Landscape Ecology (2005)
DOI 10.1007/s10980-005-1436-7

Research Article

Is nutrient contamination of groundwater causing eutrophication of groundwater-fed meadows?

N.M. Pieterse*, H. Olde Venterink, P.P. Schot and A.W.M. Verkroost
*Faculty of Geosciences, Utrecht University, PO Box 80115, 3508TC Utrecht, The Netherlands; *Author for correspondence: Current addresses: Netherlands Institute for Spatial Research, PO Box 30314, 2500 GH Den Haag, The Netherlands; Willem Witsenplein 6, 2596 BK Den Haag, The Netherlands; (e-mail: pieterse@rpb.nl)*

Received 5 September 2002; accepted in revised form 31 January 2005

Key words: Chloride tracing, Ecological restoration, Environmental quality, Groundwater pollution, Nature management, Nutrient-enrichment

Abstract

There is an ongoing debate as to whether nutrient contamination of groundwater under agricultural fields may cause nutrient-enrichment and subsequent eutrophication in discharge areas. Often, there is only circumstantial evidence to support this supposition (proximity of agricultural fields, direction of water flow, highly productive vegetation). Research on solute transport along a flow path is necessary to evaluate the risk for eutrophication. In this paper we present results of such a study. Two transects were established in a discharge meadow, a few meters downstream from fertilized cornfields. Highly productive vegetation in parts of the meadow suggested nutrient-enrichment caused by inflow of contaminated groundwater. This supposition was supported by an analysis of groundwater flow paths, residence times and chloride as tracer for pollution. However, the fate of nutrients along the flow path indicated otherwise. While we found high concentrations of DIN (dissolved inorganic nitrogen), P and K under the cornfields, DIN and P concentrations drop below detection limit when groundwater enters the meadow. Only K progressed into the meadow but did not enter the root zone. We conclude that (1) polluted groundwater from the cornfields did not cause the nutrient-enrichment, as indicated by the highly productive vegetation. Restoration projects in discharge areas should not focus upon measures in upstream areas if only circumstantial evidence is available. Solute transport should be considered as well. (2) Because K clearly showed to be the most mobile nutrient, its importance for nutrient-enrichment in discharge wetlands merits more attention in future research.

Introduction

Eutrophication is a major threat for species-rich meadows in Europe (Anonymous 1992; Stanners and Bourdeau 1995; Rich and Woodruff 1996; McCollin et al. 2000). Eutrophication is the process of nutrient-enrichment, causing a shift from low-productive and species-rich meadows towards highly productive and species-poor meadow (Grootjans et al. 1985, 1986; Oomes et al. 1996). More specific: enrichment with nitrogen (N), phosphorus (P) and/or potassium (K) may cause such a shift since the vegetation in European meadows is generally growth-limited by one or more of these nutrients (Olff and Pegtel 1994; Verhoeven et al. 1996; van Duren et al. 1997; Olde Venterink et al. 2002). Atmospheric N-deposition, and increased soil nutrient release rates through altered site conditions are important sources of nutrient enrichment

(Koerselman and Verhoeven 1992; Olde Venterink et al. 2002b).

There is ongoing debate as to whether inflow of nutrient-contaminated groundwater can be regarded as one of the nutrient sources in discharge areas (e.g. Bijlmakers et al. 1987; van der Aart et al. 1988; Verhoeven et al. 1988; Pedroli 1989; Maltby et al. 1994; Poiani et al. 1996). Some of these authors believe that groundwater inflow is a real cause for eutrophication of discharge meadows, and propose nature conservation plans and restoration plans from this point of view. If this supposition is true, the situation is alarming for many discharge meadows and other herbaceous wetlands since groundwater in European and North American agricultural catchments is becoming increasingly contaminated with nutrients (Barry et al. 1993; Khakural and Robert 1993; Spalding and Exner 1993; Jemison and Fox 1994; Böhlke and Denver 1995; Refsgaard et al. 1999). However, there is only limited data to support this supposition; i.e. often it is only based on circumstantial evidence such as proximity of a fertilized agricultural field and enhanced biomass production in the discharge area.

The objective of this study was to examine more closely whether nutrient-contaminated groundwater really causes nutrient-enrichment in a discharge meadow and possibly eutrophication; i.e. by analyzing nutrient transportation along the groundwater flow-path. We established two transects in a discharge meadow of which circumstantial evidence suggests nutrient-enrichment through contaminated groundwater: First, the meadow is located only a few meters adjacent to fertilized cornfields. Second, the meadow is lower in elevation than the adjacent cornfields and therefore is likely to receive groundwater from these cornfields. Third, the cornfields have been heavily fertilized for many years, so the groundwater is likely to be contaminated with nutrients. Fourth, a part of the meadow, including a zone adjacent from the cornfields, is covered with highly productive vegetation. Garritsen (1988) concluded from these factors that eutrophication within the meadow might be caused by inflow of nutrient enriched groundwater, originating from the adjacent cornfield. We adapt his hypothesis.

To test the hypothesis, we answered the following questions: (1) does groundwater flow from the cornfields into the meadow, and what is the travel time? (2) does groundwater convey nutrients and/or other solutes from the cornfields to the meadow? and if so: (3) do the nutrients N, P and K enter the root zone of the meadow?

Study area

The study was carried out in two transects within the Dommelbeemden meadow, in the southern part of The Netherlands (Figure 1).

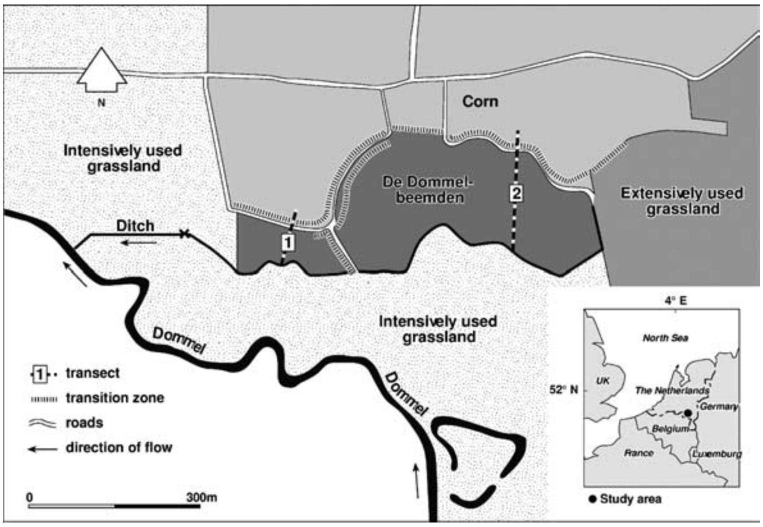

Figure 1. Nature reserve 'De Dommelbeemden' with the land use situation between 1970 and 1990.

The meadow is situated within a former meander of the river Dommel, cut 2 to 3 m deep into Pleistocene sand. The meander is filled with peat and clay deposits, beneath which is a sandy aquifer connected to a sandy plain bounding the north side of the meadow. Up until 1955 local farmers used the meadow to produce hay, after which it became a nature reserve. Since 1961 the meadow is mown every year; hay is removed. The meadow has never been fertilized (Garritsen 1988). The vegetation of the meadow consists of relatively low productive *Junco-Molinion* and *Calthion palustris* communities along the most eastern transect, and of the high productive *Valeriano-Filipenduletum* community along the western transect (nomenclatura follows Schaminèe et al. 1996). The sandy plain is used primarily for growing corn, which has been intensely fertilized since the 1970s with approximately 600 kg N ha^{-1} yr^{-1} and 175 kg P ha^{-1} yr^{-1} (Statistics Netherlands 1998), which is amongst the highest in the world (Chapin et al. 2002). The transition between the sandy plain and the meadow is abrupt; the sandy plain is approximately 1.5 m higher in elevation than the meadow. The transition zone (which is neither mown nor fertilized), is covered with highly productive shrubs, herbs, and grasses (e.g. *Rubus* sp., *Urtica dioica*). To the south, the meadow is bounded by a ditch, which discharges to the river Dommel. Occasional floods enter the meadow through this ditch during peak discharge events of the river.

Methods

Transects

Information on the location and depth of sampling tubes is shown in Figures 2–4. Transect 1 was established in the western part of the meadow, was 80 meters long and contained four sampling locations. Transect 2 was established in the eastern part of the meadow, was 200-m long and contained seven sampling locations. The direction of the transects was perpendicular on the general direction of groundwater flow, taken from hydraulic maps (Pieterse et al. 1998b). Six other sampling locations were used for a statistical analysis and for a nutrient balance study (Olde Venterink et al. 2002b). Groundwater tubes were placed on three depths below the surface for most locations: two tubes were placed in shallow

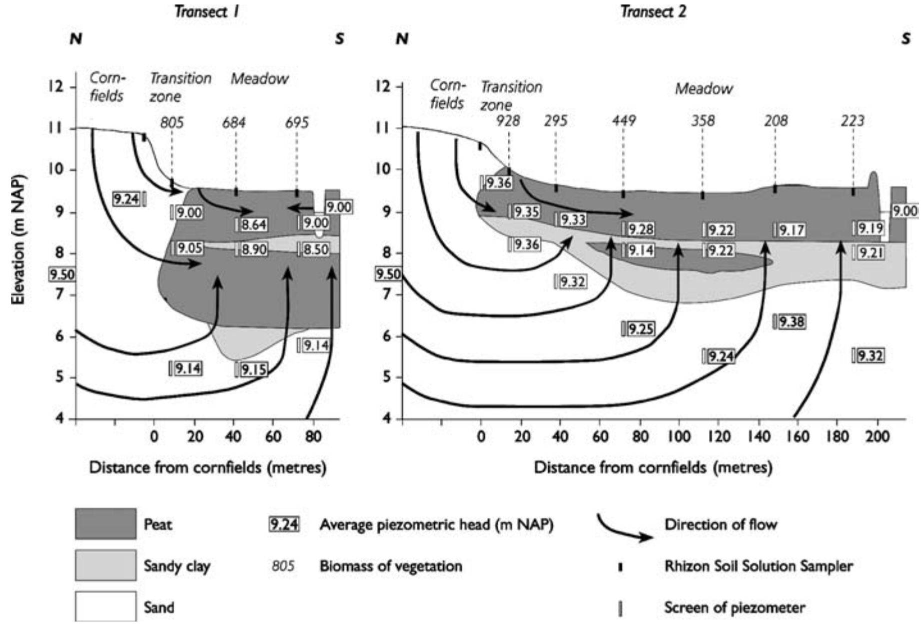

Figure 2. Lithology, piezometric heads and groundwater flow paths in transects 1 and 2 in 'De Dommelbeemden' meadow. The piezometric head of groundwater 200 m upstream from the transition zone is presented at the left side of the *y*-axis. Biomass of the vegetation is printed in italics above the sampling locations.

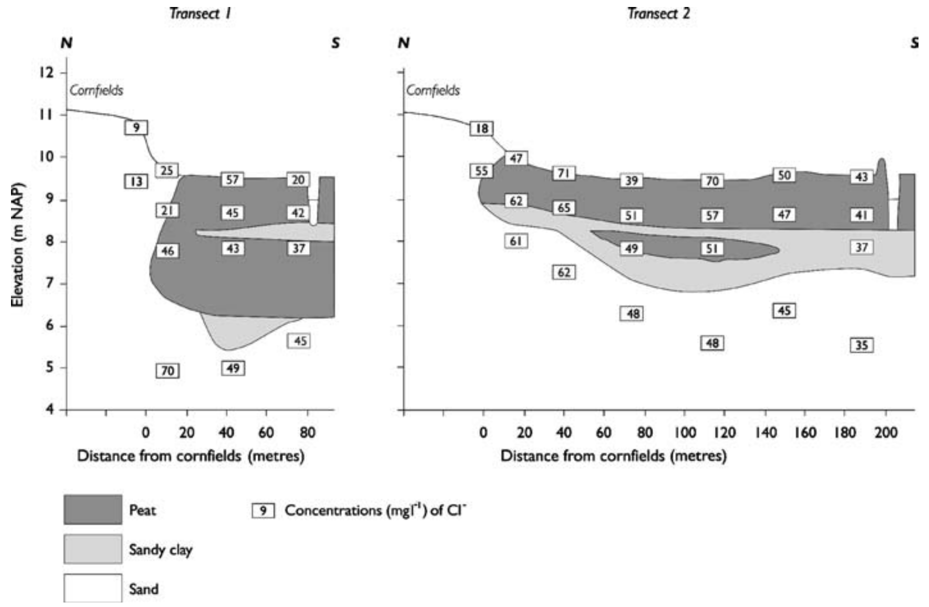

Figure 3. Median Cl^- concentrations in transects 1 and 2. Concentrations are in mg l^{-1}.

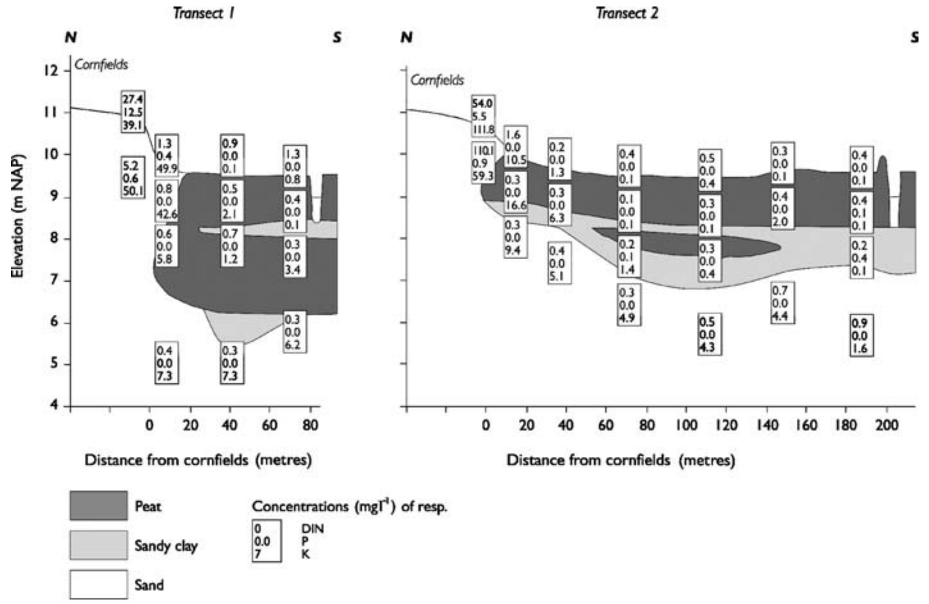

Figure 4. Median concentrations for DIN, total-P and K in transects 1 and 2. Concentrations are in mg l^{-1} .

groundwater at 90 cm and at 140 cm depth, and one tube was placed in the sandy aquifer under the meadow at 500-cm deep. Some locations had two tubes, omitting the 140-cm tube, or had only one tube at a depth of 90 cm because the peat and clay sediments on corresponding locations were thin or absent. The PVC groundwater tubes had an inner diameter of 3.5 cm and contained a 30-cm long screen at the end. The tubes were protected from dust and rain with a screw cap, containing a small hole to equalize the air pressure in the tube with atmospheric air pressure. The tubes were ground-leveled. Three Rhizon SSS soil moisture samplers (Meijboom and Noordwijk 1991) were placed at every location to measure soil moisture concentrations of the upper 10 cm of the soil.

Once a month, from August 1995 to August 1996, piezometric heads were measured and water samples were collected from groundwater in the piezometers and from the soil moisture samplers. In addition, surface water was sampled by storing 0.5 l of surface water in a PVC bottle. One day before the actual sampling, the piezometers were pumped dry to allow the wells to recharge and vacuum tubes were connected to the Rhizon SSS.

All water samples were immediately sealed from the air with a cap and stored in a cold chamber at 4 °C. The samples were centrifuged and acidified for conservation within 2 days. We centrifuged the samples to prevent large particles from dissolving in the acid environment or jamming the measurement device. We used centrifugation instead of filtration, because it is known that orthophosphate easily absorbs to the filtration material (Stuyfzand 1983). Phosphorus (P) and Potassium (K) were analyzed on an Inductive Coupled Plasma device working with atomic emission spectrometry (ICP-AES). Phosphorus concentrations are dominated by PO_4^{3-} but also include P that was incorporated in organic compounds that easily degrade in the high temperature (>8000°K). Chloride (Cl^-) and dissolved inorganic nitrogen (DIN: $NH4^+$, NO_3^- and NO_2^-) were analyzed in an Auto-analyzer (Continuous Flow System), by means of colorimetry.

At the peak of the growing season (July 1996), aboveground vegetation was harvested at all locations. The vegetation (standing living + standing dead of vascular plants) was cut at 2 cm above soil surface in three squares (0.25 m^2) close to the groundwater tubes. The samples were dried at 70 °C during 48 hours and weighted. Average biomass values were calculated for every location. The biomass values represent productivity of one growing season because the meadow is mown annually and hay is removed.

Groundwater flow and travel times

To find out whether the groundwater was flowing from the cornfields into the meadow groundwater flow paths and travel times were determined using the measured piezometric heads. The direction of groundwater flow was drawn by hand from locations with high piezometric heads to locations with low heads. Travel time between recharge area and meadow was estimated with Equation (1) (Appelo and Postma 1993):

$$V = \frac{dx}{dt} = \frac{Qx}{D\varepsilon} \tag{1}$$

where v is the groundwater velocity at point x (m yr^{-1}), Q is the precipitation surplus (m yr^{-1}), which is 0.213 m for cornfields in the region (Pieterse et al. 1998a), x is the distance from the catchment boundary, approximated at 300 m (Garritsen 1988). D is the thickness of the aquifer (m), which is 22 m (Garritsen 1988), and ε is the effective porosity, which is set to 0.3 (Wösten et al. 1994).

Vertical flow velocity between the aquifer under the meadow and the root zone is calculated with Darcys law:

$$q = -k\frac{\Delta\phi}{\Delta h} \tag{2}$$

where q is the upward flow velocity (m day^{-1}), $\Delta\ \phi$ is the vertical hydraulic gradient (m) and Δh is the vertical distance between root zone and top of the aquifer (m), which is on average 2.5 m. The conductivity (k) is 1×10^{-1} m day^{-1} for peat, and 7×10^{-2} m day^{-1} for sandy clay (after Weerts 1996). The lowest, restrictive, conductivity of 7×10^{-2} m day^{-1} is used.

The travel time of groundwater between the edge of the cornfields and (for instance) the middle of each transect can be assessed by dividing the distance by the calculated horizontal flow velocity and add up the vertical travel time (D/q).

Transport of solutes from cornfields to meadow

Chloride could be used as indicator for pollution because the investigated area is not under marine influence (c.f. Schot and Van der Wal 1992; Altman and Parizek 1995). The origin of chloride in these systems is the abundant use of artificial fertilizers containing high amounts of chloride.

We considered groundwater in our meadow to be contaminated with fertilizer if chloride concentrations in the meadow were significantly larger than background concentrations. Background concentrations were deducted from groundwater samples taken in the Zwarte Beek catchment

(Belgium). This neighboring catchment of the Dommel catchment is assumed to represent natural conditions, because it has not been exposed to intensive agricultural practices in the last 150 years. Because the hydrochemistry of the Zwarte Beek catchment may be somewhat different from the Dommel catchment, also groundwater samples were collected from nature reserves in the wide surroundings of the meadow providing background concentrations for the Dommel catchment. A Mann–Whitney *U*-test (Davis 1986) was used to test the differences in groundwater chloride concentrations between the meadow and background concentrations of both the Zwarte Beek and the Dommel region.

The fate of nutrients

The fate of DIN, P and K during transport in groundwater and soil moisture was assessed by plotting their respective concentrations along both transects. To check whether nutrient concentrations in our meadow could be distinguished from natural background concentrations, DIN, P and K concentrations were compared with those in background groundwater of the Zwarte Beek catchment and Dommel catchment (see above), using a Mann–Whitney *U*-test.

Results

The aboveground biomass values along the transects illustrate the differences in productivity of the vegetation in the Dommelbeemden meadow (Figure 2). High-productivity was found in the western part of the meadow (transect 1), and near the cornfields in the entire meadow (both transects 1 and 2). Low- and intermediate productivity was found in the central part of the meadow (larger part of transect 2).

The assessed flow paths of water show that rainwater infiltrates in the cornfields and subsequently flows as groundwater from the cornfields to the wetland (Figure 2). Groundwater levels 200 m upstream from meadow are approximately 0.5 m higher in elevation than within the meadow. Using Equation (1), the horizontal flow velocity from cornfield to wetland (within the aquifer) was calculated at 10 m yr^{-1}. The direction of groundwater flow under and in the meadow is predominantly upward (Figure 1). The vertical flow velocity within the meadow was calculated at 1.3 m yr^{-1}, using Equation (2) and given a hydraulic gradient of 0.1 m between aquifer and the root zone of the meadow. For transect 1, it will take 6 years for a raindrop to infiltrate in the cornfield and seep up in the middle of the transect (40 m/10 m yr^{-1} + 2.5 m/1.3 m yr^{-1}). For transect 2 the travel time is assessed at 12 years.

Chloride concentrations in the Dommelbeemden meadow were significantly higher than background chloride concentrations in the Zwarte Beek catchment as well as elsewhere in Dommel catchment (Table 1). High chloride concentrations in the groundwater were particularly found near the cornfields (60–70 mg l^{-1}); the concentration decreased towards the centre of the wetland to 40–50 mg l^{-1}, in both transects (Figure 3).

Concentrations of DIN and K were significantly higher under the cornfields than background concentrations (Table 1). Similar to chloride, high concentrations of DIN, P and K were found in the direct proximity of the cornfield (Figure 4). However, in contrast to chloride, DIN and P concentrations in groundwater were practically down to zero a few meters further downstream. Only K had progressed into the first few meters of the meadow.

Discussion

The objective of this study was to examine whether nutrient-contaminated groundwater from cornfields might cause nutrient-enrichment in a discharge meadow. The chosen meadow ‘The Dommelbeemden’ is one of most likely wetlands in the Netherlands where eutrophication due to inflow of nutrient enriched groundwater might take place. This supposition was based upon the circumstantial evidence that: (1) the wetland is a discharge meadow, which is lower in elevation than its surroundings; (2) the meadow is located adjacent from an intensely fertilized cornfield (up to 600 kg N ha^{-1} yr^{-1} and 175 kg P ha^{-1} yr^{-1} (Statistics Netherlands 1998); and (3) that highly-productive vegetation

Table 1. Comparative statistics of concentrations of DIN, Total-P, K^- and Cl^- in groundwater, surface water and soil moisture.

	n	DIN	Total-P	K^-	Cl^-
Soil moisture (0.1 m below surface)					
Dommelbeemden	18	0.5 (0.3–1.6)^{a}	*	0.2 (0.1–2.0)^{a}	46.7 (32.1–61.5)^{a}
Dommel region	35	0.5 (0.3–2.0)^{a}	*	0.8 (0.1–2.4)^{a}	25.5 (13.9–30.1)^{b}
Zwarte Beek region	21	0.4 (0.2–1.1)^{a}	*	0.1(0.1–2.3)^{a}	6.5 (4.5–14.3)^{c}
Shallow groundwater (0.8 m below surface)					
Dommelbeemden	25	0.3 (0.2–0.6)^{a}	*	0.9 (0.1–5.8)^{a}	46.0 (36.3–54.4)^{a}
Dommel region	44	0.4 (0.2–0.7)^{a}	*	1.0 (0.4–1.7)^{a}	16.7 (13.0-24.6)^{b}
Zwarte Beek region	23	0.2 (0.1–0.6)^{a}	*	0.6 (0.1–1.5)^{a}	5.6 (4.1–14.9)^{c}
Deep groundwater (5.0 m below surface)					
Dommelbeemden	15	0.5 (0.3–0.7)^{a}	*	4.3 (1.9–5.6)^{a}	47.6 (38.8–54.7)^{a}
Dommel region	21	0.5 (0.3–0.6)^{a}	*	1.4 (1.1–1.8)^{b}	16.1 (13.4–19.5)^{b}
Zwarte Beek region	5	0.3 (0.3–0.3)^{a}	*	2.1(1.7–2.5)^{b}	5.8 (4.8–16.0)^{c}
Surface water					
Ditch	1	3.1	0.19	5.3	44.2
Pools after flooding	7	1.8 (1.2–2.2)	0.30 (0.26–0.39)	9.3 (8.7–9.5)	25.8 (25.5–26.4)
River Dommel (embanked flow)	1	7.9	2.06	14.0	64.3

Data is collected over the period August 1995– August 1996. Values are shown for the studied meadow (De Dommelbeemden), six fens and meadows in the Dommel region (The Netherlands) and three fens in the neighbouring Zwarte Beek region (Belgium). A Mann–Whitney *U*-test ($p < 0.05$) is carried out for each depth between the 3 sites. Significant differences are indicated with different characters. To avoid pseudo replication (Hurlbert 1984), median values were taken per location; n = number of locations. Concentrations are given as mg l^{-1} of the atomic weights. Values between brackets indicate 25 and 75 percentiles. *At or below detection limit for phosphorus (0.03 mg P l^{-1}).

was found within the meadow (up to 900 g m^{-2}, Figure 2) despite 35 years of hay removal without fertilization. The high productive vegetation might indicate that eutrophication has taken place.

Additional field measurements seem to support the circumstancial evidence. Reconstruction of groundwater flow paths suggests that groundwater from below the cornfields is bound to the meadow (Figure 1). The average time for groundwater to travel from cornfield tot meadow is approximately 6–12 years. Because fertilization has started much earlier than 12 years before the moment of measuring (the early 70s and 1980 respectively), it is likely that leached fertilizer could have been transported into parts of the meadow. Chloride as a tracer for pollution also suggest that polluted groundwater from the cornfields has entered the meadow: chloride concentrations in the aquifer below the meadow were above natural background values (Table 1), with a noticeable decrease from cornfields to the meadow (Figure 3) due to dilution with groundwater from below (Garritsen 1988). Could there be other sources of chloride? First, a combination of flooding and evapotranspiration might be a potential source. Flooded water contains approximately 25 mg l^{-1} chloride (Table 1), which can be tripled for soil and groundwater concentrations in The Netherlands due to evapotranspiration (Schot and Van der Wal 1992). Although the combination of river water and evaporation may have caused enhanced concentrations at the southeastern side of the meadow, it cannot explain enhanced chloride concentrations in the western and upper parts of the meadow. Second, spraying the local road with salt under winter conditions might be a source for chloride for the western and upper parts (e.g. Boutt et al. 2001). However, we disregard spraying with salt as a possible source because only locals use the road, and it is common policy to spray intensely used roads only. Furthermore, we sampled one of our regional piezometers one meter away from the road (only its piezometric heads are shown in Figure 2). Analyses reveal very low chloride concentrations (5.4–12.5 mg l^{-1}) at 2 meter deep.

Although the evidence presented so far indicates that nutrient enriched groundwater flows from the cornfields towards the meadow, it does not prove that groundwater was the source of nutrient enrichment of the meadow. Our data suggests that groundwater under the cornfields was contaminated with DIN and P (Figure 4). This corresponds with studies concerning N and P output to groundwater under agricultural fields (e.g. Jemison and Fox 1994; Schnabel et al. 1996). In addition, we also found high K concentrations (between 50 and 74 mg l^{-1}) in groundwater below the cornfields. However, our data seems to suggest that DIN and P never entered the meadow (Figure 4). Only K progressed within the aquifer – diluted by influx of deep groundwater – and into the first 50 m of the meadow in the direct proximity of the cornfields. Other parts of the meadow were not contaminated with K.

While DIN concentrations under the cornfields were high, DIN concentrations drop to zero at greater distance from the cornfields (Figure 4). This sudden drop of DIN was also found in other studies (e.g. Dorge 1994; Gross et al. 1995; Lowrance et al. 1995; Hill 1996; Hessen et al. 1997; Martin and Reddy 1997; Willems et al. 1997). These studies and a review on nitrogen retention (Altman and Parizek 1995) showed that nitrate was removed from groundwater through denitrification in riparian zones and wetlands. Although we did not measure the processes involved, it seems safe to assume that the same processes take place in our meadow; i.e. the predominant form of DIN in groundwater was NO_3^-, and the necessary anaerobic conditions could be created by a high oxygen demand of the organic material in the meadow.

We found high phosphorus concentrations in the immediate proximity of the cornfield, and very low concentrations in the aquifer and within the meadow (Figure 4). This suggests that P is retained immediately after leaching from the cornfields. Numerous processes might have accounted for this result, such as microbial immobilization, plant uptake and absorption to iron sesquioxides (c.f. Richardson 1985).

In contrast to DIN and P, our data shows that K concentrations were high along the whole length of transect 1 and up to halfway transect 2. These high values could not be explained by weathering of clay minerals, because the concentrations significantly exceed the natural background concentrations in groundwater (Table 1). Moreover, the enhanced K concentrations were not found in the peat and clay deposits but only in the aquifer, and they showed a gradient from cornfield to wetland. Both the high concentrations and the gradient suggest that K was originating from fertilizer. Although is possible that the clays in the wetland could account for some sorption, the sandy material of the aquifer does not have much sorption capacity (Appelo and Postma 1993). The gradual decrease in the aquifer can therefore be accounted to dilution. Assuming that the sudden decrease in the clay soils is due to sorption, we expect that it is only a matter of time before potassium will seep upward into the root zone. The soil will eventually become saturated with K if fertilization will continue to take place. Because we did not investigate the CEC of the clay and the peat lithology, we cannot give an indication of time before this will occur.

Although chloride seems to indicate that groundwater in both transects was influenced by recharge water from the cornfields, recharging groundwater did not cause nutrient-enrichment in the meadow. Alternative sources for nutrients and the impact of alternative nutrient export via haying has not been analyzed within in the context of this study but has been examined in a study by (Olde Venterink et al. 2002b). Likely sources may be lateral transport of fertilizer, for instance due to strong winds and overland flow after storm events. However, the distance seems too far and the slope too low to allow fertilizer to penetrate deep within the meadow. Most likely sources are mineralization due to high water level dynamics (Grootjans et al. 1985, 1986; Olde Venterink et al. 2002a, b) and flooding of the river that might convey particulate phosphorus and nitrogen that are bound to suspended particles (Meyer and Likens 1979; Vighi et al. 1991; Kronvang 1992; Norton and Fisher 2000).

As long as there is an abundance of active organic material, DIN will be easily denitrificated. In general however, it cannot be concluded that DIN in groundwater would never seep into the root zone. A study by Lowrance et al. (1997) in Chesapeake Bay shows that, in his case, the amount of DIN that seeps to the root zone largely depends on the type of vegetation, the thickness of the permeable layer, the magnitude of upwards seepage and the percentage of organic material in the soil. Phosphorus has not year reached the root zone of the meadow, but may cause an increasing problem in the future. Phosphorus is only retained and not removed from the soil, except if it is taken up by plans and removed from the area by producing hay. Because the P-absorption capacity of the soil is limited, leached P from the cornfields may progress into the groundwater system over time. Although the adsorption capacity of the sandy soils is low, it may still take a very long time – sometimes up to a century – before this may happen (Oenema and Van Dijk 1995). Our study showed that K was the most mobile nutrient. It is likely that K will be the first nutrient to enter the root zone of the discharge meadow. Since K can be growth-limiting in meadows and other herbaceous wetlands (van Duren et al. 1997; Olde Venterink et al. 2002b), such K-enrichment may cause eutrophication in our meadow, as well as other discharge areas. Given the limited attention for K in previous studies, more research is needed to analyze the implications of leaching of K to discharge wetlands and its potentials to cause eutrophication in the short and long term.

Based on our results and international literature, we expect that groundwater will not be an important source for N and P in the root zones of similar (peat rich) discharge zones in European and American discharge meadows, only K may cause problems in meadows that are (co)limited by K. We conclude that ecological reconstruction plans for riparian zones need to underpinned carefully and should preferably be based on hydrochemical- and hydrological measurements. Even if circumstantial evidence seems to suggest nutrient-enrichment due to inflow of contaminated groundwater, additional research on the fate of nutrients in groundwater remains necessary and alternative sources need to be investigated.

Acknowledgements

This research was a part of the EU-LIFE demonstration project for the development of integrated management plans for Trans-border lowland river catchments. We would like to thank Andre de Hamer for his field assistance and Dick Belgers and Wilma Peeters for field assistance and lab work. In addition, we would like to thank the NGOs Staatsbosbeheer, Natuurmonumenten, the municipality of Eindhoven and the Ministry of Defense of Belgium for providing us access to the areas under their custody. Finally, the suggestions from the anonymous reviewer improved our paper considerably.

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