorption capacity is in the model WARTUUN set at a level of 14 mmol P/kg. In this sorption capacity over-productions from the past are taken into account. In practice values varying from 3.6 to 21 mmol P/kg in the top soil of several fields are found, as has been shown by VISSERS et al. (1985).

In the saturated zone far more soluble phosphates are formed. Therefore, when the saturation front reaches the groundwater table, phosphate leaching will increase rapidly (BREEUWSMA 1984). In fact, the whole over-production of phosphate may then contaminate groundwater. Because of this, most vulnerable

for phosphate leaching are soils in which high watertables occur, i.e. farming land in seepage zones.

At the moment, leaching of phosphate only occurs on a local scale (VAN RIEMSDIJK et al. 1983, DE WIT et al. 1986). Calculation of the phosphate contamination of groundwater therefore points at a mere future situation. In the model WARTUUN, these considerations are taken into account by calculating the phosphate concentration in shallow groundwater of only those watersheds in which, within a period of 10 resp. 25 years after 1983, the saturation front will have reached a depth of 25 cm, corresponding with the mean highest watertable in seepage zones. The periods of 10 and 25 years correspond with middle-long and long term planning respectively.

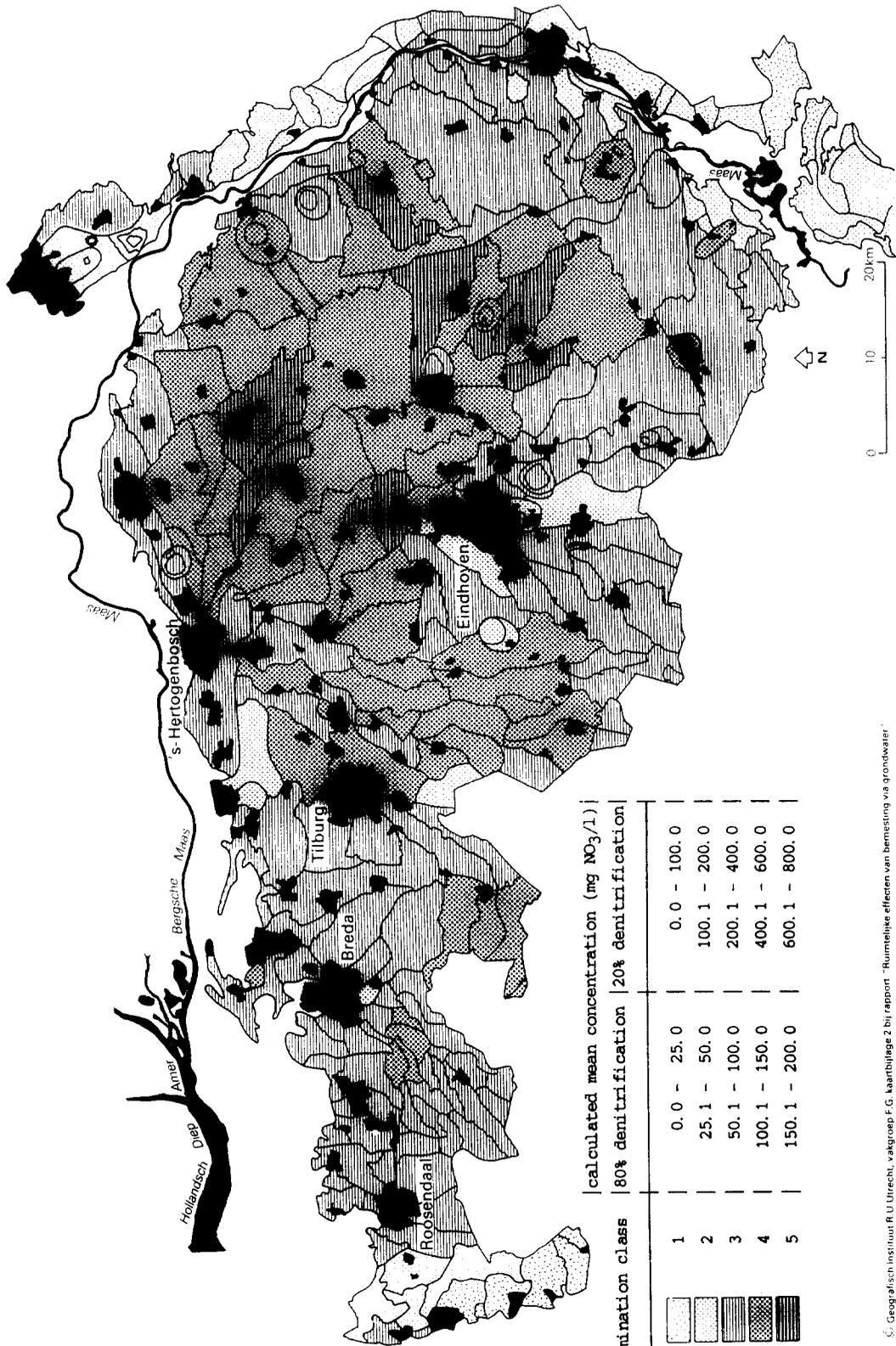
Of every municipality in a watershed that satisfies these conditions, the area of wet farming land is measured and multiplied with the phosphate over-production. It is assumed that neither dry farming land nor natural areas contribute to the total phosphate load of groundwater. This means that the phosphate concentration of shallow groundwater is only calculated for seepage areas of watersheds.

3.3 Results

3.3.1 Interpretation

The results of the calculation of the nitrate and phosphate concentrations of shallow groundwater are presented in figures 4–11.

In order to get an overview over the regional differences, it is assumed that landspreading of manure is proportional to the acreage of grassland and arable land. In practice however, some fields



contamination class	80% denitrification	calculated mean concentration (mg NO ₃ /l)	20% denitrification
1	0.0 - 25.0	0.0 - 100.0	0.0 - 100.0
2	25.1 - 50.0	100.1 - 200.0	100.1 - 200.0
3	50.1 - 100.0	200.1 - 400.0	200.1 - 400.0
4	100.1 - 150.0	400.1 - 600.0	400.1 - 600.0
5	150.1 - 200.0	600.1 - 800.0	600.1 - 800.0

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Fig. 4: Calculated nitrate concentration in shallow groundwater. mean concentration per catchment based on figures of 1983 — Southern sand district.