MASTER'S THESIS

Persistence of Eutrophicated Vegetation on Banks of Recharge Ponds in Dune Area Meijendel, the Netherlands

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Thesis

Persistence of Eutrophicated Vegetation on Banks of Recharge Ponds in Dune Area Meijendel, the Netherlands

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Persistence of Eutrophicated Vegetation on Banks of Recharge Ponds in Dune Area Meijendel, the Netherlands

Persistentie van geëutrofieerde vegetatie op oevers van infiltratieplassen in duingebied Meijendel

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Picture on front page: bank vegetation near the boat - and recharge water inlet point of recharge pond "26.1" in Meijendel (own collection)

Content

Abstract

In Meijendel, a coastal dune area used for drinking water production, the supply of nutrient rich river water to recharge aquifers since 1955 has resulted in eutrophication of the vegetation. Despite phosphate stripping of the recharge water since 1975, eutrophication has persisted, whereas the management target is a more biodiverse mesotrophic vegetation. This thesis explores possible causes of the persistent eutrophication, focussing on the complex interactions between nutrients, vegetation, and hydrology. As a measure of eutrophication, the mean N-Ellenberg value (N-value) of the bank vegetation of two recharge ponds was determined. Also orthophosphate and nitrate concentrations of soil, groundwater and nearby surface water and hydrological parameters were measured and relationships between these factors statistically analysed. The N-value is associated with nutrient concentrations in soil and groundwater, orthophosphate in surface water, and the distance to the recharge water inlet. The concentration of orthophosphate in soil and groundwater is associated with the groundwater flow rate. Although no direct relationship has been demonstrated between mineralisation and N-value, its influence cannot be ruled out either. On lower banks surface water influence certainly predominates, on higher banks mineralisation could play a (stronger) role. Remarkably, concentrations of orthophosphate in soil and water were below target values for a similar habitat type after restoration. It appears that nutrient concentrations in soil and groundwater can be relatively low in the persistence of eutrophic vegetation, lower than concentrations for establishing such vegetation composition. The difference in N-value between the two ponds could be explained by a difference in the amount of sludge in the ponds which may absorb orthophosphate in winter and release it early in spring. To regain a more diverse dune specific vegetation, a complete reset is necessary, by removing the current vegetation and the upper (acidified and organic matter enriched) soil layer down to the calcareous sand. Regular sludge removal of the bottom of the recharge ponds may prevent accumulation of orthophosphate. More research is needed on the exact mechanisms behind the persistence of eutrophic vegetation at low nutrient concentrations. The roles and influence of nutrient loads and - fluxes, acidity, humidity, phosphate binding and release, and vegetation composition itself, are not yet sufficiently understood.

Samenvatting

In Meijendel, een kustduingebied dat wordt gebruikt voor drinkwaterproductie, heeft de aanvoer sinds 1955 van voedselrijk rivierwater om grondwaterbuffers aan te vullen geleid tot eutrofiëring van de vegetatie. Ondanks de verwijdering van fosfaten uit het infiltratiewater sinds 1975 is de eutrofiëring doorgegaan, terwijl het beheerdoel een meer biodiverse mesotrofe vegetatie is. In deze thesis worden de mogelijke oorzaken van de aanhoudende eutrofiëring onderzocht, waarbij de nadruk ligt op de complexe interacties tussen nutriënten, vegetatie en hydrologie. Als maat voor eutrofiëring werd de gemiddelde N-Ellenbergwaarde (N-waarde) van de oevervegetatie van twee infiltratieplassen werd bepaald. Ook werden orthofosfaat- en nitraatconcentraties van bodem, grondwater en nabijgelegen oppervlaktewater en hydrologische en ruimtelijke parameters gemeten en de relaties tussen deze factoren statistisch geanalyseerd. De N-waarde bleek gerelateerd te zijn aan nutriëntenconcentraties in bodem en grondwater, orthofosfaat in oppervlaktewater en de afstand tot het inlaatpunt van het infiltratiewater. De concentratie van orthofosfaat in bodem en grondwater wordt beïnvloed door het grondwaterdebiet. Hoewel er geen direct verband is aangetoond tussen mineralisatie en N-waarde, kan de invloed ervan ook niet worden uitgesloten. Op lagere oevers overheerst zeker de invloed van het oppervlaktewater, op hogere oevers zou mineralisatie een (sterkere) rol kunnen spelen. Opmerkelijk is dat de concentraties van orthofosfaat in bodem en water onder de streefwaarden lagen voor een vergelijkbaar habitattype na renovatie. Het lijkt erop dat de nutriëntenconcentraties in bodem en grondwater relatief laag kunnen zijn bij het voortbestaan van een eutrofe vegetatie, lager dan de concentraties voor het tot stand brengen van een dergelijke vegetatiesamenstelling. Het verschil in N-waarde tussen de twee infiltratieplassen zou kunnen worden verklaard door een verschil in de hoeveelheid slib in de plassen, dat in de winter orthofosfaat kan binden en vroeg in het voorjaar afgeven. Om weer een meer diverse duinspecifieke vegetatie te krijgen, is een volledige reset nodig, door de huidige vegetatie en de bovenste (verzuurde en met organisch materiaal verrijkte) bodemlaag tot op het kalkhoudende zand te verwijderen. Regelmatige verwijdering van slib van de bodems van infiltratieplassen kan accumulatie van orthofosfaat voorkomen. Er is meer onderzoek nodig naar de exacte mechanismen achter het voortbestaan van eutrofe vegetatie bij lage nutriëntenconcentraties. De rol en de invloed van nutriëntenbelasting en -fluxen, zuurgraad, vochtigheid, fosfaatbinding en -afgifte, en de vegetatiesamenstelling zelf, zijn nog onvoldoende begrepen.

1. Introduction

Meijendel, a dune area in South Holland used for drinking water production, is a protected nature area managed by the drinking water company “Dunea”. From the middle of the 19th century, water is extracted from the freshwater aquifer under the Dutch coastal dunes for the production of drinking water. Over time more water was extracted than added by natural precipitation. In Meijendel, in 1955, artificial recharge of aquifers was started to prevent desiccation and vegetation change. This is done by filling natural dune valleys with river water, creating managed aquifer recharge (MAR) ponds. In the first years since 1955 this seemed successful as the original vegetation returned in the areas fed by seepage water from the MAR ponds. However, this diverse oligo- and mesotrophic vegetation, specific for calcareous dune areas, soon was displaced by eutrophic vegetation. The nutrient-rich recharge water was believed to be the cause of this eutrophication process (Van Dijk, 1984). For this reason, from 1975 onwards, the recharge water is pre-purified by phosphate stripping (“P-stripping”), which led to a substantial decrease in the concentration of orthophosphate in the recharge water (Van Dijk, 1984). Research by Van Dijk (1984) confirmed that the nutrient content of the recharge water had caused the eutrophication, and identified the speed of supply of these nutrients to the plants via the groundwater flow as a major contributing factor. Van Dijk (1984) introduced the concept of the "External Nutrient Load" (ENL), defined as the product of the volume flow density of the water through the bank and the annual average nutrient concentration of the nearby recharge water. According to Van Dijk (1984) next to the external nutrient load, also the “Internal Nutrient Load” (INL) is relevant for plant growth, which is based on the mineralisation of organic matter. The INL could be significant as due to eutrophication, a substantial amount of biomass had accumulated on the banks. Van Dijk (1984) made it plausible that P-stripping (started in 1975), would decrease the ENL of P and make P the limiting nutrient, and thus would lead to a more diverse vegetation and a decrease in eutrophic plant species on the banks of recharge ponds. However, in the fall of 2020, the bank vegetation of the MAR ponds in Meijendel was still dominated by eutrophic species and the cover of shrubs and trees appeared to even have increased considerably (M. Werink, personal observation). The abundance of shrubs and trees may indicate a relatively undisturbed succession of eutrophic species (Berendse et al., 1998; Sýkora et al., 2004; Van Dijk, 1984). So, Van Dijk's prediction obviously did not come true.

Most of the literature on restoration of eutrophicated dune vegetation (Adema & Grootjans, 2003; Berendse et al., 1998; Ernst et al., 1996; Grootjans et al., 2002; Koerselman & Meuleman, 1995; Kooijman et al., 2020; Lammerts & Grootjans, 1997; Rhymes et al., 2014; Sýkora et al., 2004; Van der Hagen et al., 2007; Van Dijk & Grootjans, 1993) is about degradation and restoring of wet dune slacks and the drier parts of (Dutch) dunes affected by eutrophication in general. After Meltzer & Van Dijk (1986) no further research about the specific characteristics of nutrient supply around MAR ponds and the dominant role of groundwater flow velocity has been published, with the exception of the report on the redevelopment of the water extraction area Middle- and East dunes in Goeree (The Netherlands) by Aggenbach & Annema (2016). In general it appears that vegetation change due to eutrophication is persistent. Only reducing the nutrient load to the situation before eutrophication is often not sufficient for restoration (Perring et al., 2015; Suding et al., 2004).

A new, degraded, state of the ecosystem has regularly proved persistent and resilient and concepts such as "alternative (stable) states", "ecological thresholds" and "hysteresis" have been developed to explain the difficulty and complexity of reversing degradation (Groffman et al., 2006; Scheffer et al., 2001; Schröder et al., 2005; Suding et al., 2004). If certain thresholds are exceeded, an ecosystem can change relatively sudden from one state with a dominance of certain species, to another state with other dominant species. Hysteresis means that not always when a threshold is reached back again, the original state will be re-established.

Ecosystems (also newly arisen after, for example, exceeding thresholds by eutrophication) can be resilient due to certain feedback mechanisms that strengthen the conservation of species in an ecosystem. By modifying several features of the environment, including water, pH, soil elements, light, temperature, wind, fire or allelopathic toxins plant communities can modify the environment making it more suitable for that community. Wilson and Agnew (1992) named this process “vegetation positive-feedback switch”. Eutrophic plant species in dune areas grow fast early in the season and are competing for light (Lammerts & Grootjans, 1997; Van Dijk & Grootjans, 1993) and contribute to the increased production of organic matter by forming biomass (Ernst et al., 1996; Koerselman & Meuleman, 1996).

Scheffer et al. (2001, Table 1) suggest “positive feedback of plant growth” as a main cause of hysteresis in woodlands where the original herbaceous vegetation has shifted to woodlands by an event. They also state that feedbacks involve biological, physical and chemical mechanisms. In a recent study about coastal dune grasslands Kooijman et al. (2020) concluded that soil organic matter and pH play an important role in resilience to environmental change and affects nutrient availability, plant strategies and soil community composition and patterns.

Suding et al. (2004, p. 47) state “….. the dynamics of the degraded state are very different from those in the pristine or target state and that the trajectory to recovery will probably be different from that of degradation. In these systems, restoration efforts might need to manipulate more than the single dimension (factor or process) that led to the original collapse.”. They indicate that (among other things) species could influence biochemical cycling and possible restoration and “once species have changed ecosystem processes, positive feedbacks can increase the resistance of the system in its degraded state and make it resilient to restoration efforts.” (p. 48).

Alternative state models, particularly in situations of hysteresis, show that recovery could be slow (and costly) when the pressure is back to the point where recovery is expected “and depending on feedbacks, possibly could not occur at all”. (Suding et al., 2004, Box 2). A natural or managed perturbation then “could more directly influence the return trajectory”.

Top soil (organic matter) removal and mowing and removal of biomass are successfully used where eutrophication caused degradation. Selective removal of species causing strong feedbacks can also be used (Suding et al., 2004). Adema & Grootjans (2003) found that later successional species in wet calcareous dune slacks could lower phosphate binding of soil by releasing carbon dioxide, thus increasing phosphate availability to plant roots.

From studies that investigated the eutrophication of dune areas and the possibilities for restoration (Adema & Grootjans, 2003; Aggenbach et al., 2013; Aggenbach & Annema, 2016; De Groot, 1981; Ernst et al., 1996; Grootjans et al., 2002; Lammerts et al., 1992; Rhymes et al., 2014; Van Dijk & Grootjans, 1993; Van Oosterhoud et al., 1982), it can be concluded that the origin, fate, availability and cycling of nutrients in water and soil is complex, and dependent on acidity, soil organic matter and soil moisture content. Current understanding of these processes is insufficient, however, to explain the persistence of the eutrophicated vegetation in Meijendel.

1.1 Aim of the Research and Research Questions

The aim of this study was to better understand why the eutrophicated MAR bank vegetation in Meijendel has persisted for 40 years, despite the strong reduction in external P load. Given the research aim, the main research question was formulated as follows:

What is the relationship between nutrient load and the current state of the vegetation on the banks of managed aquifer recharge ponds in Meijendel?

This question leads to the following sub-questions:

1. How has the bank vegetation developed over the past 40 years?
2. How have the external and internal nutrient loads developed over the past 40 years?
3. What is the relationship between nutrient loads (orthophosphate, nitrate and ammonium) and associate variables (pH, distance to groundwater), and the occurrence of eutrophic species?

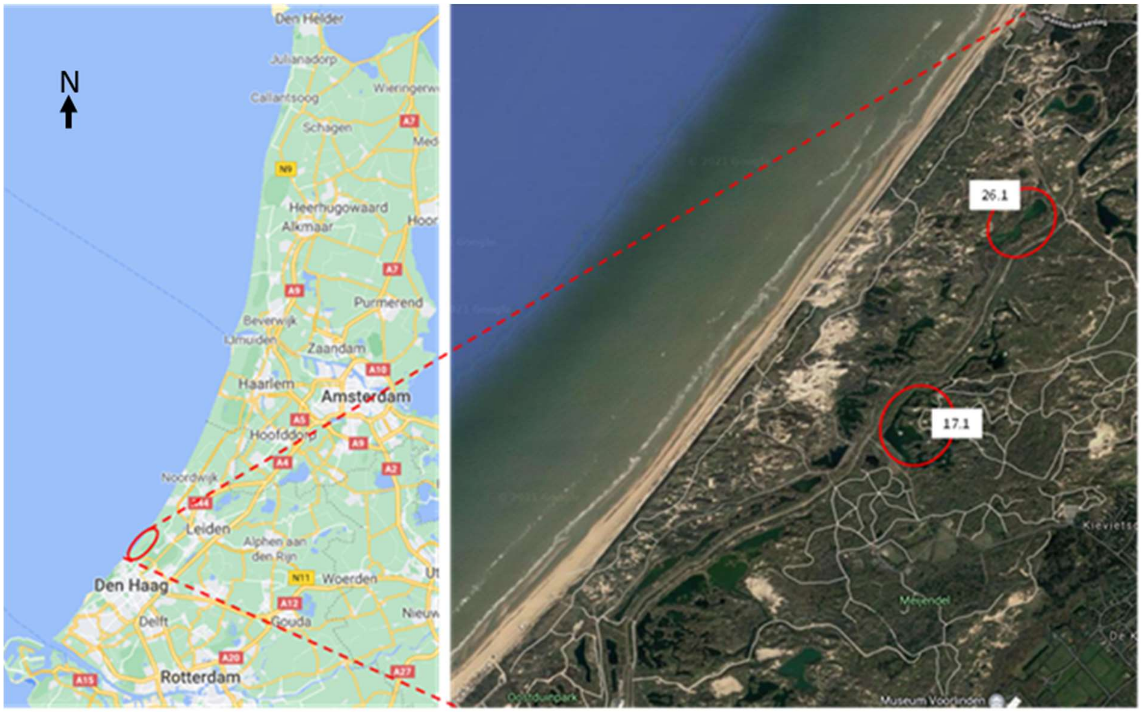
To answer these questions, relevant relationships between hydrological and chemical variables and the current state of the vegetation were investigated. The focus was on the relation between the ENL and INL and vegetation composition, as it was hypothesized that the INL plays an important role in the persistence of the eutrophicated bank vegetation. Based on the results, recommendations are given on how the nature management target of a more biodiverse mesotrophic vegetation can be achieved.

2. Methods

2.1. Study Site and Sample Plots

The study site Meijendel covers an area of 20 km^2 and is located at the coast of South Holland, to the north of The Hague (Den Haag, Figure 1A). Figure 1B depicts the location of the two studied MAR ponds (17.1 and 26.1). Both are considered to be representative of the MAR ponds in the area (H. van der Hagen, personal communication). Pond 17.1 is in the middle of the area. To the north- and southwest of this pond the water extraction wells are situated, a few meters lower than the MAR pond water level. On the "active banks" (the banks towards the extraction wells) of the pond the groundwater flow rate is relatively high. The active sides of pond 26.1 are on the south- and northeast. For each pond ten sample plots were selected, evenly distributed along the banks (Figure 2). Each sample plot measured 2m (along the waterside) by 1m. In pond 17.1 the recharge water inlet point is near plot 1, and in pond 26.1 near plot 4. Figure 3 shows a schematic representation of a sample plot and the adjacent part of the pond, including an overview of the variables measured.

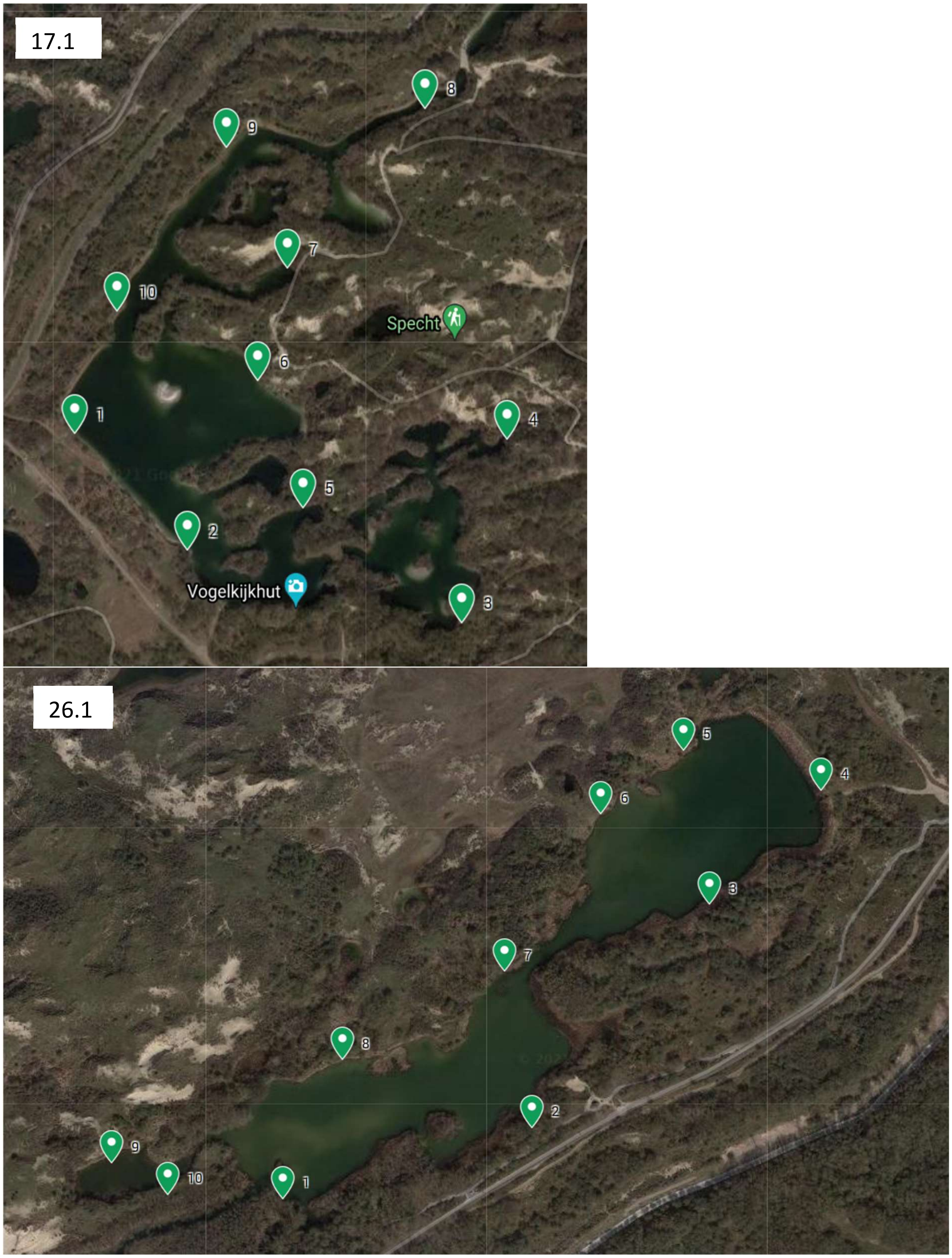
Figure 1
Location of the study



Note. The left map (A) shows the location of Meijendel (red ellipse), the right map (B) shows the location of the two ponds (in the red ellipses) where the bank vegetation was studied. Source of the maps: Google Maps.

Figure 2

Sample Plots



Note. The sample plots around the MAR Ponds.
Source of the maps: Google Maps.

2.2. Definition of Terms and Measurements

Below follows a description of relevant terms in the context of the study.

Nutrients

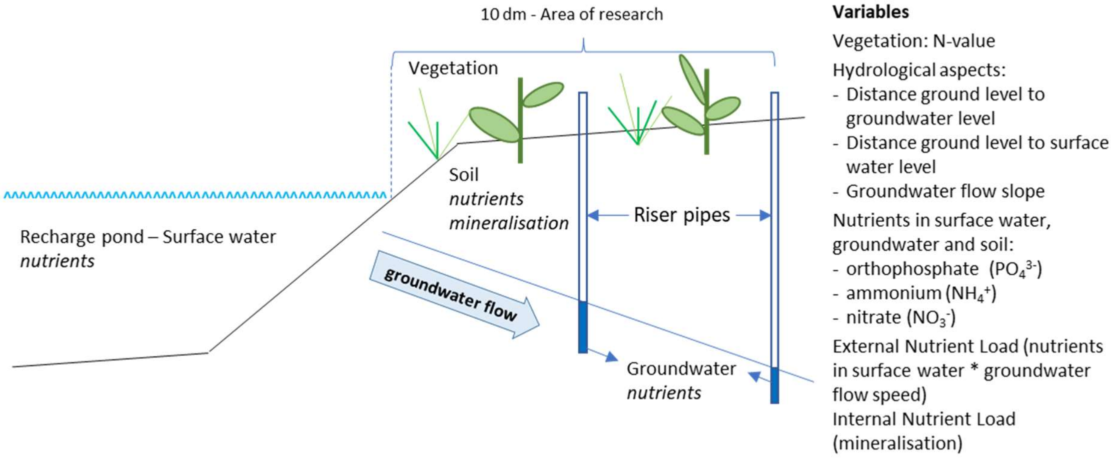
The concentration of the nutrients orthophosphate (PO_4^{3-}), ammonium (NH_4^+) and nitrate (NO_3^-) in surface -, groundwater and soil is measured and analysed in the study. In the statistical analysis the part of the nutrient (P in PO_4^{3-} and N in NH_4^+ and NO_3^-) in the molecule is used, these are noted as respectively P-PO4, N-NH4 and N-NO3.

Nutrient Load

Nutrient load is the concentration of nutrients that is available to plant roots. Van Dijk (1984) distinguished two determining loads; the external load which is the load of nutrients that infiltrates in the bank soil from the MAR pond and the internal load which comes available after mineralisation of organic matter (see also Figure 3). See sections 2.6 and 2.7 for the definitions and measurements of internal – and external load.

Figure 3

Overview of the Variables Measured and Calculated for Each Sample Plot



Variables

Vegetation: N-value

Hydrological aspects:

- Distance ground level to groundwater level
- Distance ground level to surface water level
- Groundwater flow slope

Nutrients in surface water, groundwater and soil:

- orthophosphate (PO_4^{3-})
- ammonium (NH_4^+)
- nitrate (NO_3^-)

External Nutrient Load (nutrients in surface water * groundwater flow speed)

Internal Nutrient Load (mineralisation)

Eutrophic Species and Ellenberg's Nitrogen Indicator Value

Van Dijk (1984) mainly used Ellenberg's Nitrogen Indicator Value ("N-value") to qualify found vegetation. The N-value gives an indication of the presence of a plant species in a gradient of available nutrients (not nitrogen only). The lowest value given is "2" indicating extreme oligotrophic conditions and the highest is "9" indicating excessive nutrient supply. Van Dijk (1984) used "Ellenberg, H., 1979. Ecological indications of vascular plants in Central Europe. Scripta Geobotanica IX, Göttingen" and processed them in a list of 53 plants found during his research (see Appendix 1). In this list the (lowest) value "2.5" represents mesotrophic plant species (the only specie found by Van Dijk with this value was *Mentha aquatica*), values 3 till 5 are representing eutrophic species where "5" is indicating excessive nutrient supply. (It is unknown why Van Dijk converted the N-value from a scale from 2 to 9 to a scale of 2.5 to 5, this probably originate in limitations of computers/processors used at that time.) This list will also be used in the current study. For species found not presented on this list, the relevant N-value is searched.

Temporal scale – last 40 years

Measurements and part of the analysis of Van Dijk's research (1984) took place from about 1975 till 1980. The measurements of vegetation and nutrients of the current study were taken in 2021. In this timescale the differences in vegetation growth and nutrient loads are analysed. The temporal scale of current research is aimed at developments in the availability of nutrients to plants in groundwater in the growing season from March to July. Due to time constraints, soil samples are only taken in June, mineralisation is measured in a six weeks period in June-July.

Surface water and Recharge water

In the study "surface water" means the water in MAR ponds, mainly fed by recharge water. Recharge water is the water from the Meuse river to recharge aquifers via the MAR ponds. The quality of the recharge water is measured just before it is pumped into the MAR ponds.

Measurements and Analysis

All methods and measurements are environmental monitoring techniques as the study is about relationships between nutrient levels in surface -, groundwater and soil and vegetation covers. Figure 4 gives a relation scheme of the parameters studied by Van Dijk (1984). The basis is vegetation survey (census) and chemical and hydrological measurements. Relationships between data from these measurements are statistically analysed. Measurements and statistical analysis will be discussed in more detail in the following sections.

In order to give answers to research sub-questions 1 and 2 and compare vegetation and nutrient loads with the situation of around 1980, the research followed Van Dijk's methods as much as possible. To gain more insight in the current situation about vegetation and nutrients and possible reasons why Van Dijk's expectation did not come true, some additional (exploratory) measurements were executed.

Appendix 2 gives an overview of the measurements and methods/approaches per measurement for the research. Here also deviations from the approach from Van Dijk (1984) are given.

In the current research, following Rhymes et al. (2014), also the nutrient concentration of the (upper layer, 10 to 30 cm) groundwater is analysed as this concentration is supposed to be influenced by the external and internal load.

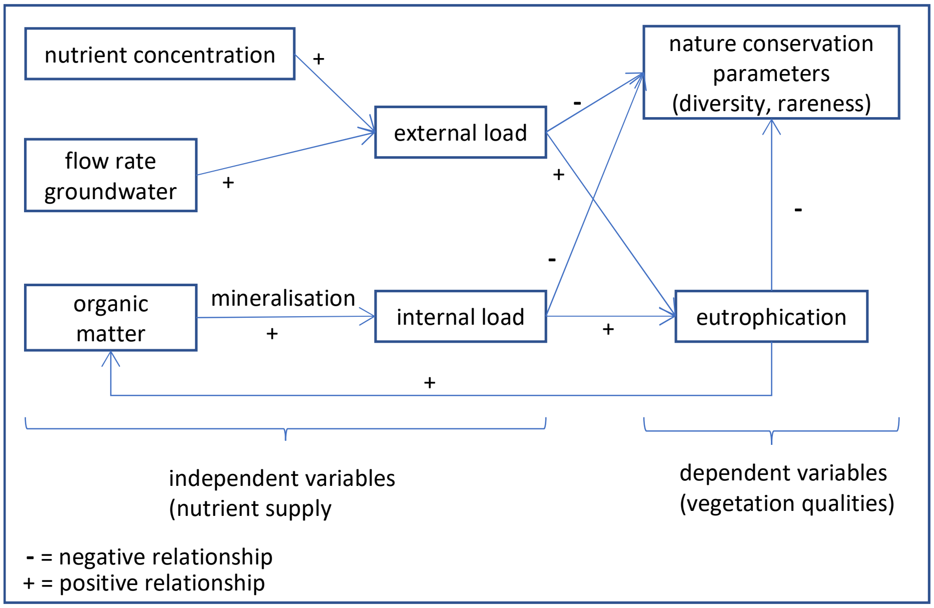
As stated in Chapter 1 the occurrence and availability of nutrients to plants is complex. Nitrate denitrifies in surface water, sludge and in the soil, phosphate can be bound and accumulates in surface water, sludge and soil and mobilises under certain conditions. Nitrate and phosphate are absorbed (and released again via natural processes) by organisms in water, sludge and soil. In order to estimate the consequences of these processes, the nutrient concentrations in the upper groundwater (accessible to plant roots) is measured. Also Van Dijk and Bakker (1984) found a high dispersion of the concentration of orthophosphate in the groundwater influenced by recharge water from the ponds, especially high peaks in spring and summer. They concluded that precipitation was not the cause of these peaks, but they did not explain it further.

Van Dijk (1984) only measured pH of the groundwater further away (tens to hundreds of meters) from the MAR ponds. Because of the high significances in the multiple regression analysis, Van Dijk concluded that acidity is negligible compared to the parameters - internal and external loads - studied. Because of the role of acidity in adsorption and mobilisation of P and dissolving of lime in the current study pH of surface – and groundwater and soil is measured to make an analysis possible. Kooijman et al. (2020, abstract) concluded "… differences in pH led to fundamental differences in P availability and plant strategies, which overruled the normal soil community patterns, and influenced resilience to N deposition."

Also the distance from ground level to groundwater level partly determines vegetation type (Laan, 1979; Rhymes et al., 2014). Because this distance can be quite different (some banks are very flat, moist and sometimes inundated, others rather steep and drier) which could influence vegetation directly, but also by a different regime of nutrient supply. Van Dijk (1984) did not take into account this parameter, the current research did.

Figure 4

Relation scheme of the parameters studied by Van Dijk



Note. Source: Van Dijk, 1984, translated.

2.3. Flowchart, Data collection and Sample Size

Flowchart

Figure 5 shows the flowchart of the research. The first steps are the collection of relevant data about surface – and groundwater, soil and vegetation. Based upon mineralisation data, the internal nutrient load will be determined and based upon nutrient concentration of the surface water and flow rate of the groundwater, the external nutrient load. Basis of the study is to find out if there is relationship between nutrient concentrations in surface -, groundwater and soil and vegetation growth. Once all data is gathered and statistical analysis of possible relationships between nutrient supply and vegetation growth a final analysis of additional gathered data (pH, distance ground level to groundwater level, organic matter content) in relation to the statistical analysis will be performed, including the study of relevant literature.

Data collection

All data necessary for the research is primary data. To compare the development of the level of nutrients in water and soil and vegetation with the situation 40 years ago, data and results of the Van Dijk (1984) research are used. Data is sampled around the two MAR ponds as described in section 2.1. The sample plots are as much as possible on the same location as Van Dijk (1984) or as close as possible. Plot locations are recorded and numbered on a detailed map (Figure 2).

Sample size

A sample size of 20 is expected to be sufficient for the research. In four analysed publications (Berendse et al., 1998; Meltzer & Van Dijk, 1986; Rhymes et al., 2014; Van Dijk, 1984) sample sizes were two times 20, one worked with a sample size of 69, divided over three areas, average 23 per area, and one worked with 15 plots for groundwater level, -nutrients and vegetation and 8 plots for surface water analysis (see Appendix 3). The latter had a smaller size because a preliminary survey was carried out. Ultimately tests are performed to analyse data/variables and models (see Section 2.8 “Statistical Analysis” below).

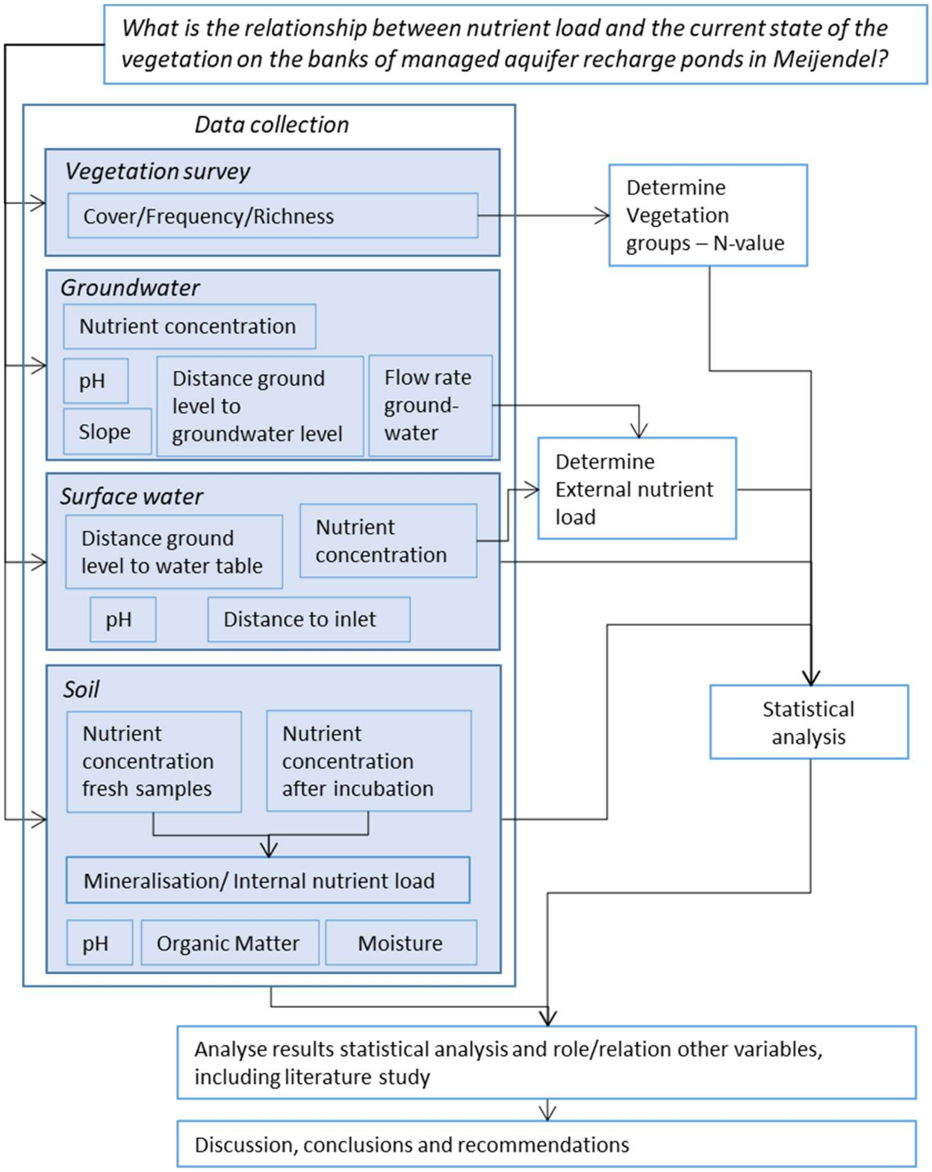
2.4. Vegetation Survey

In the vegetation survey the cover and presence of plant species was determined in each plot (using decimal scale %, Braun-Blanquet approach). The survey was conducted in the first week of August, 2021, and the results, subdivided into tree-, shrub- and herb layer, were entered and processed in Turboveg (for Windows 2.152). For the herb layer of each plot, the weighted mean N-value, as a measure of eutrophication, and species richness (number of herb species), a measure of biodiversity, were calculated. Furthermore, for each herb species the frequency (% plots with species present) of occurrence across all plots was calculated.

2.5. Water Samples and Measurements

Groundwater was collected from riser pipes. These riser pipes were completely surrounded by a nylon filter sleeve (Miltex-PRO BRL-K56), and placed at 0.5 and 1 m from the water line in the middle of the plots (Figure 3), in February 2021, one month before the first water samples were taken. When placing the pipes, care was taken that rainwater could not flow into the pipes. Groundwater samples were taken in March, May and July 2021, on days without any precipitation 24h prior to sampling. Samples were taken of fresh groundwater from the first 10 cm of the water level in the riser pipes, immediately after refilling of the riser pipes after they first had been emptied. Surface water samples also were taken in March, May and July 2021 at 1m from the bank, 10cm below surface. All water samples were stored in a refrigerator at 4°C and analysed the next day by Het Waterlaboratorium (“The Water Laboratory”) in Haarlem. Spectro-photometric determination (Gallery plus, discrete analyser) was used to measure the concentrations of orthophosphate (after addition of ammonium molybdate and antimony potassium tartrate), ammonium (after addition of sodium salicylate solution) and nitrate (after addition of sodium hydroxide solution), in accordance with NEN-ISO 15923-1. Concentrations of P-PO4, N-NH4 and N-NO3 were measured in mg/l. Acidity (pH) of each water sample was directly measured in the field with a calibrated pH meter (Hach HQ40d multi). For all measurements, the average per month and average over the three months of pH and nutrient concentrations were calculated for each plot.

Figure 5
Flowchart of the Research



2.6. Hydrological Aspects & External Nutrient Load

Ground level (elevation) was measured with a GPS/Geosystem (Leica GS15, vertical accuracy ± 0.5 cm). Groundwater levels in the riser pipes were measured with an electronic gauging tape. The distance between ground level and groundwater level per plot was calculated as the average of the two riser pipes (in m). Groundwater flow slope (m/m) was determined based on the difference between the groundwater levels in the two riser pipes divided by the distance between the two pipes (0.5 m). Groundwater flow direction was determined using the difference in groundwater level in the riser pipes. The groundwater flow slope was checked and proved to match with groundwater level data (isohypes) as recorded by Dunea in ArcGIS-Pro. Elevation of the surface water (on the same day the ground level was measured) was obtained from Dunea. Based on these data, the distance (in m) from the ground level, at the first riser pipe from the waterline, to the surface water table was calculated. The distance from the water recharge inlet point to the plots was determined using Google Maps, in m.

The ENL was defined following Darcy's Law to estimate the groundwater flow velocity, following Van Dijk (1984), using the Meijendel standard for the permeability constant (k = 13). ENL from surface water (in g.m^2.day), was calculated as: ENL = v.c, and v = k.i, where

v = groundwater flow velocity (m/day)
k = permeability constant of the soil (m/day)
i = slope of groundwater flow (m/m)
c = nutrient concentration (kg/m^3), of surface water near the sample plot (per month and average of the three measurements).

In five plots, a "negative" groundwater flow direction was measured, the water level in the pipe one metre from the waterline was higher than the pipe at half a metre when the measurements were taken. This indicates groundwater flow towards the pond. In these cases, the groundwater flow slope was set to very low (0.001 m) when calculating the ENL to avoid calculating a negative ENL value.

2.7. Soil samples & Internal Nutrient Load

Fresh soil samples (five per plot) were collected with a soil gouge, up to 25 cm depth, in June 2021. The five samples of each plot were well mixed, stored in a refrigerator at 4°C and analysed the next day. Soil acidity (pH-KCl) was measured with a calibrated meter. Dry matter (DM) and soil moisture (Moist) in % was determined after 24 h drying at 105°C. Van Dijk (1984) determined soil organic matter (OM) content by igniting soil samples for 4 hours at 450°C. As this results in the loss of carbonates (Sutherland, 2006), in the current study soil samples were also ignited at 375ºC for 16 hours to prevent this. In this way, a comparison could be made with Van Dijk (1984) and content of carbonates in the soil could be estimated. Per plot the mean OM% was calculated based on the outcomes per temperature.

To measure mineralisation, in each plot soil five samples were taken with PVC tubes, 30 cm long and 2.4 cm wide, which were carefully driven into the soil with a rubber hammer, in June 2021. Vegetation was removed and the original soil stratification was kept to prevent mineralisation being influenced by mixing of soil layers. The sample tubes were stored in a refrigerator at 4°C and incubation started the next day for six weeks at 25°C and 80% relative humidity. After incubation, the five samples from each plot were thoroughly mixed and analysed the same day.

Concentrations of orthophosphate (after Olsen extraction), ammonium and nitrate (KCl-shake sample) in soil (P-PO4, N-NH4 and N-NO3, in mg/kg), in fresh samples and mineralised samples were determined with a Segmented Flow Analyser (Skalar San-Plus System). All soil analyses, including incubation of soil samples for determination of mineralisation, were performed in the Plant Ecology Laboratory of Wageningen University & Research Centre.

INL was calculated in g/m^3/6 weeks (dry weight) as the difference between the nutrient contents of the fresh and incubated samples.

2.8. Statistical Analysis

The statistical analysis was conducted with SPSS version 26, with Confidence Intervals set to 95%. Appendix 4 lists all variables included in the statistical analysis. First, bivariate correlation analysis (Spearman and Pearson) and simple scatter plots were used to check for possible relationships between variables, including relationships between nutrients in soil and groundwater and other variables. The variables involved in significant correlations from the bivariate correlation analysis were further analysed using multiple and simple linear regression (Table 1).

For the regression models, the following statistics were calculated: R (multiple correlation coefficient), R^2 (coefficient of determination), Adjusted R^2, F-ratio and p-value. Standard testing of linearity, normality, homoscedasticity, multicollinearity and outliers (including leverage and influential points) was performed.

Table 1

Variables Included in the Regression Analysis

Dependent variable	Independent variables
N-value	- SoilP-PO4 - SoilN-NO3 - GwP-PO4Avg - GwN-NO3Avg - SurfP-PO4Mar - DistanceInlet
SoilP-PO4	- GroundwaterFlowSlope - DistanceInlet - ENL-P-PO4Avg
SoilN-NO3	- GroundwaterFlowSlope
GwP-PO4Avg	- DistanceInlet - ENL-P-PO4Avg - DistanceGroundSurf
GwN-NO3Avg	- DistanceInlet - ENL-N-NO3Avg
ENL-P-PO4Avg	- DistanceInlet - DistanceGroundSurf
ENL-N-NO3Avg	- DistanceInlet - DistanceGroundSurf

Differences in mean N-value and P-PO4 concentration in the surface water between the two ponds were analysed with a T-Test in MS Excel.

3. RESULTS

3.1. Vegetation

The mean N-value of the vegetation of all 20 plots was 6.8, which can be considered relatively high for a Dutch coastal dune area. The N-value differed markedly between the plots (Table 2) and is (marginally significantly) different between the two ponds (p = 0.08).

Table 2
N-value of the Vegetation

N-value	Pond 17.1	Pond 26.1
Mean	6.4	7.1
StDev	1.0	0.7
Range	5.0-7.6	5.9-8.4

Note. Mean Value per Pond (n=10), Standard Deviation and Range.
Mean N-value of all plots is 6.8 (n=20).

Van Dijk (1984) qualified the vegetation in the same area at the time as eutrophic. Since then mesotrophic species were displaced by eutrophic species, partly with (very) high N-values of 8 and 9 (see below). It can therefore be argued that N-value has increased. Another observation is that succession towards shrubs and trees has continued and diversity (species richness) has further decreased. Van Dijk counted 46 species in 21 plots around pond 17.1. A total of 25 species were counted in the current study. Admittedly in 10 plots, but the difference seems meaningful. In the current research around pond 17.1 11 species were “new” related to Van Dijk, so 37 species “disappeared”. Around pond 26.1 7 “new” species were counted, and also 7 “disappeared”.

Of the seven species most commonly found by Van Dijk (1984), one is mesotrophic namely *Mentha aquatica*. This species was not found in the plots surveyed in the current study. The by Van Dijk six most frequently found eutrophic species are *Urtica dioica, Cirsium Arvense, Epilobium hirsutum, Eupatorium cannabium, Lycopus europaeus* and *Calamagrostis epigejos.* Only *Eupatorium cannabium* increased in coverage and frequency, the other species are less abundant in the current study.

A relatively strong increase in frequency, next to *Eupatorium cannabium*, is observed in the newly found nutrient loving species (N-value of 7 and higher) *Galium aparine, Convolvulus sepium* and *Rubus caesius*. This latter is observed in 90% of the plots. Also a relatively strong increase is observed in *Phragmites australis*, *Iris pseudacorus*, grasses (especially *Elytrigia atherica*) and shrubs and trees.

The coverage of *Phragmites australis* seems to suppress the occurrence of other species. In plots with a coverage of *Phragmites australis* of 38% and higher, the average of other species counted is 5.2. Where the coverage is below 38%, the species richness is 8.2.

See Appendix 5 for an overview of the results of the vegetation survey and comparison with vegetation surveyed 40 years ago.

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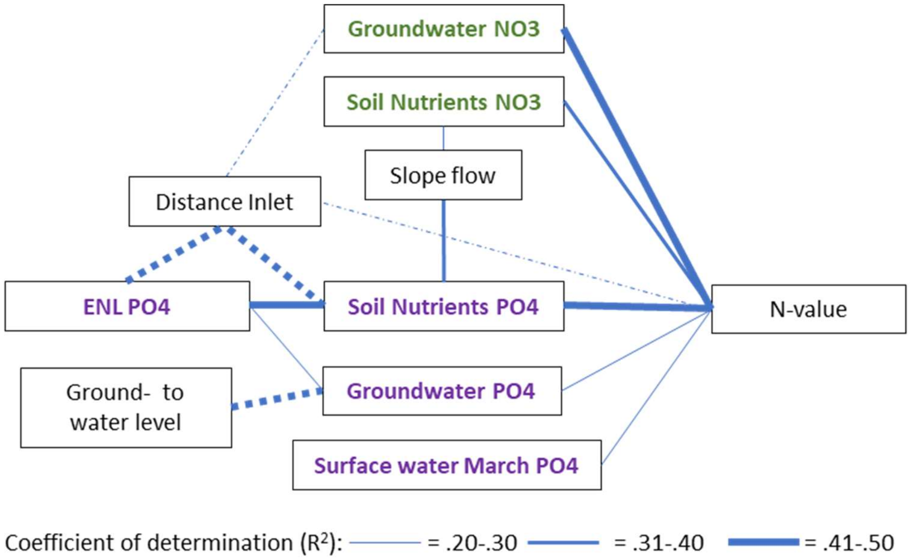
3.2. Relationships between the measured variables

Figure 6 shows the main statistically significant relationships detected aimed at explaining the differences between the N-values of the plots. The N-value appears to be directly positively influenced by the concentrations of nitrate in groundwater and soil, orthophosphate in groundwater and soil, and orthophosphate in the surface water in March. Multiple linear regression analysis showed that the N-value of a plot could best be predicted by either a combination of the concentrations of nitrate in ground water and soil, and orthophosphate in the surface water in March ($R^2 = 0.78$), or a combination of the concentrations of nitrate in ground water, and of orthophosphate in soil and in the surface water in March ($R^2 = 0.77$). Details of the statistical analysis are given in Appendix 6.

Figure 6

Statistically Significant Relations



Note. Based on the outcomes of the linear regressions.
Dashed line means a negative relationship.

A negative relationship was found between the N-values of a plot and the distance to the recharge water inlet point. The regression model predicts a decrease of about 0.2 in N-value with every 100 m distance from the inlet point. The effect of distance to inlet point is most probably indirect and mediated by other variables which have a direct relationship with N-value, as negative relationships were also found between distance to inlet point and the concentrations of orthophosphate in soil, nitrate in groundwater, and, indirectly via ENL PO4, orthophosphate in groundwater (Figure 6).

Another indirect negative relationship was found between the distance between ground level and surface water level and N-value. The first variable is directly negatively related to the concentration of orthophosphate in the groundwater.

The statistical analysis did not detect any significant relations between INL and N-value. In contrast, the analysis indicates that ENL of orthophosphate positively affects the concentration of this nutrient in the soil and groundwater, and thus indirectly influences the N-value.

3.3. Soil and water

Remarkable about the concentration of P-PO4 in the surface water, related to the mean N-value per pond (see Table 2), is that average P-PO4 in the surface water of pond 17.1 in March is 0.0016 mg/l, in pond 26.1 this average amounts 0.004 mg/l. This difference is significant ($p < 0.02$). The means over the three measured months per pond are comparable. Via the ENL the influence of P-PO4 in the recharge water also is visible in the content of P-PO4 in the soil (statistically significant with $p < 0.0005$, see Figure 4. and Appendix 6).

The concentration of orthophosphate in surface water is substantially lower than measured by Van Dijk (1984), see Appendix 7. Although Van Dijk measured the ENL with more gentle groundwater flow slopes, also the ENL of orthophosphate of the current study was lower. The concentration of nitrate in the surface water is comparable to that measured by Van Dijk, meaning, with the steeper groundwater flow slopes of the current study, a higher ENL of nitrate. The measured INL of orthophosphate was higher than measured by Van Dijk (1984), while the INL of nitrate was lower. See Appendix 7 for a comparison of the measurements of the current study with those of Van Dijk.

3.4. Groundwater flow slope and - direction

The groundwater flow measurements showed that in some plots the groundwater flow direction was towards the ponds. A relationship was detected between the flow slope (which is “negative” when the groundwater flow direction was measured towards the pond) and concentrations of orthophosphate ($p < 0.005$, $R^2 = .41$) and nitrate ($p < 0.02$, $R^2 = .27$) in the soil.

4. DISCUSSION AND CONCLUSION

4.1. Discussion

The results of the study show that vegetation has further degraded compared to 40 years ago. The N-value of the vegetation composition most probably increased, mesotrophic species disappeared and species with a (very) high N-value appeared, and succession continued. Compared to 40 years ago, the ENL decreased, as did the INL of nitrate. INL of orthophosphate increased. A relationship has been demonstrated between the N-value of the vegetation and N-NO3 concentration in soil and groundwater, and P-PO4 concentration in soil, groundwater and surface water. Also the distance to the recharge water inlet point is related to the N-value. Contrary to expectations, the INL was not determined to play a role in vegetation composition.

Remarkable is that orthophosphate concentration of the surface water has decreased considerably compared to 40 years ago. Orthophosphate concentration in soil, surface water and groundwater also is considerably lower than values given as target for restoration of calcareous wet dune slacks. This means that even low concentrations of this nutrient allow the eutrophic vegetation to persist. It appears that nutrient concentrations for the establishment of a eutrophic vegetation are different than for persistence of that vegetation. From this study, it seems that the annual cycle of biomass mineralisation is not the explanation for the persistence. Given the broad issues around improving eutrophicated vegetation, fundamental plant-ecological research on this should be a priority.

The relations of the distance to the inlet point and P-PO4 in the surface water with the N-value and relations between ENL P-PO4 and P-PO4 in soil and groundwater, between the distance to the inlet point and ENL P-PO4 and the concentration of this nutrient in the soil, and groundwater flow slope and P-PO4 in the soil are evidence for the role of the concentration of orthophosphate in the recharge water related to the N-value. Orthophosphate content in surface water is thus still a main factor explaining the variation in the N-value of the vegetation. There also are indications that the concentration of N-NO3 in the recharge water influences the concentration of this nutrient in the soil and groundwater, looking at the relations of these concentrations with the distance to the inlet point respectively the groundwater flow slope.

Groundwater in the banks of the recharge ponds mainly is fed from surface water, definitely on the active banks (Van Dijk, 1984), therefore the correlation of the groundwater flow slope and N-NO3 and P-PO4 concentration in the soil indicates the influence of surface water on this nutrient concentration in the soil. The role of the influence of the distance from the inlet point was strengthened after visual inspection of (passive) banks of another part of pond 17.1, more than 1000 m away from the inlet point in November 2021. This inspection revealed several mesotrophic plant species which were not found in the plots surveyed and less abundance of eutrophic species, indicating a possible lower N-value on these banks.

Literature (Aggenbach & Annema, 2016; Ernst et al., 1996; Jones et al., 2008; Koerselman & Meuleman, 1995; Provoost et al., 2018; Rhymes et al., 2014; Smolders et al., 2006, 2011; Sýkora et al., 2004; Van Dijk & Grootjans, 1993) confirms a causal relationship between N-value and P-PO4 and N-NO3 concentrations in soil and groundwater.

Also the following observation strengthens the reasoning around the role of nutrient concentrations in surface water and groundwater flow rates. In areas with passive slopes and where higher dunes lie behind the bank a nutrient poor groundwater stream possibly can reach the pond bank. This certainly can be observed after a period of rainfall (B. Baartman, personal communication). Figure 5 suggests that plots with groundwater flow towards the pond (plots 5, 6, 7) or with a relatively low groundwater flow speed (plot 3, 4, 8) and/or further away from the recharge water inlet point (plot 4 and 8) have a lower N-value. Plot 6 has a relatively high N-value in combination with groundwater flow towards the pond and a relatively slow groundwater flow, but also has a shorter distance to the inlet point. This possible influence of a flow of nutrient-poor groundwater, fed by rainwater, towards the MAR ponds, on N-value could be further investigated.

It was hypothesized that the INL plays an important role in the persistence of the eutrophicated bank vegetation. An influence of the INL on the variation of the N-value of the vegetation has not been statistically demonstrated. The negative relation of the bank height (distance ground level to surface water level) and the concentration of P-PO4 in the groundwater (a greater distance corresponds with lower concentration P-PO4 in groundwater) is likely an indication that less orthophosphate is leaching into deeper soil layers and groundwater through percolating rainwater on higher banks. On lower banks, the N-value seems to be influenced more by surface water, on higher banks perhaps more by mineralisation. The possible role of mineralisation, including the possible influence of bank height in the persistence of vegetation could be investigated further.

Figure 5

Pond 17.1 With Flow Directions of Surface – and Groundwater

Note. The thickness and length of the “groundwater flow arrows” represent the flow speed of the groundwater. Short and thin is slowest measured.
Source of the map: Google Maps.

The values of the soil and water variables having a significant relationship with the N-value of the vegetation (Figure 4) are compared to thresholds given by Aggenbach et al. (2017). Aggenbach et al. (2017) call these thresholds “target values” for soil and water of habitat type “calcareous wet dune slacks” *after* restoration. All but “Soil Nutrients N-NO3” are below these thresholds (Table 3). See Appendix 7 for a complete overview of a comparison of currently measured parameters to Van Dijk’s values and the thresholds (where applicable).

Table 3

Comparison of Values of Significant Variables to Thresholds from Aggenbach et al. (2017) and Measurements by Van Dijk (1984)

Variable	Compared to thresholds	Compared to Van Dijk
ENL P-PO4	NA	-
Soil P-PO4	-	NA
Soil N-NO3	+	NA
Groundwater N-NO3	-	NA
Groundwater P-PO4	-	NA
Surface water P-PO4	-	-

Note. NA = Not Applicable; + = Higher than the threshold; - = Lower than the threshold, lower than measured by Van Dijk; =/- = The measurement tends to be lower than threshold. See Appendix 7 for details about the comparisons.

The difference in N-value between the ponds (Table 2) could be explained by the significant difference of the concentration of P-PO4 in the surface water in March between the two ponds (see Section 3.3 Soil and water). Accumulation of sludge and fixation of phosphorus in it could play a role in this. In pond 26.1 in 1997 sludge is removed, in pond 17.1 in 2015 (H. van der Hagen personal communication). Meaning a thicker layer of sludge accumulated over the years, after removal, in pond 26.1. As P-stripping stops from October to February, in this period the sludge can be (re)loaded with P. When P-stripping starts in March, and the concentration of P-PO4 in the recharge water decreases considerably, P will be released again from the sludge to the surface water. This indication is in accordance with Boers & Uunk (1990) who state that after decreasing external P load on surface water, P can be subsequently supplied by the sludge. Koerselman & Meuleman (1995) state that the periodic removal of sludge in recharge ponds may limit the subsequent supply of P to the water column. Provoost et al. (2018) and Smolders et al. (2011) indicate that P, unlike N, accumulates very strongly in the soil. Years of P supply lead to a large stock, bound to soil particles. Once bioavailable orthophosphate in soil and groundwater is absorbed by plants, it is rebalanced by phosphate bound to calcium, aluminium, iron and OM in the soil. It may therefore take up to decades until P does indeed becomes a limiting nutrient. However, if P is continuously supplied via the recharge water, it is uncertain whether P will ever become a limiting nutrient. Additional research can show what stock of P is actually in the soil and sludge. It can be determined to what extent this stock can be reduced by measures such as mowing and removing the clippings, and/or removal of the soil top layer. When also is determined to what extent the stock is replenished by the recharge water, it can be calculated if the P stock then will decrease. It also is relevant to measure the concentrations of Fe and S, because this influences, affected by pH, the binding of P to soil – and sludge particles (Smolders et al., 2006).

Also remarkable, and interesting in the sense of binding and releasing of P to soil particles, is the range of measured soil pH. This ranges from 4.6 to 8.5, with a mean of 6.6 and standard deviation of 0.9. In the study no relations were detected between soil pH and content of OM or concentration of orthophosphate in soil or groundwater or other variables measured. The cause of these differences, and consequences related to binding and releasing of phosphates also could be a subject for further research.

A limitation of the study is the limited time in which the study was conducted: one spring/summer. This while processes such as vegetation development/succession and possible nutrient accumulation and supply take place over years. The results of the statistical analysis are significant and give a rather clear picture of the current nutrient load compared to the current state of the vegetation. However, both variables evolve over time. The soil analysis took place in June. The growing season starts around March and eutrophic plant species grow rapidly just at the beginning of the growing season. Measuring nutrient concentrations in the soil in March would therefore probably give a better picture in relation to eutrophication. The relationship of the P-PO4 content in March of the surface water with the N-value reinforces this assumption.

4.2. Conclusion and recommendations for management

Despite more than 40 years of P-stripping of the recharge water, the vegetation still is eutrophic and succession has continued. The orthophosphate content of the surface water decreased considerably compared to 40 years ago, while the content of nitrate is comparable. The measured INL of orthophosphate was higher than 40 years ago, the INL of nitrate was lower.
The study showed no evidence of a direct relationship between ENL of nutrients, soil pH or distance from ground level to groundwater with the measured N-value of current vegetation. Also the hypothesised role of the INL on vegetation composition has not been confirmed.

The results of the study indicate that the concentration of orthophosphate, as well as nitrate, in surface water and groundwater flow rate influences the N-value of the vegetation on the banks of the MAR ponds. Next to the groundwater flow rate, also the distance from the bank to the recharge water inlet point, the flow direction of the groundwater, and the distance from ground level to surface water level influence the N-value. The results suggest that without intervention, succession will continue and there will be no improvement in vegetation composition, also probably further acidification and accumulation of OM will occur.

With the P-stripping of the recharge water, Dunea tried to achieve that P would become a growth-limiting nutrient and that this would improve vegetation. As the concentration of orthophosphate in surfacewater, groundwater and soil are below target values after restoration it can be concluded that current nutrient loads are contributing to the persistence of current vegetation growth. This finding gives direction to management measures that could be taken. Removal of the current vegetation and sod cutting, where the soil top layer should be excavated down to the calcareous sand, is expected to lead to regrowth of desired vegetation. The higher pH of the recharge water and the calcareous sand then cause phosphate to be bound, which reduces the phosphate available for plants.

The soil of banks further away from the intake point, where the groundwater flows relatively slowly or even towards the pond and where the height of the bank prevents regular flooding have a relatively low pH. Because of this a relatively larger amount of phosphates is available to plants. If soil pH decreases further, less P will be bound to soil particles and below a soil pH of 4.5, toxic aluminium can mobilise, creating toxic conditions for many plant species (in one plot a soil pH of 4.6 was measured). This will further deteriorate the vegetation and hinder recovery (Provoost et al., 2018). This acidification of the soil is an additional reason to remove the top soil layer down to calcareous sand.

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Appendices

Appendix 1 - Van Dijk’s List of (Eutrophic) Plant Species

Appendix 2 - Overview of the Measurements and Methods of the Research

Appendix 3 - Overview of methods used in reviewed papers

Appendix 4 - All Variables used in the Bivariate Correlation Analyses

Appendix 5 - Developments Bank Vegetation

Appendix 6 - Outcomes Regression Analyses

Appendix 7 - Measured Parameters versus Thresholds and Measures by Van Dijk

Appendix 1 - Van Dijk's List of (Eutrophic) Plant Species

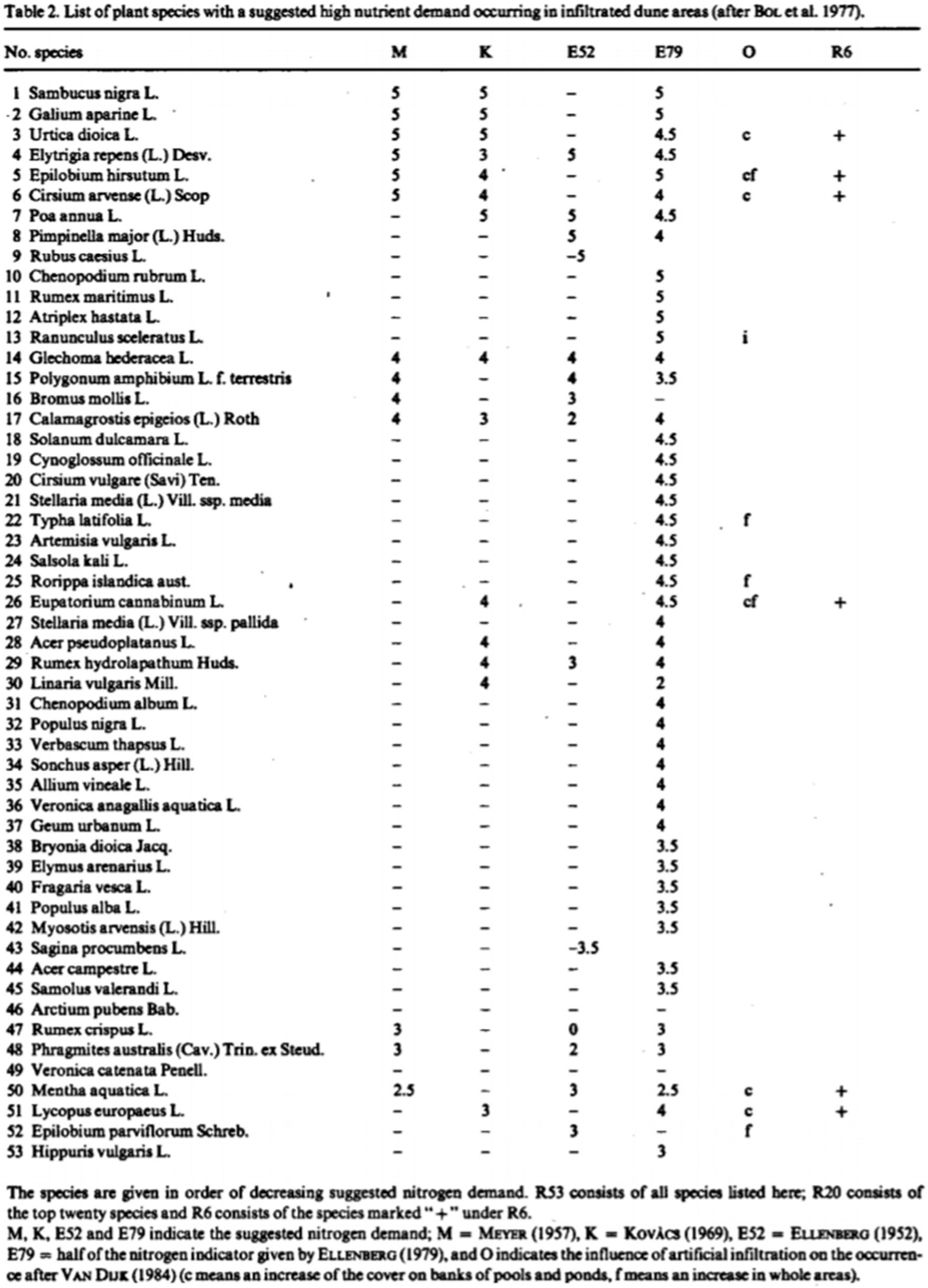


Table 2. List of plant species with a suggested high nutrient demand occurring in infiltrated dune areas (after Bol et al. 1977).

No. species	M	K	E52	E79	O	R6
1 Sambucus nigra L.	5	5	–	5		
2 Galium aparine L.	5	5	–	5		
3 Urtica dioica L.	5	5	–	4.5	c	+
4 Elytrigia repens (L.) Desv.	5	3	5	4.5		
5 Epilobium hirsutum L.	5	4	–	5	cf	+
6 Cirsium arvense (L.) Scop	5	4	–	4	c	+
7 Poa annua L.	–	5	5	4.5		
8 Pimpinella major (L.) Huds.	–	–	5	4		
9 Rubus caesius L.	–	–	–5			
10 Chenopodium rubrum L.	–	–	–	5		
11 Rumex maritimus L.	–	–	–	5		
12 Atriplex hastata L.	–	–	–	5		
13 Ranunculus sceleratus L.	–	–	–	5	i	
14 Glechoma hederacea L.	4	4	4	4		
15 Polygonum amphibium L. f. terrestris	4	–	4	3.5		
16 Bromus mollis L.	4	–	3	–		
17 Calamagrostis epigeios (L.) Roth	4	3	2	4		
18 Solanum dulcamara L.	–	–	–	4.5		
19 Cynoglossum officinale L.	–	–	–	4.5		
20 Cirsium vulgare (Savi) Ten.	–	–	–	4.5		
21 Stellaria media (L.) Vill. ssp. media	–	–	–	4.5		
22 Typha latifolia L.	–	–	–	4.5	f	
23 Artemisia vulgaris L.	–	–	–	4.5		
24 Salsola kali L.	–	–	–	4.5		
25 Rorippa islandica aust.	–	–	–	4.5	f	
26 Eupatorium cannabinum L.	–	4	–	4.5	cf	+
27 Stellaria media (L.) Vill. ssp. pallida	–	–	–	4		
28 Acer pseudoplatanus L.	–	4	–	4		
29 Rumex hydrolapathum Huds.	–	4	3	4		
30 Linaria vulgaris Mill.	–	4	–	2		
31 Chenopodium album L.	–	–	–	4		
32 Populus nigra L.	–	–	–	4		
33 Verbascum thapsus L.	–	–	–	4		
34 Sonchus asper (L.) Hill.	–	–	–	4		
35 Allium vineale L.	–	–	–	4		
36 Veronica anagallis aquatica L.	–	–	–	4		
37 Geum urbanum L.	–	–	–	4		
38 Bryonia dioica Jacq.	–	–	–	3.5		
39 Elymus arenarius L.	–	–	–	3.5		
40 Fragaria vesca L.	–	–	–	3.5		
41 Populus alba L.	–	–	–	3.5		
42 Myosotis arvensis (L.) Hill.	–	–	–	3.5		
43 Sagina procumbens L.	–	–	–3.5			
44 Acer campestre L.	–	–	–	3.5		
45 Samolus valerandi L.	–	–	–	3.5		
46 Arctium pubens Bab.	–	–	–	–		
47 Rumex crispus L.	3	–	0	3		
48 Phragmites australis (Cav.) Trin. ex Steud.	3	–	2	3		
49 Veronica catenata Penell.	–	–	–	–		
50 Mentha aquatica L.	2.5	–	3	2.5	c	+
51 Lycopus europaeus L.	–	3	–	4	c	+
52 Epilobium parviflorum Schreb.	–	–	3	–	f	
53 Hippuris vulgaris L.	–	–	–	3		

The species are given in order of decreasing suggested nitrogen demand. R53 consists of all species listed here; R20 consists of the top twenty species and R6 consists of the species marked "+" under R6.
M, K, E52 and E79 indicate the suggested nitrogen demand; M = Meyer (1957), K = Kovàcs (1969), E52 = Ellenberg (1952), E79 = half of the nitrogen indicator given by Ellenberg (1979), and O indicates the influence of artificial infiltration on the occurrence after Van Dijk (1984) (c means an increase of the cover on banks of pools and ponds, f means an increase in whole areas).

Source: (Van Dijk et al., 1985)

Appendix 2 – Overview of the Measurements and Methods of the Research

Subject	***Measurements and Methods/Approaches***
Census - vegetation	- Cover and abundance of all species (decimal scale %, Braun-Blanquet) - Frequency of all species (% presence of all quadrats) Assign vegetation/herbaceous plant species to groups following Ellenberg's Nutrient Indicator Value. - Richness: number of species per sample plot
	Quadrats. 2x1 m (2 m along the waterside)
Internal nutrient load ("mineralisation")	- Ammonium and nitrate: salt extract (KCl-shake sample) - Orthophosphate after Olsen extraction - Organic matter
	Fresh samples (5 per sample plot) with a soil gouge, up to 25 cm. depth. The five samples well mixed per sample point, stored in a refrigerator at 4 °C and analysed the next day. Incubation: 5 PVC tubes, 30 cm long, 2,4 cm width, carefully into the soil with a rubber hammer. Vegetation removed. Original soil stratification kept, so no increased mineralisation due to mixing of soil layers. The samples were incubated in the tubes for 6 weeks at 25° C and 80% relative humidity. After the period of 6 weeks, the 5 samples per sampling point were thoroughly mixed and analysed the same day. Organic matter: soil sample 4 hours at 450 °C and *also after 16 hours at 375 °C to prevent loss of carbonates.* *Sigmented Flow Analyser (Skalar San-Plus System).*
Surface - and *groundwater*	Ammonium, nitrate and orthophosphate. *Additional to Van Dijk (1984): nutrient concentration of the upper layer (1-3 dm.) of the groundwater in the first meter from the waterline (at 0,5 and 1 m).*
	Discrete analyser spectrophotometer (Gallery plus).
External nutrient load	"Gross momentary nutrient load". This is the product of "Groundwater velocity/flux density" and nutrient (N, P) concentration (annual average) of the recharge water near the bank. Since 2019, P-stripping only takes place in the growing season (March- September), this could be relevant if orthophosphate concentration differs during the growing season. *So no annual average of the recharge water is used in the present study, but measurements of nearby surface water in March, May and July.*
	"Gross momentary nutrient load" "b" ($g.m^{-2}.day^{-1}$) = v.c - v (m/day) "Groundwater velocity/flux density", according to Darcy: v = k.i (k = permeability constant of the soil (m/day); i = slope of groundwater in the ground (m/m)). k = 13. - c = nutrient (N, P) concentration (of the surface water near the bank (kg/m^{-3}).
pH/acidity	*Measurement of pH of surface and groundwater (5 and 10 dm from waterside) and soil.*
	Soil: pH-KCl and calibrated pH-meter. Water: Calibrated pH-meter.
Groundwater levels and distance to ground level	*Van Dijk (1984) did not measure groundwater levels in the first meter from the waterside. The distance to ground level could be relevant to vegetation growth, see Rhymes et al. (2014).*
	Elevation of the ground surface at each riser pipe. With calibrated GPS/Geosystem (Leica GS15).

Note. In red italic text the deviations from the approach from Van Dijk (1984)

Appendix 3 - Overview of methods used in reviewed papers

1. Van Dijk, 1984

Study: Invloeden van oppervlakte-infiltratie ten behoeve van duinwaterwinning op kruidachtige oevervegetaties. Van Dijk, 1984		
Subject	***Measurements***	***Approach***
Sample size (soil, surface water, vegetation survey)	20 plots, spread over 5 areas, 3 with MAR ponds and 2 "untouched" dune reference areas.	
Census - Vegetation	- Cover and abundance of all species (decimal scale %, Braun-Blanquet) - Frequency of all species (% presence of all quadrats) Assign vegetation/herbaceous plant species to groups following Ellenberg's Nitrogen Indicator Value. - Richness: number of species per sample plot - Rarity: according to standard list of Arnolds & Van der Meijden.	Quadrats. 2X1 m. (2 m. along the waterside)
Vegetation - biomass analysis	Content of: - Potassium - Total nitrogen - Phosphorus	To determine the nutrient concentration of the vegetation, all plants were cut off in the middle of the test area over an area of 0.5 by 0.5 m. near the ground. After determining the wet and dry weight, part of the dried plant material was processed into powder. The following analyses were carried out on destruates obtained with sulfuric acid-hydrogen peroxide (method according to Allen, 1974): - potassium content (direct measurement with Perkin-Elmer 460 A.A.S. spectrophotometer) - total nitrogen content (Kjelldahl analysis) - phosphorus content (spectrophotometrically by the molybdate blue method according to Allen, 1974).
Internal nutrient load ("mineralisation")	- Ammonium - NH_4^+: extraction with KCl-solution; ion-specific electrode (Orion 951000); - Nitrate - NO_3^-: extraction with a solution of $Al_2(SO_4)_3$, H_3BO_3, Ag_2SO_4 en NH_2SO_3H; ion-specific electrode (Orion 930700); - Availaible (ortho)phosphate - PO_4^{3-}: Molybdenum blue method after sodium bicarbonate extraction according to Olsen; - Available potassium, K^+: direct measurement with an atomic absorption spectrophotometer after extraction with glacial acetic acid diluted 40 times (5 g dry soil/100 ml) for one hour. The nutrient concentrations were converted to kg dry weight.	Fresh samples (5 per sample plot) with a soil gouge, up to 25 cm. depth. Mix the five samples well per sample point and analyze these mixed samples for moisture content and volume weight on the same day Incubation: 5 PVC tubes, 30 cm long, 2,4 cm width, carefully into the soil. Vegetation removed.Keep original soil stratification so that no increased mineralisation due to mixing of soil layers can occur. Incubate the samples in the tubes for 6 weeks at 25° C and 80% relative humidity. After the period of 6 weeks, thoroughly mix and analyze the soil samples from the 5 incubation test tubes per sampling point. Organic matter: soil sample 4 hours at 450°C.

Van Dijk, 1984 – continued

Subject	***Measurements***	***Approach***
Surface - and ground water	- Ammonium - NH_4^+: '- direct measurement with ion-specific electrode (Orion 95-10); - Nitrate - NO_3^-: spectrophotometric determination after addition of sodium salicylate; - Availaible (ortho)phosphate - PO_4^{3-}: spectrophotometric determination after addition of ammonium heptamolybdate and tin chloride; - Available potassium, K^+: direct measurement with atomic absorption spectrophotometer (Perkin Elmer 460)	Water samples. Groundwater: risers with filters at the base.
External nutrient load	“Gross momentary nutrient load” “b” ($g.m^{-2}.day^{-1}$) = v.c - v (m/day) “Groundwater velocity/flux density”, according to Darcy: v = k.i (k = permeability constant of the soil (m/day); i = slope of groundwater in the ground (m/m)). k = 13. - c = nutrient (N, P, K) concentration (annual average of the recharge water near the bank (kg/m-3) (this value is used by Van Dijk for the nutrient concentration of the groundwater.)	The Gross momentary nutrient load is a method by Van Dijk. The product of the groundwater flow velocity and the nutrient concentration of the surface water. Groundwater flow velocity: Darcy's law. Monthly measurement of nutrient concentration, the annual average has been used.
pH/acidity	Van Dijk only measured acidity of the groundwater. Because of the high significances in the multiple regression analysis, Van Dijk concluded that acidity is negligible compared to the parameters studied.	Calibrated pH meter.
Statistics/ relations	Dependent variable: coverage roughness species Independent variables: external and internal nutrient loads (N, P, K) Coverage roughness species (cover of nitrophilous tall hemicryptophytes) for three ecological groups consisting of 6, 20 and 53 nitrophilous species (labelled respectively R6, R20 and R53)	Multiple regression analysis using SPSS.

2. Meltzer & Van Dijk, 1986

Study: The effects of dissolved macro-nutrients on the herbaceous vegetation around dune pools. Meltzer & Van Dijk, 1986		
Subject	***Measurements***	***Approach***
Sample size (surface water and vegetation survey)	99 sample plots in 7 areas. 69 sample plots in the 3 areas with MAR ponds.	
Census - Vegetation	See Van Dijk, 1984	
Vegetation - Biomass analysis	See Van Dijk, 1984	
Surface water	Concentrations of $N.NO_3^-$, $P.PO_4^{3-}$ and K^+. Nitrate (mg $N.NO_{3-}\ l^{-1}$): extinction determination at 440 nm after adding sodium salicylate; Orthophosphate (mg $P.PO_4^{3-}\ l^{-1}$): extinction determination at 720 nm after adding ammonium molybdate; Potassium (mg $K^+\ l^{-1}$): direct measurement with an atom absorption spectrophotometer.	Water sample.
External nutrient load	See Van Dijk, 1984	
Statistics/ relations	The relations between the nutrient supply variables and the vegetation variables were subjected to two different correlation tests: the product-moment correlation test (Pearson) and the Spearman nonparametric rank correlation test.	Correlation

3. Rhymes et al., 2014

Study: Evidence for sensitivity of dune wetlands to groundwater nutrients. Rhymes et al., 2014		
Subject	***Measurements***	***Approach***
Sample size	Groundwater levels: 15 piezometers. Monthly during a year. Surface water: N = 8. Vegetation: 3 sample sites per piezometer = 45 quadrats.	
Groundwater level and flow direction	In a preliminary survey, elevation of the water table at each piezometer and at additional locations around the site was measured by auguring down to the water table and then referred to ground surface elevation measured using a Leica 1200 RTKGPS, with a vertical accuracy of ±1 cm, and correcting for water table depth. Groundwater flow direction was estimated by contour analysis in ArcGIS v10.1.	
Groundwater analysis	Samples collected from the top 10 cm of the water table at each piezometer. Monthly. - pH was recorded for each sample, then filtered through 0.45 µm nylon syringe filter (Avonchem™). - Dissolved inorganic anions (chloride, nitrite, nitrate, phosphate and sulphate) and cations (sodium, ammonium, potassium, calcium and magnesium) were then measured.	Water samples. Samples were stored in darkness at 5 °C prior to chemical analysis. On an ion chromatograph (Metrohm, UK Ltd.). Detection limits for all anions and cations were 0.005 mg/L apart from nitrite (0.003 mg/L), nitrate (0.002 mg/L) and ammonium (0.001 mg/L). Dissolved inorganic nitrogen was calculated as the sum of NO_3–N, NO_2–N and NH_4–N.
Surface water from streams.	For analysis, see "Groundwater analysis"	Water samples. Dipping a clean collecting container into the surface flow. Samples were stored in darkness at 5 °C prior to chemical analysis.
Botanical survey	Species occurence. Communities corresponding to UK National Vegetation Classification.	Quadrats. At each of the 15 piezometers vegetation was surveyed in three 1m×1m quadrats. The quadrats were placed at a 3 m distance from the piezometer and arranged on cardinal bearings (North, West and East). Species occurrence was recorded using visual estimates of % cover for all species of vascular plants, bryophytes and lichens. Cover of bare ground and litter were also recorded. Mean UK-modified Ellenberg indicator values (Hill et al., 1999, 2007) were then calculated for each quadrat using species presence data.
Topographical resolution	Elevation of the ground surface at each piezometer and quadrat.	Leica 1200 RTKGPS to 1 cm vertical resolution, which allowed groundwater levels for each quadrat to be calculated using their relative elevation difference from the nearest piezometer

Rhymes et al., 2014 - continued

Subject	***Measurements***	***Approach***
Soil	- thickness of the organic horizon - organic matter content - pH - electrical conductivity - Organic anions (chloride, nitrite, phosphate and sulphate) and cations (sodium, ammonium, potassium, calcium and magnesium)	At each quadrat a soil core (5 cm diameter, 15 cm depth) was collected and stored in darkness at 5 °C, prior to analysis. Any vegetation and large roots were removed. The soil was then homogenised by hand and a sub-sample (10–15 g field moist soil) was weighed and dried at 105 °C and reweighed to measure moisture content. The samples were then re-heated in a furnace at 375 °C for 16 h and re-weighed to determine organic matter content through Loss on Ignition (Ball, 1964). A sub-sample was prepared for chemical analysis using a water extraction of 10 g homogenised sample of fresh soil, mixed with 10 ml of ultra-high purity water (1:10 wt/vol) on a laboratory blender (Stomacher 80, Seward UK). pH was recorded using a calibrated pH electrode and electrical conductivity was measured using a conductivity meter (Primo 5, Hanna Instruments Ltd. UK). The remaining solution was centrifuged for 15 min at 5000 rpm and filtered through 0.45 µm nylon syringe filter (Avonchem™). Organic anions and cations were then measured on the Metrohm ion chromatograph, detection limits described above.
Rooting depth	Rooting depth. On one clean vertical face in each soil pit, the number of visible roots in a 30 cm wide × 20 cm deep section were recorded at 4 depth bands below the surface (−20 to −40 cm, −40 to −60 cm, −60 to −80 cm and −80 to −100 cm). It was not possible to count visible roots in the main rooting zone (top layer 0 to −20 cm) due to the high abundance of roots.	Soil pits > 30 cm wide and 1m deep were dug at 5m distance from six of the piezometers in order to measure rooting depth. Three of these were dug in slacks with a hydrological regime supporting wet slack vegetation communities and three in dry slack communities.
Statistics/ relationships	Chemistry and pH - water Soil chemistry Soil characteristics Vegetation: water table variation in relation to rooting depth. Ellenberg values F, N, R	Multivariate analysis. Quadrats and piezometers were grouped into three classes based on their distance from the south-east site boundary (0–150 m N = 15, 150–300 m N = 18, 300–450 m N = 12). Monthly groundwater (including inundation samples) and streamwater (N = 8) chemistry values and pH for each sampling point were averaged to give an annual mean, as preliminary analysis showed no seasonal differences in groundwater chemistry.

4. Berendse et al., 1998

Study: Soil organic matter accumulation and its implications for nitrogen mineralisation and plant species composition during succession in coastal dune slacks. Berendse et al. 1998		
Subject	***Measurements***	***Approach***
Sample size	Vegetation: 20 subplots (5X5 m.) in four plots/areas (25X20 m.) Soil: - 20 samples, one per subplot, to measure organic matter and nitrigen contents - 20 samples, one per subplot, to measure root biomass in the various soil layers	
Soil organic matter and N mineralisation. pH.	The soil in each first sample was dried at 105 °C, weighed and ground. The organic matter content was determined as the loss of mass upon ignition (650 °C, 2 h). Total N contents were measured using a Heraeus CHN-RAPID elemental analyser. Net N mineralisation, analysis of the soil: 20 g field-moist soil was extracted with 50 ml 1 *N* KCl. The extract was analysed for NH_4^+ and NO_3^- using an autoanalyzer. Net N mineralisation was calculated as the difference between the NH_4^+-N plus NO_3^--N content of the incubated sample and its paired initial sample, whereas net nitrification was taken as the difference in NO_3^--N content. These amounts were divided by the surface area of the tube to obtain results in g N m^{-2}. In each of these samples soil moisture contents were determined by weighing soil samples after drying at 105 °C. Soil pH was measured after extracting 10 g field moist soil with 50 ml 1 *N* KCl.	On 6 August 1991 ten soil cores (diameter 7 cm) were taken in each of the four plots (two samples per sub plot) to a depth of 10 cm below the boundary between the L and the FH layers and from 10 to 20 cm. The samples were subdivided into the loose litter (L), the humus layer (FH) and the underlying mineral soil (M). The net mineralisation of nitrogen was measured *in situ* during 6 periods of about 8 weeks (year round). On each sampling date ten pairs of soil cores were taken in each plot (two pairs per subplot). They were taken with a 4.3 cm diameter polyvinyl chloride tube so that the sample was an undisturbed column of the first 10 cm of soil. Depth was measured from the top of the FH layer. One of each pair of samples was transported to the laboratory in a cooled box and extracted within 24 h. The other tube was incubated *in situ* after being closed with plastic lids that prevented water moving through the tube, but allowed air to enter through holes that remained above the soil surface during incubation. After the field incubation the incubated soil tube was also taken to the laboratory. There, the soil in the retrieved tubes was mixed and analysed.
Plant biomass and species composition	Plant biomass and species composition. Nitrogen concentrations.	On 6 August 1991 a square of 50 by 50 cm was laid out in each of the 20 subplots in which all plants were clipped off flush with the ground. The harvested plants were separated per species into living and dead parts and into stems and non-woody parts. Roots were collected from 7 cm diameter soil samples taken to a depth of 10 cm and between 10 and 20 cm. These soil columns were washed out and thereafter roots were cleaned carefully from adhering soil particles. It proved impossible to distinguish between dead and living roots or between the roots of different plant species. The harvested materials were weighed after drying at 70 °C. Nitrogen concentrations were measured with a Heraeus CHN-RAPID elemental analyser.
Statistical analysis	Soil organic matter and N mineralisation Plant biomass and species composition	An one-way ANOVA was carried out to analyse site effects on amounts of soil organic matter, N mineralisation and plant biomass. Differences between means were tested a posteriori using the Student-Newman Keuls test. For this analysis we used the average of the two values of the N mineralization rate that were measured within each replicated subplot.

Appendix 4 - All Variables used in the Bivariate Correlation Analyses

Vegetation

- N-Ellenberg value (nutrients)
- F-Ellenberg value (moist)
- L-Ellenberg value (light)
- R-Ellenberg value (pH)
- CoverageTreesShrubs
- Coverage *Phragmites australis*
- Biomass indicator.

Soil & Internal Nutrient Load

- SoilP-PO4
- SoilN-NH4
- SoilN-NO3
- INL-P-PO4
- INL-N-NH4
- INL-N-NO3
- Soil-pH
- Soil-OM (organic matter)
- Soil-DM (dry matter)
- Soil-Moist.

Groundwater

- GwP-PO4Mar, -May, -Jul
- GwN-NH4Mar, -May, -Jul
- GwN-NO3Mar, -May, -Jul
- GwP-PO4Avg (the average of the three samples)
- GwN-NH4Avg
- GwN-NO3Avg
- GwPH-Mar, -May, -Jul
- GwPH-Avg
- GwSlope
- DistanceGroundGw (the average distance of the groundwater table in the two riser pipes to ground level).

Surface water

- SurfP-PO4Mar, -May, -Jul
- SurfN-NH4Mar, -May, -Jul
- SurfN-NO3Mar, -May, -Jul
- SurfP-PO4Avg (the average of the three samples)
- SurfN-NH4Avg
- SurfN-NO3Avg
- SurfPH-Mar, -May, -Jul
- SurfPH-Avg
- DistanceGroundSurf.

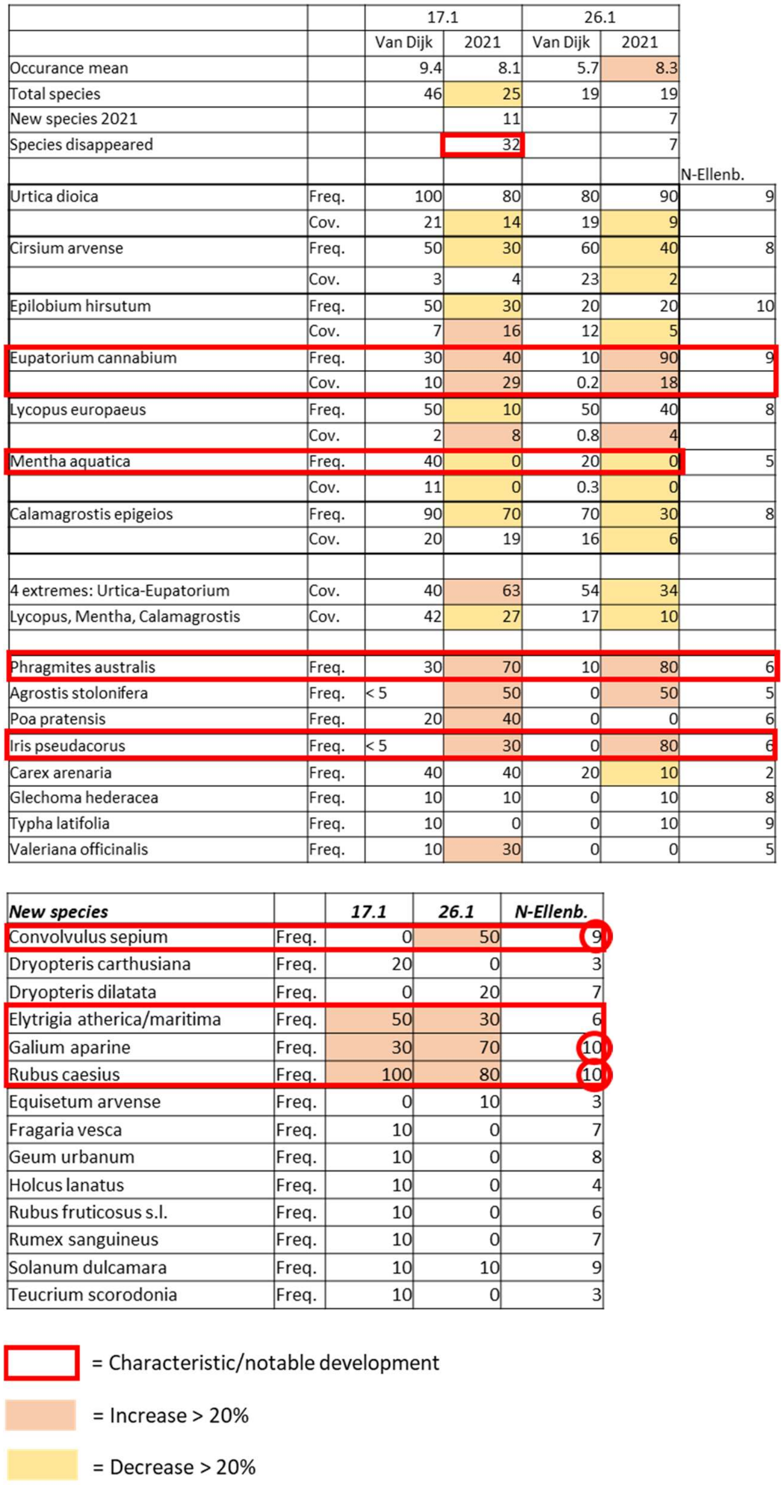
External Nutrient Load

- ENL-P- PO4Mar, -May, -Jul
- ENL-N- NH4Mar, -May, -Jul
- ENL-N- NO3Mar, -May, -Jul
- ENL-P-PO4Avg
- ENL-N-NH4Avg
- ENL-N-NO3Avg.

Distance to inlet

- DistanceInlet.

Appendix 5 – Developments Bank Vegetation



		17.1		26.1		
		Van Dijk	2021	Van Dijk	2021	
Occurance mean		9.4	8.1	5.7	8.3	
Total species		46	25	19	19	
New species 2021			11		7	
Species disappeared			32		7	
						N-Ellenb.
Urtica dioica	Freq.	100	80	80	90	9
	Cov.	21	14	19	9	
Cirsium arvense	Freq.	50	30	60	40	8
	Cov.	3	4	23	2	
Epilobium hirsutum	Freq.	50	30	20	20	10
	Cov.	7	16	12	5	
Eupatorium cannabium	Freq.	30	40	10	90	9
	Cov.	10	29	0.2	18	
Lycopus europaeus	Freq.	50	10	50	40	8
	Cov.	2	8	0.8	4	
Mentha aquatica	Freq.	40	0	20	0	5
	Cov.	11	0	0.3	0	
Calamagrostis epigeios	Freq.	90	70	70	30	8
	Cov.	20	19	16	6	
4 extremes: Urtica-Eupatorium	Cov.	40	63	54	34	
Lycopus, Mentha, Calamagrostis	Cov.	42	27	17	10	
Phragmites australis	Freq.	30	70	10	80	6
Agrostis stolonifera	Freq.	< 5	50	0	50	5
Poa pratensis	Freq.	20	40	0	0	6
Iris pseudacorus	Freq.	< 5	30	0	80	6
Carex arenaria	Freq.	40	40	20	10	2
Glechoma hederacea	Freq.	10	10	0	10	8
Typha latifolia	Freq.	10	0	0	10	9
Valeriana officinalis	Freq.	10	30	0	0	5

New species		***17.1***	***26.1***	***N-Ellenb.***
Convolvulus sepium	Freq.	0	50	9
Dryopteris carthusiana	Freq.	20	0	3
Dryopteris dilatata	Freq.	0	20	7
Elytrigia atherica/maritima	Freq.	50	30	6
Galium aparine	Freq.	30	70	10
Rubus caesius	Freq.	100	80	10
Equisetum arvense	Freq.	0	10	3
Fragaria vesca	Freq.	10	0	7
Geum urbanum	Freq.	10	0	8
Holcus lanatus	Freq.	10	0	4
Rubus fruticosus s.l.	Freq.	10	0	6
Rumex sanguineus	Freq.	10	0	7
Solanum dulcamara	Freq.	10	10	9
Teucrium scorodonia	Freq.	10	0	3

☐ = Characteristic/notable development

🟧 = Increase > 20%

🟨 = Decrease > 20%

Appendix 6 - Outcomes Regression Analyses

ENL P-PO4 – SoilP-PO4
ENL-PO4 statistically significantly predicted SoilPO4, F(1, 18) = 19.804, $p < 0.0005$, $R^2 = .524$.

Slope flow – SoilP-PO4
Slope flow statistically significantly predicted SoilPO4, F(1, 17) = 11.619, $p < 0.005$, $R^2 = .406$.

Slope flow – SoilN-NO3
Slope flow statistically significantly predicted SoilNO3, F(1, 18) = 6,621, $p < 0.02$, $R^2 = .269$.

Distance Ground – to Surface water level – Groundwater P-PO4
DistanceGS statistically significantly predicted , F(1, 18) = 16,513, $p < 0.002$, $R^2 = .478$.

Distance Inlet – Groundwater N-NO3
Distance Inlet statistically significantly predicted GwNO3, F(1, 18) = 6,637, $p < 0.02$, $R^2 = .269$.

Distance Inlet – SoilP-PO4
Distance Inlet statistically significantly predicted SoilPO4, F(1, 17) = 12,846, $p < 0.005$, $R^2 = .430$.

Distance Inlet – N-value
Distance Inlet statistically significantly predicted N-value, F(1, 18) = 7,637, $p < 0.02$, $R^2 = .298$.

ENL-P-PO4 – GroundwaterP-PO4
ENLPO4 statistically significantly predicted GwPO4, F(1, 18) = 5,508, $p < 0.05$, $R^2 = .234$.

Groundwater PO4 – N-value
GwPO4 statistically significantly predicted N-value, F(1, 18) = 7,758, $p < 0.02$, $R^2 = .301$.

SoilN-NO3; GroundwaterN-NO3Avg.; SurfaceWaterP-PO4Mar – N-value
SoilN-NO3, GroundwaterN-NO3Avg. and SurfaceWaterP-PO4Mar statistically significantly predicted N-value, F(3, 16) = 18.650, $p < .001$, $R^2 = .78$. All three variables added statistically significantly to the prediction, $p < .05$.

SoilP-PO4; GroundwaterN-NO3Avg.; SurfaceWaterP-PO4Mar – N-value
SoilP-PO4, GroundwaterN-NO3Avg. and SurfaceWaterP-PO4Mar statistically significantly predicted N-value,, F(3, 16) = 17.433, $p < .001$, $R^2 = .77$. All three variables added statistically significantly to the prediction, $p < .05$.

Appendix 7 - Measured Parameters versus Thresholds and Measures by Van Dijk

Parameter	**V. Dijk**	**Threshold**	**Measured**	**Remarks**
Statistically significant				
Surface water in March P-PO4 mg/l	0.082 avg/yr	0.016 max.	March 2021 avg. 0.003	Substantially lower than Van Dijk Lower than recharge water, later increase/accumulation
ENL P-PO4 g/m2/6 weeks	2.1 avg/yr	NA	March/May/Jul 2021 avg. 0.15 (max. 0.48)	Substantially lower than Van Dijk, even with higher slopes
Groundwater P-PO4 mg/l	NA	0.02-0.23	0.004-0.028 (avg. 0.014) Avg. Mar: 0.010, May: 0.012, Jul: 0.021	Below threshold
Groundwater N-NO3 mg/l	NA	0.02-2.7	0.1-2.0 (avg. 1.1)	Below threshold
Soil P-PO4 µmol/l	NA	75-225 (max. 300)	37-542 (avg. 108) Without outlier: 37-167 (avg. 85)	Below threshold
Soil NO3 µmol/l	NA	15-65 (max. 100)	18-777 (avg. 219)	4 plots below max. of range, 7 below max. of 100.
Non-significant parameters				
Recharge water P-PO4 mg/l	0.1 avg/yr	NA	April-June 2021 avg 0.02 November 2020-October 2021 avg 0.04 Oct 2020-Feb	Substantially lower than Van Dijk
Recharge water N-NO3 mg/l	4.0 avg/yr	NA	November 2020-October 2021 avg 2.3	Substantially lower than Van Dijk
Recharge water N-NH4 mg/l	0.12 avg/yr	NA	November 2020-October 2021 avg 0.008	Substantially lower than Van Dijk
Recharge water pH	NA	NA	8.0 avg/yr March-July: 8.0 avg.	
Surface water P-PO4 mg/l	0.082 avg/yr	0.016 max.	March/May/Jul 2021 avg. 0.006. Max. 0.018. Avg Mar: 0.003, May: 0.007, Jul: 0.010	Substantially lower than Van Dijk Accumulation after start of the growing season?
Surface water N-NO3 mg/l	2.3 avg/yr	0.11 max.	March 2021 avg. 2.4 (max. 2.7) March/May/Jul 1.7	Comparable to Van Dijk Decrease after start of the growing season
Surface water N-NH4 mg/l	NA	0	March 2021 avg. 0.024 March/May/Jul 0.039	Accumulation after start of the growing season?
Surface water pH (KCl)	NA	NA	March 7.8-9.0 (avg. 8.6) March-July 7.4-9.0 (avg. 8.3). July avg. 8.0	Decreases from March to July
ENL N-NO3 g/m2/6 weeks	28.3 avg/yr	NA	March/May/Jul 2021 avg. 48 (max. 152)	Due to higher slopes substantially higher than Van Dijk.
ENL N-NH4 g/m2/6 weeks	NA	NA	March/May/Jul 2021 avg. 0.99 (max. 6.48)	
Groundwater N-NH4 mg/l	NA	0.04-0.66	0.02-0.1 (avg. 0.037)	Below threshold

Parameter	**V. Dijk**	**Threshold**	**Measured**	**Remarks**
Groundwater pH (A+B)	NA	7.1-7.6	March 6.6-8.0 (avg. 7.5) July 6.2-7.2 (avg. 6.8)	Partly lower than threshold. Decreases from March to July
Groundwater pH A	NA	7.1-7.6	May 6.9-8.0 (avg 7.33) May-Jul 6.4-8.0 (avg. 7.05)	Partly lower than threshold. Decreases from March to July
Groundwater pH B	NA	7.1-7.6	May 6.7-7.5 (avg. 7.26) May-Jul 6.2-7.5 (avg. 7.00)	Partly lower than threshold. Decreases from March to July
Soil NH4 µmol/l	NA	15-60 (max. 90)	Avg. 239. 41-653	One plot below max. of range. 2 plots below of max. of 90.
Soil O.M. %	Avg. 2.3	1.2-15.5 (avg. 5.1)	2.0-16.5 (avg. 5.0, 4.4 without outlier)	19 plots below max. target value
Soil pH (KCl)	NA	6.4-7.1 (avg. 6.8) min-max 5.8-8.2)	Avg: 6.6 (4.6-8.5)	Nine plots <= 6.5*
INL P-PO4 mg/kg	1	NA	1.5	Higher than Van Dijk
INL N-NO3 mg/kg	10	NA	6.5	Lower than Van Dijk
INL N-NH4 mg/kg	NA	NA	21.5	

* = pH in soil between 4.5 – 6.5 means no carbonates present (Smolders et al., 2011)