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Project

Area based monitoring and regional attenuation factor (APLM/2018/1)

Summary

Client

VLM

Supervision:

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Study and reporting:

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Objectives of the study

The objective of the study was twofold:

- On the one hand, the calculation of attenuation factors in the investigated areas, in order to refine the knowledge of the attenuation factor for nitrogen at the level of a small-scale catchment, and to establish a method so that it can also be used in a user-friendly way in other catchments in Flanders;
- And on the other hand, generating a dataset suitable to validate/calibrate the NEMO model and its sub-modules. The validation/calibration of the model itself was outside the scope of the study.

Selection of the test sites

From a list of 15 potential test areas proposed by the commissioner, 2 stream basins were to be chosen to be used in the project as test areas for the methodology. A selection methodology was developed for this purpose, based on 3 criteria. In a first step, a comprehensive Multi Criteria Analysis of the unsaturated zone was carried out that took into account 9 parameters: number of agricultural plots, number of nitrate residue measurements, number of years with nitrate residue measurements, soil texture, crops, after crops, fertilizer types, land use and drainage class. Furthermore, 2 other criteria were weighed: scale of the test site (because the methodology should be applicable over a wide range of watershed sizes) and the practical aspect of accessibility. Care was also taken to choose both catchments in different HHZ (different hydrogeological condition). Based on these considerations, the test areas Maldegem and Huise were chosen.

A selection of 18 plots within each catchment was made where data were collected during 2 winter periods for calibration and validation of the model EU-Rotate_N used by the project partners, and for the Flemish Government's model NEMO, and in this selection the experimental stations PCS (in Maldegem) and PCA (in Huise) had an important role (contacts with local farmers). On the basis of information on current and planned crops (the main crop groups represented) and fertilization (representative forms of fertilization), soil texture (sufficient variation) and presence or absence of artificial drainage (as many artificially drained plots as possible), the final selection was made. The plots in Huise were scattered throughout the entire watershed, while the plots in Maldegem were located partly in the western sub-basin of the Biest Watergang and partly in the eastern sub-basin of the Ede.

The main textures were well represented on the 36 plots, albeit no plots were found on loam, but rather on (heavy) sandy loam, and within each crop group as much diversity in soil textures as possible was sought. A large part of the selected plots were artificially drained, but sampling was not possible everywhere (drainage pipes sometimes can no longer be found, drains draining below the water level in the ditch). In terms of animal manure forms there was also a wide variability, with large shares of the main forms of fertilization (cattle slurry, pig slurry and cattle manure).

Plan of the measuring campaign

During the first 18 months, an extensive measurement campaign was implemented throughout the basin. Monitoring wells were installed, in which measurements were taken 13 times (monthly during winter, bi-monthly during summer). Groundwater levels and nitrate levels (with reflectometer) in groundwater were measured in the field (and in the absence of nitrate, iron was also measured). On two occasions, groundwater samples were also brought to the laboratory, and a complete analysis was performed. Well tests were conducted on the monitoring wells in each catchment for one day to determine hydraulic permeability. The drains in the catchments were mapped and for 18 months, nitrate content was determined monthly on the running drains, and the flow rate was estimated as accurately as possible. In addition, nitrate content was also determined 18 times at 10 locations in the surface water, including at the level of the flow meter. Drain water (from 10 selected drains) and the 10 surface waters were also analyzed 2 times in the laboratory. Moreover, a mandatory option was included, whereby for 12 months the analysis of a sample near the flow meter was carried out twice a month. The intention was that these measurements would run in parallel with continuous flow and nitrate measurements at the flow meter by VMM. In Huise these continuous measurements were indeed made available. A groundwater flow model of both catchments was prepared using the MODFLOW code.

In the first 18 months, all 36 selected plots (18 per study area) were sampled at 3 time points for measurement of soil mineral N, and in addition, general soil parameters were also determined. Macrorhizons were installed on a selection of plots for measurement of nitrate concentrations in soil water at the bottom of the rooting zone. Data were collected on applied organic fertilization (including nutrient analyses) and from crops (including yields and N and P contents). For each of the two catchments, the data already collected from the "Nitrate Rich Sources" project were further supplemented, extending the datasets to 2019.

Validation and calibration of the EU-Rotate_N model

With the collected data, model simulations were run with the EU-Rotate_N model (which had also been similarly deployed in a previous project for the VLM) on a selection of 10 plots, focusing on a diversity of soil textures and crops, and these simulations were validated using above-ground N yield, Nmin from 0-90 cm, soil moisture content, nitrate concentration at 90 cm and nitrate concentration in drainage water. For larger deviations between simulations and measurements for any of the above parameters, it was checked whether a limited calibration could provide improvement. In general, the simulations were satisfactory. For the sandy soils in Maldegem, the measured soil moisture contents at the end of winter were mostly underestimated by the simulations, perhaps due to shallow groundwater levels, which cause saturation of the soil profile. Simulated weighted average nitrate concentrations in leachate were usually within or slightly above the range of measured nitrate concentrations in leachate, with large differences between concentrations measured in soil water (using macrorhizons) and in drainage water. This may be because of mixing with partially reduced groundwater, and because due to late winter saturation of the soil profile, more denitrification may also occur than is simulated. N uptake at harvest was simulated quite well for most crops (potato, silage corn, winter wheat, winter barley, triticale, permanent pasture, green beans) even without calibration, but for sugar beet and temporary pasture an increase in target yield was necessary to achieve good validation. The N uptake of catch crops (grass, mustard, cut rye) was sometimes overestimated and sometimes underestimated before calibration. Discussions with the farmers involved pointed out that conditions during and shortly after sowing determine the growth and development of the catch crops. This effect is not very well simulated by the model, in fact the user is supposed to input whether the catch crop is more likely to develop poorly, moderately or well.

Calculation of nitrate input to groundwater with the EU-Rotate_N model

The EU-Rotate_N model was used to simulate the evolution of groundwater recharge and nitrate content in the soil leachate during the period 1969 to 2020 (53 years), using an area-wide regular grid with the EU-Rotate_N model run for each grid point. All parameters and input data were assigned to the related grid points from plot level. This provided the NO3 concentrations, drainage amounts, and thus the NO3 load that eventually reaches the groundwater from the bottom of the root zone, which serves as input to the saturated zone model, for each grid point. The average groundwater recharge over the entire simulation period at Huise is 160.2 mm/year, and the average since 2010 is 165.5 mm, despite the occurrence of dry summers in recent years. The annual values vary between ca 100 (e.g., 2011) and ca 300 mm (e.g., 2010), which is still a fairly wide range. Nitrate levels in soil leachate in Huise show a sharp increase in the first half of the 1970s, remain high and peak around 1990, with concentrations up to more than 1000 mg/l. This is followed by a decline until around 2005, after which concentrations fall below 300 mg/l. Over the last 10 years, they have fluctuated between 100 and 250 mg/l. The average groundwater recharge over the entire simulation period in Maldegem is 228.7 mm/year, and the average since 2010 is 267 mm. During some wet years, the recharge exceeds 400 mm, but in dry years it can drop to less than 100 mm. Also in Maldegem, nitrate levels rise sharply in the first half of the 1970s, and remain high until around 1990, with concentrations exceeding 1000 mg/l. After 1990 the levels decrease with a stabilization from about 2010 onwards. After 2010, concentrations are mostly between 100 and 150 mg/l.

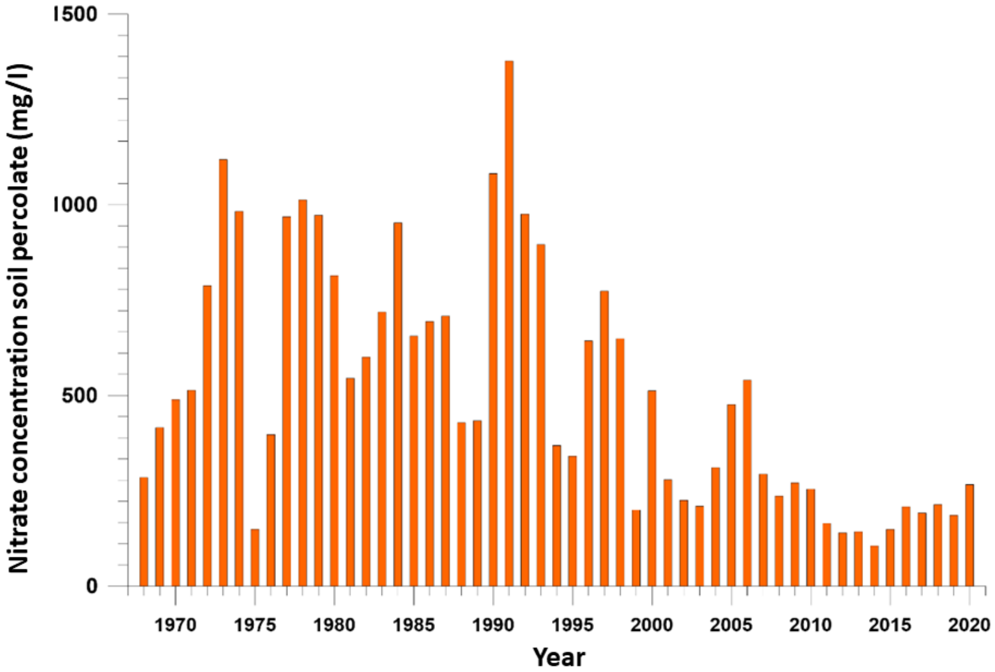


Fig 1a. Average nitrate concentrations in the soil percolate (1968-2020) calculated with the EU-Rotate_N model for the Huise test site

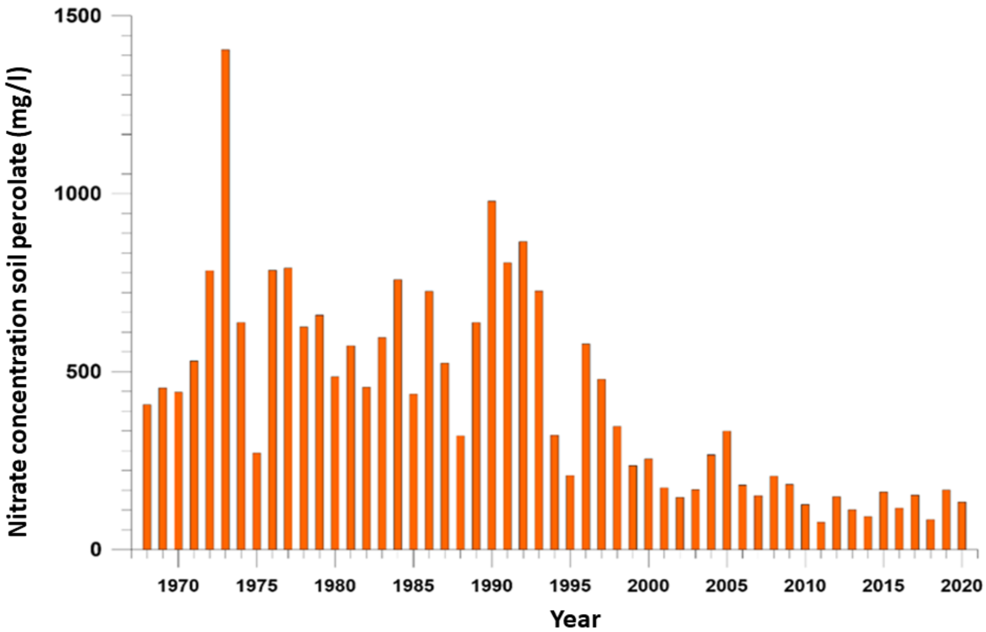


Fig 1b. Average nitrate concentrations in the soil percolate (1968-2020) calculated with the EU-Rotate_N model for the Maldegem test site

Interpretation of the measurement data

From all measurement data and interpretations conducted in the two test areas, a conceptual model was developed for both sites to understand the occurrence of nitrate in ground and surface water.

In Huise, drainage pipes are the main source of nitrate, and nitrate levels are especially high in the upstream (western) section, which receives water from the top of the hill which is highly oxidized. Downstream, nitrate is diluted. Nitrate levels in groundwater are highly variable, especially spatially. The phreatic layer here consists of more loamy deposits that have a smaller permeability. Flow occurs in this aquifer mainly vertically to the underlying sands of the Ypresian Aquifer system. As a result, nitrate concentration is mainly determined by local inputs. Some monitoring wells have systematically low concentrations, others systematically high concentrations, so the range of nitrate concentrations is very large. The drainage pipes almost always provide oxidized shallow water with high nitrate levels. In the Plank Brook water itself, nitrate levels decrease downstream. The continuous nitrate measurements show that flow and nitrate peaks can be both positively (in spring and summer) and negatively (in fall) correlated.

In Maldegem, especially in the southern part of the study area, the tertiary clay substrate occurs at shallow depth, sometimes at a depth of less than one meter. In this part of the area, the phreatic layer falls dry in summer and there is no lateral groundwater flow. Only in the deepest parts of the incised valleys, corresponding to the current alignment of the watercourses, there is flow throughout the year. But here the top of the reduction zone is only a few meters deep, so that in the summer, when the drainage pipes have stopped running, mainly reduced and nitrate-poor groundwater feeds the streams. Nitrate concentrations are then also low. But in winter, many drainage pipes are flowing and nitrate inputs rise very sharply. The drainage pipes have high concentrations of nitrate, but measurements show that both flow rates, the start and stop of flow, and the nitrate concentrations themselves vary greatly from drainage pipe to drainage pipe. Their influence is very large, but difficult to predict. On the other hand, the number of drainage pipes in the large drainage basin of Maldegem is too large to monitor them all.

Deduction of attenuation factors: methodology and results

A major objective of this project is to deduce attenuation factors for groundwater and for surface water. Attenuation factors are defined as the ratio between the nitrate concentration in groundwater (for AF GW), respectively in surface water (for AF OW) at one hand, and the nitrate concentration in the soil leachate on the other hand. A low AF will thus imply strong lowering of nitrate in groundwater/surface water compared to the concentration that is leached out of the soil profile, due to processes occurring on the water's pathway, such as nitrate reduction and dilution. In this project, we have developed a methodology in which we have concretised the precise meaning and method of calculation of "nitrate concentration in groundwater", "nitrate concentration in surface water", "nitrate concentration in the soil percolate" (where, when, averaging or not, …) . Other studies may well give a different interpretation to these concepts, to define the attenuation factor.

A methodology was developed to derive surface water attenuation factors (AF OW) in the two test sites, taking into account the water balance of the test areas. This allows quantifying the main components contributing to the observed nitrate levels. These are groundwater inflow (baseflow) and inflow from drainage pipes (drainflow) both of which can contribute high levels of nitrate, as well as surface runoff (runoff) and wastewater discharges which in turn have a diluting effect. To calculate the AF correctly, corrections must be made for this diluting effect. The methodology first establishes an average seasonal water balance, the balance components are budgeted per month. For groundwater recharge, the annual groundwater fluxes calculated with the EU-Rotate_N model are distributed over the year with weighting factors. Baseflow and drainflow are calculated with a combination of two linear reservoirs, namely one slow reservoir for groundwater recharge and one fast reservoir for drains. The distribution between the two is done using a fractionation coefficient. Discharges were estimated from the number of known discharge points and an average water consumption. Groundwater abstractions could be obtained through the DOV portal. The AF were calculated for the reference period 2010-2020 by comparing the monthly average measured levels at the MAP monitoring point, corrected for the diluting effect of runoff and wastewater discharges, with the calculated concentrations in the soil leachate. This results in monthly AF values that reflect seasonal fluctuation. In addition to this sophisticated method based on the water balance, the AF were also calculated in a simple manner by simply comparing the average measured nitrate concentration at the MAP monitoring point without corrections with the nitrate concentration in the soil leachate.

Applied to the Huise test site, with the simple method without correcting for dilution, this gives AF OW that are around 5 in winter, but reach well over 10 in summer. In the Maldegem test site, the variation in AF over the season is much greater. The lowest nitrate levels and thus highest AF occur in spring, when the drains have stopped flowing. The AF is then above 10. After this, the AF drops toward the following winter, and is only around 2.

When correcting the nitrate concentrations with the water balance, the variation of AF over the year at both sites is remarkably smaller. In summer months, the corrected AF is lower because runoff in these months is higher due to the occurrence of summer thunder storms. This runoff is diluting, leading to an increase of the uncorrected AF. When correcting for dilution, the AF is lowered. In summer, the corrected AF at both sites is between 7 and 8.

However, for other MAP drainage areas, no water balance will be available and no EU-Rotate_N simulations will have been performed to simulate nitrate concentration in the soil leachate. Consequently, a simpler, more pragmatic approach needs to be followed here. In this MAP drainage areas, an empirical method is proposed that estimates the nitrate concentration in the soil leachate from available nitrate residue measurements and average groundwater recharge, as available in an area-wide grid of Flanders and calculated with the WETSPASS model. A dataset was compiled covering the period 2007 to 2021. By dividing the average nitrate residue by the volume of groundwater recharge, the average nitrate concentration in the soil leachate can be calculated. It is assumed here that the nitrate residue leaches out completely during the current year. The AF are then determined by comparing the average concentration in the soil leachate over the period 2007-2021 with the monthly average nitrate concentrations at the MAP monitoring point. This provides an AF value per month, so that a picture of the seasonal variation of the AF can be obtained. For smaller MAP runoff areas, (too) few nitrate residue measurements may be available within the basin itself. In that case, the slightly wider area can be looked at under the assumption that the average nitrate concentration of the soil leachate of the extended area is the same as in the MAP area in question.

This empirical method was tested on 9 (out of 10) test areas of the nitrate-rich sources project. Indeed, for these, EU-Rotate_N simulations had also been run and the soil leachate concentration calculated from the nitrate residue could be compared with the EU-Rotate_N simulations. This was also done for the two test sites Huise and Maldegem. The comparisons showed that the calculation method based on the nitrate residue underestimated the nitrate concentrations of the soil leachate compared to the simulations with the EU-Rotate_N model. However, a correction factor could be derived from the equation to compensate for this bias. It amounts to 1.71. As a result, monthly AF for the 11 sites were obtained. These could be averaged to seasonal (quarterly) AF. The following conclusions can be drawn from this seasonal AF OW:

- In test sites with high winter peaks and low summer concentrations, such as Luikbeek (Staden), Maldegem, Assenede and Huise, the AF OW during winter peaks is between 4 and 6. In summer, when concentrations go to a minimum, the AF rises to values between 10 to more than 20.

- In test sites where concentrations peak in summer and are lower in winter, such as Asse, Balegem and Lubbeek, the AF OW during summer peaks is around 5. In winter, the AF here is higher, between 5 and 10.

- On the Campine plateau, in Peer, and in the Noorderkempen, in Brecht, the AF OW are around 2 resulting in high nitrate levels at the MAP monitoring point. In Overijse and in Wortegem, the AF are slightly higher, between 3 and 5, but there is little difference between winter and summer, again resulting in rather high nitrate concentrations.

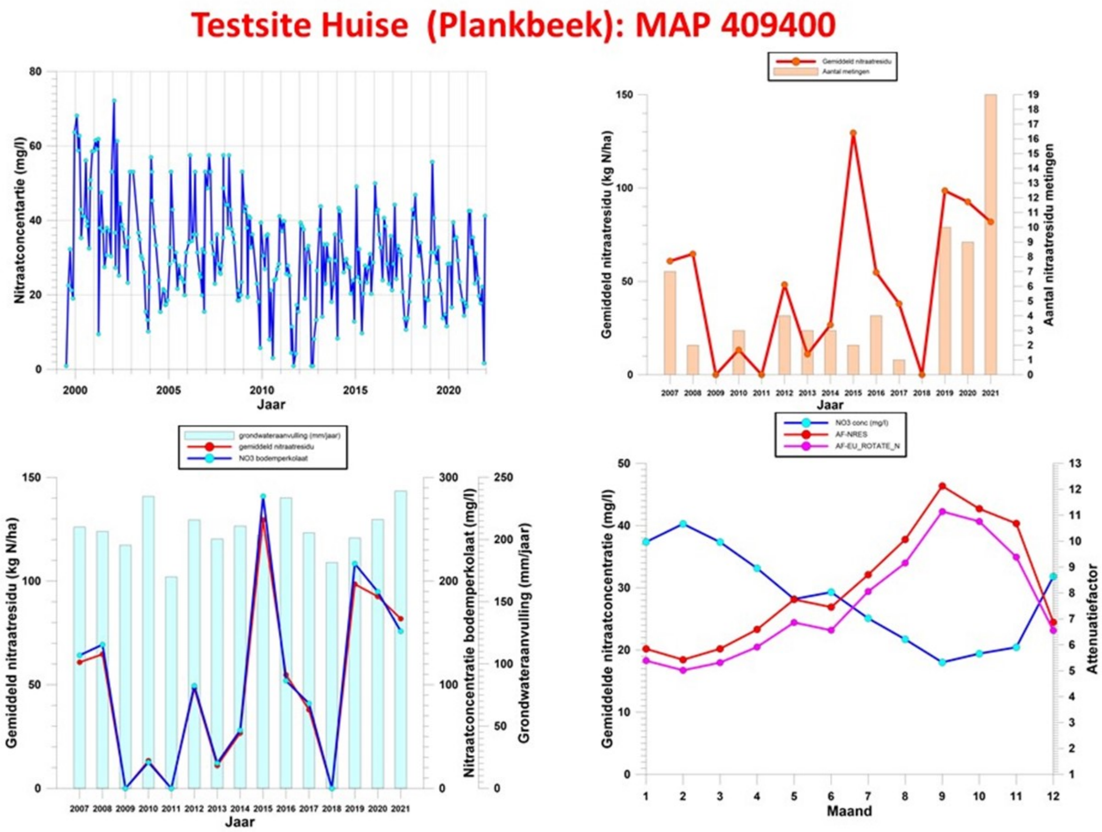


Fig. 2a. Attenuation factor surface water: results from the empirical model for the Huise test site

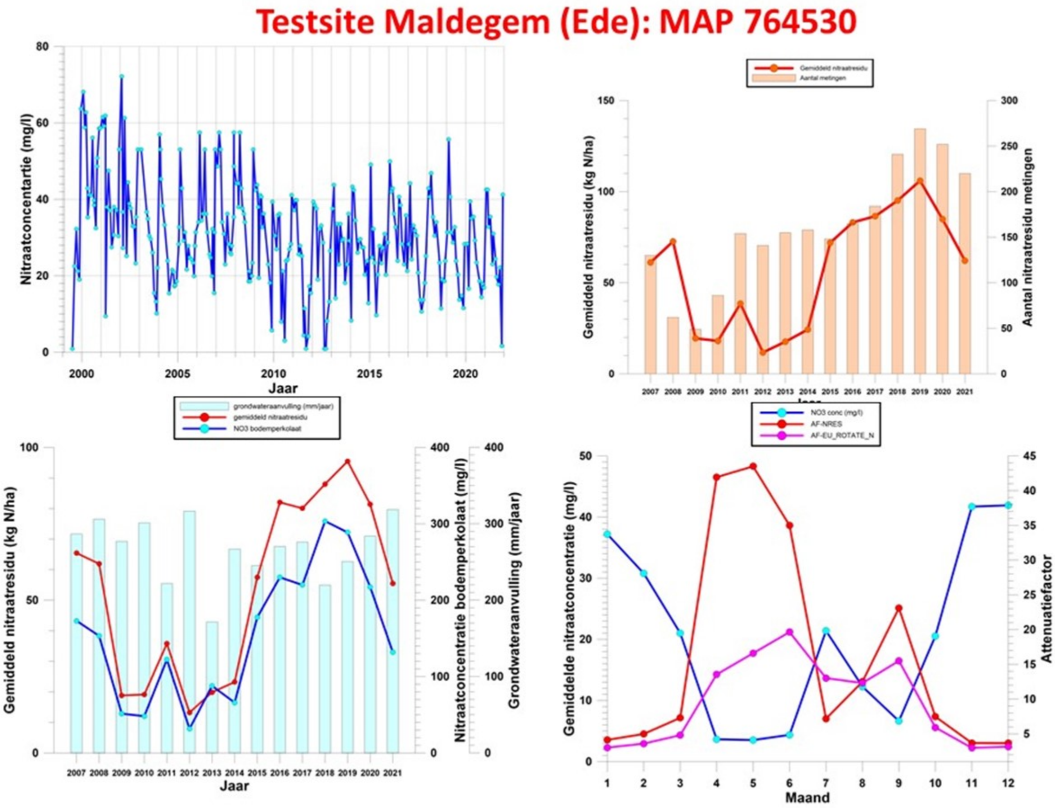
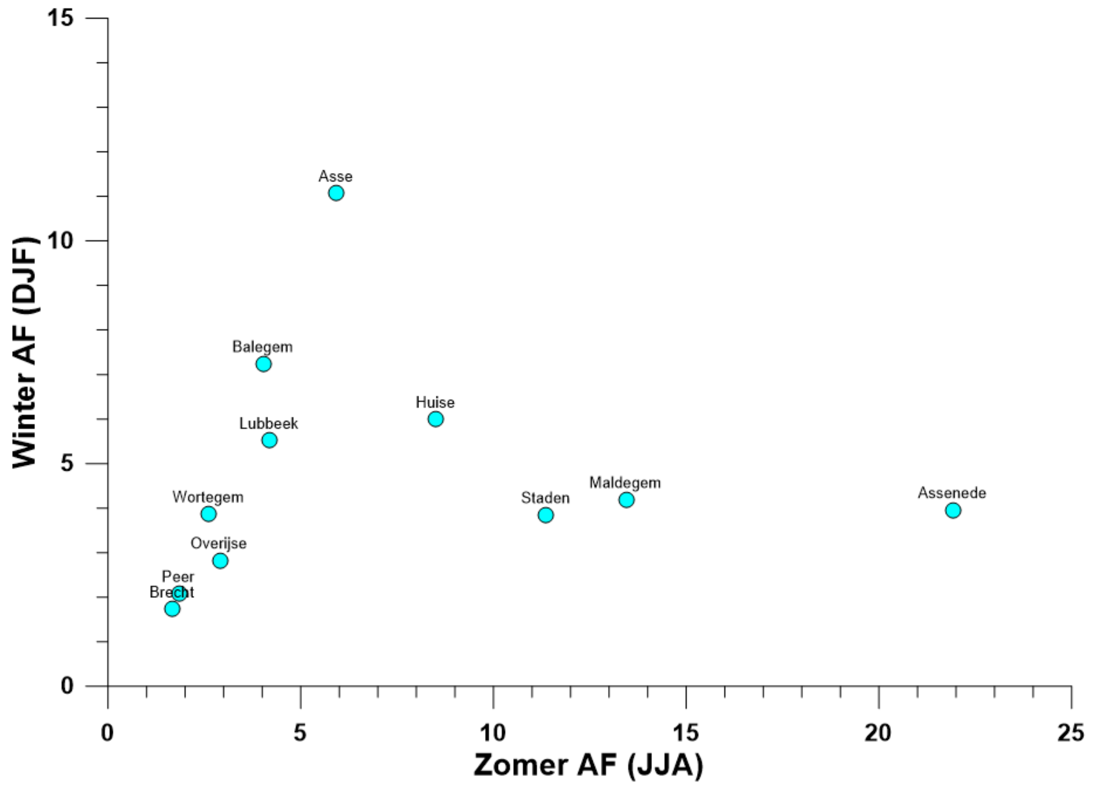


Fig. 2b. Attenuation factor surface water: results from the empirical model for the Maldegem test site



Figuur 3. Crossplot of the AF surface water in summer and winter, determined with the empirical method, for the 11 test sites.

Finally, groundwater attenuation factors (AF GW) were also determined. Attenuation factors groundwater should be derived by comparing the nitrate concentration in the soil leachate with the nitrate concentration in the shallow groundwater. Here, the ages of the groundwater were taken into account. Based on the filter depths of the monitoring wells, the travel time from the water table to the filter is calculated from estimated vertical velocities. Then, using this travel time, each nitrate measurement is time-referenced to the soil leachate the nitrate concentrations of which were calculated with EU-Rotate_N. From the ratio, the AF GW can then be determined.

In the test site Huise, however, widely varying AF were found in this way, so its significance was somewhat questionable. Therefore, the AF GW was more simply determined by comparing the average of all measurements in groundwater with the average nitrate concentration in the soil leachate during the last 5 years. Thus, an AF GW of about 7.6 was obtained.

In Maldegem, the time-referenced method did yield consistent AF values , which corresponded well with values calculated in the simple way. The AF GW is between ca 2.5 and 2.6 in the Maldegem test site.

Recommendations

Based on the results of the study, the following recommendations were derived:

Recommendation 1

Calculating AF is a particularly complex exercise, requiring multidisciplinary teams to work for many years to reach a given result. This project, with limited resources and in a limited time frame, has proposed an innovative and pragmatic methodology that can calculate AF from a limited set of measurement data. When using AF in policy instruments, one should be aware of the fact that these AF have a rather large uncertainty margin, which, however, cannot be precisely quantified statistically. Policy measures based on AF should therefore be taken cautiously, monitored closely, and adjusted if necessary.

Recommendation 2

For AF groundwater: these do not depend on MAP monitoring points but on the availability of monitoring wells, in this case those of VMM's shallow groundwater monitoring network (PM8). Thus, the regions for which AF GW are established need not be drainage areas. It would be best to choose these zones based on

- the location (= availability) of monitoring wells of PM8

- the HHZ zoning (hydrogeological condition).

A minimum of 5 monitoring wells is really necessary, and 10 is recommended. The monitoring wells should be located in areas where groundwater recharge occurs (no seepage areas) and should have the filter screen close to the water table.

Recommendation 3

For the AF OW, empirical method: a limiting criterion here is the number of nitrate residue measurements. Therefore, the empirical method is not suitable (recommended) for small upstream basins. The AF OW would be best determined on larger stream basins first. After that, zoom in on sub-basins.

Recommendation 4

Surface water attenuation factors should be determined monthly/seasonally, because of the often observed seasonal variation of surface water nitrate concentration. This is not the case for groundwater attenuation factors. Obviously, for AF OW, the smaller values are the most problematic, and policy should be focusing on them.

Recommendation 5

In the framework of this project, attenuation factors were determined in different ways. The surface water attenuation factor was determined monthly (and then averaged to seasonal: quarterly), on the one hand using a balance method and relying on EU-Rotate_N calculated concentrations in the soil leachate, and on the other hand empirically and based on nitrate residue measurements. We recommend the use of the latter empirical method for application to all catchments, because of the lower data requirements.

The groundwater attenuation factor was determined, on the one hand, by back-calculating for each individual monitoring well the age of the groundwater in the filter screen to the soil leachate produced in that year. A simplified method consists in calculating AF GW by comparing the average of all measurements in groundwater (made during the last year or so) with the average nitrate concentration in the soil leachate during the last 5 years (assuming that travel times to the well screens will be 5 years or less, as all wells are close to the watertable). We recommend the use of this latter simple method for application to all watersheds.

Recommendation 6

Nitrate residue measurements are an important source of information to pragmatically calculate attenuation factors, which allow estimating nitrate pollution of ground and surface waters. It is recommended that they be systematically processed to deduce a proxy for the soil leachate nitrate concentrations, in order to calculate attenuation factors to estimate nitrate concentrations in ground- and surface water. It should be kept in mind, however, that these estimates should not be made on an individual basis, but that averaging across the catchment is necessary. A rule of thumb for the number of data needed to calculate a reliable mean is that at least 5 measurements are needed. If fewer than 5 nitrate residue measurements are available in a watershed, the area should be expanded to estimate an attenuation factor.

Recommendation 7

In the Nitrate Rich Sources project, we found that nitrate concentrations in water leaching from soil were high in all test areas. This was also the case for the test areas in this project. Considering that groundwater of different ages are mixed in the phreatic (upper) aquifer, this means that the nitrate concentration in the leachate is too high to fall below 50 mg nitrate/l without natural diminution (attenuation). We can lower the average nitrate percolation in the basin by reducing nitrate inputs from agriculture. Attenuation factors can be used to estimate future scenarios, which calculate nitrate concentrations in ground- and surface water when nitrate residues in soil are reduced.

There are many ways to influence and decrease nitrate residues, and thus nitrate percolation from agriculture. For example, judicious fertilization, according to the 4J' (right dose, right time, right type of fertilizer and right application technique) can reduce nitrate residue.

In addition to nitrate percolation from the soil profile, also artificial drainage, the thickness of the oxidation zone and the travel times of groundwater determine nitrate concentrations in surface water. These elements co-determine the attenuation factors of a catchment. We can influence them to a lesser extent (drainages) or not (thickness of oxidation zone and travel times), but they are important for response times to measures taken at the surface. Response times will vary from only a few years for MAP monitoring points influenced mainly by drains, to decades for MAP monitoring points located in hilly areas such as e.g. the Flemish Ardennes. To detect 90% of the effect of an action taken at the MAP monitoring point, it is necessary to wait about three times the median age of the groundwater. So if the median age is 5 years, the effect will only be largely realized after 15 years.

Recommendation 8

In the Nitrate Rich Sources project we established the important influence of drainages, on nitrate contamination of surface water, and this project reconfirmed this influence. The presence of drainage pipes contributes significantly to the fact that surface water attenuation factors are significantly lower in winter than in summer. A major bottleneck is that little is known about artificial drainages. Drainage pipes are often not known, and/or it is not known to what extent they are still effective. There is a need for measurements of nitrate concentrations at drainage pipes to better assess the impact of drainage on surface water quality in areas with much artificial drainage.

Recommendation 9

It is recommended to test the methodology further in follow-up research, possibly in other areas where AF are calculated in other ways, so that AF obtained using this methodology can be compared with those obtained using a different methodology, whereby we initially consider cases abroad where nitrate residue measurements would be available. Furthermore, the AF from this study could also be compared with those from D'Haene et al. (2022) and possible discrepancies could be used to identify possible problems.

D'Haene, K; De Waele, J; De Neve, S; Hofman, G. 2022. Spatial distribution of the relationship between nitrate residues in soil and surface water quality revealed through attenuation factors. Agriculture Ecosystems & Environment, 330, Article number 107889. DOI 10.1016/j.agee.2022.107889