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High frequency monitoring of water fluxes and nutrient loads to assess the effects of controlled drainage on water storage and nutrient transport

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Abstract

High nitrogen (N) and phosphorus (P) fluxes from upstream agriculture threaten aquatic ecosystems in surface waters and estuaries, especially in areas characterized by high agricultural N and P inputs and densely drained catchments like the Netherlands. Controlled drainage has been recognized as an effective option to optimize soil moisture conditions for agriculture and to reduce unnecessary losses of fresh water and nutrients. We designed a small scale (1 ha) field experiment to investigate the hydrological and chemical changes after introducing controlled drainage. Precipitation rates and the response of water tables and drain fluxes were measured in the periods before the introduction of controlled drainage (2007–2008) and after (2009–2011). For the N and P concentration measurements, we combined auto-analysers for continuous records with passive samplers for time-average concentrations at individual drain outlets. Our experimental setup yielded continuous time series for all relevant hydrological and chemical parameters, which enabled us to quantify changes in the field water and solute balance after introducing controlled drainage. We concluded that controlled drainage reduced the drain discharge and increased the groundwater storage in the field. The introduction of controlled drainage did not have clear positive effects on nutrient losses to surface water.

1 Introduction

High nitrogen (N) and phosphorus (P) fluxes from agricultural areas threaten aquatic ecosystems in downstream surface waters, estuaries, and coastal zones around the world (e.g. Foley et al., 2005; Howarth, 2008). The effects of eutrophication, such as loss of biodiversity and toxic algae blooms threaten the industrial, recreational, and ecological functions of water resources (e.g. Makarewic et al., 2007; Weijters et al., 2009; Diaz and Rosenberg, 2011). The adverse effects of high nutrient inputs are most prominent in stagnant water bodies, with long residence times and low vertical and horizontal mixing, such as shallow lakes, bays and harbours. Current hotspots are the Gulf of Mexico, Chesapeake Bay, and the Great lakes in North America and The Baltic Sea and the North Sea in Europe. In addition, eutrophication-related problems arise in developing areas such as China, Southeast Asia, and South America (Seitzinger et al., 2010). Global changes, such as population growth and climate change, further increase the pressures on water resources and their vulnerability for eutrophication (e.g. Statham, 2012; Seitzinger et al., 2010).

Controlled drainage has been recognized as an effective option to optimize soil moisture conditions for agriculture and to reduce unnecessary losses of fresh water and nutrients. The strategy of controlled drainage is to stop draining as long as agricultural productivity is not threatened by wet conditions. This is achieved by control structures with adjustable overflow levels in subsurface tube drain systems. Several pilot studies (e.g. Evans et al., 1995; Wesstrom and Messing, 2007; Jaynes, 2012, Helmers et al., 2012) reported significant reductions in discharge of water via tube drains (−16 up to −89 %). Although the nitrogen concentrations in the drain effluent did not change in most cases, the reduced water discharge also reduced the nitrogen export via tube drains (−18 up to −82 %).

None of the reported studies quantified the changes of nutrient export via other flow routes, such as shallow groundwater flow and overland flow. Therefore, the fate of the reduced water and nutrient exports often remains unknown (e.g. Woli et al., 2011). Ideally, the conserved water and nutrients enhance crop production. However, the reported effects of controlled drainage on crop production vary between no significant change up to an increase of 19 % at individual fields (Wesstrom and Messing, 2007; Ghane et al., 2012). Considering the limited increase in water and nutrient uptake by crops, the possibility arises that water and nutrients are still exported towards the surface water, though via enhanced overland or shallow groundwater flow.

This study aimed at quantifying the effects of controlled drainage on water and nutrient exports from an agricultural field to the surface water. We designed a small scale (1 ha) field experiment to investigate the changes in flow route contributions to-

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wards surface water after introducing controlled drainage. Precipitation rates and the response of water tables and drain fluxes were measured in the periods before the introduction of controlled drainage (2007–2008) and after (2009–2011). For the N and P concentration measurements, we combined auto-analysers for continuous records with passive samplers for time-average concentrations at individual drain outlets. This combination yielded all relevant parameters to assess the complete hydrological and hydrochemical response of the pilot field to the introduction of controlled drainage.

2 Methods

2.1 Study area

The experimental setup was installed in the Hupsel catchment (6.64 km^2) in the eastern part of the Netherlands (Fig. 1) (52°03′ N; 6°38′ E). The surface elevations in the catchment range from 22–36 m above sea level (a.s.l.) and the land use is predominantly agricultural with maize and grassland. At depths ranging from 0.5 to 20 m a 20–30 m thick impermeable marine clay layer of Miocene age is found of which the top is carved by glacial erosion. This clay layer forms a natural lower boundary for the unconfined groundwater flow (Van Ommen et al., 1989; Van der Velde et al., 2010). The unconfined aquifer consists of Pleistocene aeolian sands with occasional layers of clay, peat and gravel. Wösten et al. (1985) classified the main soil type of the catchment as sandy, siliceous, mesic Typic Haplaquads (See Wösten et al. (1985) for more details). The catchment is drained by a dense network of artificial ditches and subsurface tube drains. The spacing between the ditches averages 300 m and tube drainage is installed in more than 50 % of the area. For a more detailed description of the Hupsel catchment we refer to Van der Velde et al. (2010).

For the field scale evaluation of controlled drainage, we selected a 0.9 ha grass field in the northern part of the catchment. Within this field, surface elevations range between 27.5 and 28.5 m + a.s.l.. The subsurface consists of a 3–4 m thick unconfined

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sandy aquifer of Pleistocene aeolian sands. Below this, a 20–30 m thick impermeable marine clay layer of Miocene age forms the natural lower boundary for the unconfined groundwater flow (Van Ommen et al., 1989). Subsurface drain tubes of 5 cm in diameter were present with spaces of 14.5 m between individual drains. The drains discharged into the eastern ditch at 90 cm below the field surface level. Over their 200 m length the tubes sloped upward by 20 to 60 cm away from the ditch, depending on the local topography (Rozemeijer et al., 2010b). Rozemeijer et al. (2010a) quantified that the tube drains contributed 80 % of the total yearly water discharge to the surface water and 90 % of the total yearly NO_3-N and P export.

2.2 Experimental setup reference period

The water and nutrient fluxes at the experimental field were monitored for the reference situation with conventional drainage from May 2007 to December 2008. During the summer of 2009, the setup was extended and we introduced controlled drainage. The monitoring period for the controlled drainage period was from November 2009 until September 2011. The farmers land management did not change during this period. During both periods, the field was used for grass harvesting and cattle grazing. Manure was applied at the experimental field up to the maximum allowed 170 kg N ha^{-1} during both the reference and the controlled drainage period.

The experimental setup for the reference period is described in detail by Van der Velde et al. (2010). We physically separated tile drain effluent from the groundwater and overland flow routes towards a 43.5 m ditch transect (Fig. 1). To separate the fluxes toward the eastern ditch via different routes, three adjacent sheet pile reservoirs were built in the eastern ditch. The in-stream reservoirs were constructed around the outlets of drains 1, 2, and 3 (Fig. 2) and captured overland flow, interflow, direct precipitation, and groundwater inflow from the thin aquifer above the Miocene clay. Excess water was pumped from the in-stream reservoirs into the ditch and the pumped volumes were recorded with digital flux meters with an accuracy of 2 %.

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The effluent from the tile drains was separated from the other flow routes by connecting each drain outlet to a 500 L vessel using a flexible tube (Fig. 2). After reaching a maximum level, the water was pumped into the ditch and the flux was measured with digital water flux meters. In addition to the discharge measurements, phreatic groundwater levels were measured weekly on 14 locations in two transects. The meteorological data were derived from the Royal Dutch Meteorological Institute (KNMI) weather station adjacent to the experimental field.

During the reference period, water quality samples were taken weekly from the three in-stream reservoirs and from the three drain effluent vessels. The samples were taken using a peristaltic pump and filtered in situ (0.45 µm). Electrical conductivity and the pH of the samples were measured directly in the field. Subsamples for ICP analysis were directly acidified with HNO3. All samples were transported and stored at 4 °C. The samples were analyzed within 48 h using IC (NO_3-N, SO_4, Cl), ICP-AES (Na, K, Ca, Fe, Mg, Si), ICP-MS (P, Al, Ni, Cu, Zn, Cd, Pb), AA (NH_4). HCO_3 was measured by titration. Samples with deviating results for ions measured by more than one analyze method and samples with an ionic unbalance were reanalyzed.

In addition to the grab sampling, we used SorbiCell-samplers (De Jonge and Rothenberg, 2005) for time-average NO_3-N concentration measurements of tile drain effluent. The samplers were replaced every month. An evaluation of SorbiCells based on duplicate analyses and comparison to conventional grab sampling and continuous measurements was published by Rozemeijer et al. (2010c).

2.3 Experimental setup controlled drainage period

After the reference period, the experimental setup was extended to study the effects of controlled drainage. The overflow levels of the drains were controlled by attaching the flexible connection tubes between the drain outlets and the collection vessels at the desired level (Fig. 3a). In the reference setup, the connection tubes were kept just below the water table in the reservoir using floaters. The excess water from the drainage effluent vessels was collected in a combined reservoir (Fig. 3b). This enabled continuous registration of NO_3-N and total-P concentrations of the combined drain effluent, for which we used a Nitratax-UV sensor and a Phosphax auto-analyser (both Hach, Germany, Fig. 3c). Phreatic groundwater levels were monitored continuously using pressure sensors in all 14 piezometers in transects B and D.

The overflow levels of the drains were adjusted roughly following the scheme in Fig. 4. To conserve as much water as possible, the overflow levels were elevated during most of the year. However, the winter ban on manure spreading ends on 15 February. Like many farmers, the land owner has a limited storage capacity for manure, which forces him to apply manure as early as possible after 15 February. To enable manure spreading, the overflow levels were lowered during February and March. In case of wet conditions at the end of the summer (grass harvest, manure spreading) the overflow levels were also lowered in consultation with the land owner.

3 Results

In this section, we first present the results for the quantitative hydrological monitoring. We focus on groundwater levels, flows and the field water balance before and after the introduction of controlled drainage. Subsequently, the results of the hydrochemical monitoring are presented.

3.1 Water levels, flows, and water balances

The most important quantitative hydrological monitoring results are summarized in Fig. 5. This graph presents the overflow level of the drains, the groundwater levels in transects B and D, the precipitation, and drainage flux. Both the reference period with a constant overflow level (black line) from May 2007 to December 2008 and the controlled drainage period from November 2009 until September 2011 are shown.

The overflow levels of the drain outlets were elevated for the first time in November 2009. Initially, the overflow level was raised up to 20 cm above the drain outlet levels. Starting in mid-December 2009, the overflow levels were raised up to +50 cm. In early spring 2010, the overflow levels were lowered to +35 cm to enable the first manure application. In the wet autumn 2010 period, and in early spring 2011, the overflow levels were lowered down to the original drain outlet level.

The groundwater levels are above the tube drain level during the winter drainage period. The differences between the individual piezometers in each transect are low, which indicates a minor groundwater level curvature between the drains. The winter groundwater levels are higher during the controlled drainage period compared to the reference period, especially in piezometers of the transect D at 80 m from the ditch. The total amount of precipitation was lower in the reference drainage season compared to the controlled drainage period (see also Table 1), which indicates that the higher groundwater levels are caused by the elevated overflow level of the drains. The groundwater levels are longer and more frequently above the land surface, which indicates that ponding and overland flow become more important. The groundwater levels at 5 m from the ditch in transect B seem to be less affected by controlled drainage. The most evident difference between the responses of transects B and D is in November 2010, when we raised the overflow levels to +50 cm. Before this, the groundwater level difference between transects B and D averages 15 cm. After elevating the overflow levels, the difference increases up to ca. 50 cm.

The tube drain fluxes are distinctly affected by the changes in overflow levels during the controlled drainage period. During the reference period, the drains were ephemerally active during the summer period of 2009. In the controlled drainage period, the tube drainage flow stops after raising the overflow levels in spring 2010 and 2011. No drainage flow was registered during the subsequent summer periods. However, the drainage flow is immediately re-activated after lowering the overflow levels. This effect is most prominent in the 2010–2011 drainage period, when the overflow levels were taken down with 50 cm at two moments, resulting in an immediate re-activation of the discharge.

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Table 1 presents the field water balances for the drainage season in the reference period (2 November 2007 – 2 April 2008) and for the same months during the controlled drainage period in 2009–2010 and 2010–2011. For these balances, precipitation and evapotranspiration were derived from the weather station next to the field. The drain discharge was directly measured during the reference and controlled drainage period. The groundwater and overland/biopore discharge towards the 45 m ditch transect were directly measured during the reference period (Van der Velde et al., 2010). Winegram (2012) used the measured groundwater discharges and groundwater level gradients to estimate the average saturated conductivity (k). This conductivity, together with the groundwater level gradients measured during the reference period, was used to estimate the groundwater discharge during the controlled drainage period. A similar approach was used to estimate the overland and biopore flow volumes during the controlled drainage period. In this case Winegram (2012) related the measured overland and biopore flow during the reference period to the amount of precipitation that fell on ponded parts of the field. The storage change in the water balance was derived from the difference in groundwater levels between the start and the end of the water balance periods. The net influx (or outflux) from the surrounding fields via regional groundwater flow cannot be measured, but was likely to occur and was needed to close the water balance (Van der Velde et al., 2010). More details on the water balance for the reference period were reported in Van der Velde et al. (2010) and for the controlled drainage period in Winegram (2012) and Rozemeijer et al. (2012).

When comparing the water balances for the reference period with the controlled drainage period, the differences in precipitation input and the groundwater storage change should be considered. The reference period was wetter than both controlled drainage periods, which may explain part of the other differences in the water balances. In addition, the groundwater levels rose during the reference water balance period. This change in groundwater storage during the reference period is compensated with a negative water volume (–108 mm), indicated as "compensation groundwater storage change" in the water balances in Table 1. During the first controlled drainage

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period, a smaller rise in groundwater levels was measured. During the second controlled drainage period the groundwater levels dropped slightly, which is compensated for in the water balance with a positive volume (+26 mm).

The discharge via the tube drains was significantly lower in the controlled drainage periods; −46 % in 2009–2010 and −58 % in 2010–2011. The discharge via groundwater increased slightly. Overland flow was slightly less in 2009–2010 and more in 2010–2011. However, these small changes in groundwater discharge and overland flow cannot compensate for the large reduction in discharge via drains. This compensation mainly comes from the net inflow of water from the surrounding fields. During the reference period, the field received a substantial influx of water from the surroundings (+154 mm). This influx was almost absent (+8 mm) during the first controlled drainage period. During the second controlled drainage period, a net outflux (−47 mm) from the field towards the surroundings was found. The change from a net influx to a net outflux is related to the elevated groundwater levels at the experimental field in the controlled drainage period.

3.2 Nutrient concentrations and loads

The measured nutrient concentrations (NO_3-N, P-tot, PO_4) in tile drain effluent for the reference period and the controlled drainage period are shown in Fig. 6. During the reference period, the NO_3-N concentrations varied between ca. 6 mg N L^{-1} in winter and 3 mg N L^{-1} in summer. During the controlled drainage period, higher NO_3-N concentrations of 8–10 mg N L^{-1} were recorded. These concentrations are well above the surface water quality standard of 2.3 mg N L^{-1} (Van der Molen et al., 2012). The NO_3-N concentrations do not directly respond to changes in the overflow levels of the drains. For P, low concentrations were measured, both before and after the introduction of controlled drainage. During the 2010–2011 drainage season, the P-tot concentrations increased after dropping the overflow levels and increasing the drain discharge.

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The results of the SorbiCell average concentration measurements for the individual drains are shown in Fig. 7. This figure shows that the largest increase in NO_3-N concentrations occurred in drain 3. During the reference period, the effluent from this drain showed NO_3-N concentrations close to zero. In the controlled drainage period however, the NO_3-N concentrations are between the concentrations measured in drain 1 and 2.

Cumulative plots of the nutrient loads from the three drains are shown in Fig. 8, together with the cumulative precipitation and drain discharge. The NO_3-N and P loads for distinct periods are given in Table 2. Because the loads partly depend on the precipitation in each period, the ratio's between loads and precipitation are presented as well.

The first three periods in Table 2 give the loads for periods of a total year. Comparing both controlled drainage years (periods 2 and 3) with the reference (period 1) shows that the P loads were reduced after introducing controlled drainage. The P load/precipitation ratios are also lower for the controlled drainage periods 2 and 3 than for the reference period. For NO_3-N, however, the yearly NO_3-N loads were higher in the controlled drainage periods. This is related to the higher NO_3-N concentrations in drain effluent after the introduction of controlled drainage, especially in period 2.

The impact of adjusting the overflow levels on nutrient loads is most clear in the 2010–2011 drainage period, when large adjustments of the overflow levels were made. Elevating the overflow levels reduced the drainage flux and loads, as indicated by the leveling of the cumulative graphs in Fig. 8 and by the lower loads and load/precipitation ratio's during period 9 in Table 2. Dropping the overflow levels however, induced higher drainage flow and higher loads. For example, the nutrient loads were relatively high during a controlled drainage period with lowered overflow levels (period 7). In Fig. 8, the cumulative discharge and load graphs steepen after dropping the overflow levels.

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4 Discussion

This study aimed at quantifying the effects of controlled drainage for water and nutrient exports from an agricultural field to the surface water. From our monitoring results we conclude that controlled drainage reduced the drain discharge and increased the groundwater storage in the field. The introduction of controlled drainage did not have clear positive effects for nutrient losses to surface water. Although the P loads via tube drains reduced, the NO_3-N loads increased.

Our monitoring setup produced valuable insights in the hydrological and hydrochemical effects of controlled drainage. First, our groundwater level monitoring revealed that on our pilot field (1) the groundwater levels were well above the drain levels during the winter drainage periods and (2) the groundwater curvature between the individual drains was limited (2–3 cm). In Fig. 9, we compare the frequently shown and modelled drainage concept with the situation at our experimental field. We suggest that the groundwater discharge by the drains is limited due to a reduced entrance resistance caused by the clogging by iron oxide around the drains. The formation of iron oxides around the water table and in tile drains is a known problem among farmers in the area and is related to reduced, iron rich groundwater that is mixed with nitrate and oxygen containing infiltrating water. The kinetics of this iron oxidation process and its effect on P immobilisation are studied for the same pilot site by Van der Grift et al. (2014).

From our groundwater level monitoring, we also observed a large difference in the effect of controlled drainage between our piezometer transect at 5 and 80 m from the ditch. The less significant response of transect B is related to the dominant effect of direct drainage towards the ditch at 5 m distance. For the area further away from the ditch, drainage via tube drains is dominant and the effects of elevating the overflow levels are more significant. This concept, where most extra groundwater storage is realized further away from the ditch, is sketched in Fig. 10. Controlling the discharge and water levels in the ditch using a flexible weir would enhance the utilization of the groundwater storage capacity close to the ditch. Especially in areas with a dense network of open

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ditches, a combination of controlling both tube drain and open ditch discharges and water levels should be considered to increase the effectiveness of controlled drainage systems.

For the reduction of drought damage in summer, the groundwater storage during the spring period is crucial. To conserve water for the growing season, the overflow levels should be elevated as early as possible after the first manure application in February. After the first controlled drainage season, the overflow levels were not elevated until 15 April 2010. After this, a dry period started and increasing temperatures and grass growth enhanced evapotranspiration. No extra water was conserved for the summer period. At the end of the second drainage season, the overflow levels were elevated on 15 March 2011. This prevented the discharge of circa 160 m^3 (ca. 18 mm) of groundwater. The two scenarios are visualized in Fig. 11. The green line represents the groundwater levels when drain discharge was prevented and water was conserved by elevating the drain outlets on time. The purple line represents the groundwater levels when the overflow levels were not elevated before the drains become inactive and no discharge was prevented. Although elevating the overflow levels of the drains in early spring reduces drought in summer, the reduced discharge may hinder farm practices in early spring. At the end of the winter ban on manure spreading on 15 February, many livestock farmers are at or close to the maximum of their manure storage capacity. This forces them to apply manure in February and March, which may still be hampered by wet conditions, especially when the drainage is reduced by elevated overflow levels. A larger manure storage capacity could reduce the pressure for early manure applications and improve the effective use of controlled drainage systems to conserve water.

The introduction of controlled drainage did not reduce the NO_3-N and P concentrations in the drain effluent. The NO_3-N concentrations even increased, although this was largely caused by elevated concentrations in one of the drains which may or may not be related to controlled drainage. Due to the increased concentrations, the NO_3-N loads increased after introducing controlled drainage. The P loads reduced, which is related to the reduced drain discharge. However, the comparison of water balances indicated

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that the reduced drain discharge is compensated by more overland flow and shallow groundwater flow, both to the surrounding fields and directly to the ditch. The increased contribution of these flow routes may increase the NO_3-N and P loads to surface water. For P, an average concentration of $0.65\,mg\,L^{-1}$ was observed in overland flow in the Hupsel catchment (Rozemeijer & Van der Velde, 2014).

At the experimental field, the tube drains contributed 80 % of the total yearly water discharge to the surface water and 90 % of the total yearly NO_3-N and P export (Rozemeijer et al., 2010a). This relatively large contribution is related to poor natural drainage through the relatively thin unconfined aquifer. The relative importance of the tube drain discharge for water and nutrient transport also results in a relatively large impact of the introduction of controlled drainage. In areas with lower contributions of tube drain discharge, the effects of controlled drainage on water and nutrient transport maybe less.

In our monitoring setup, we successfully combined continuous nutrient monitoring with passive samplers for average nutrient concentration monitoring. The equipment for continuous monitoring was applied for the registration of concentrations in the combined effluent of the three studied tube drains. Together with the continuous registration of discharge, this produced reliable estimates of the total NO_3-N and P loads from the drains. The SorbiCell-samplers were applied to measure average NO_3-N concentrations for individual drains. This information became important to understand the increase of the combined effluent NO_3-N concentrations after introducing controlled drainage. This increase could largely be explained by the increased concentrations of effluent from one of the three drains and is not necessarily related to the introduction of controlled drainage. Our strategy of combining of continuous water quality monitoring and passive samplers for individual sources is applicable for other monitoring studies as well.

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5 Conclusions

Our experimental setup produced valuable insights in the hydrological and hydrochemical effects of controlled drainage. The introduction of controlled drainage effectively reduced the drain discharge and increased the groundwater storage in the studied field-site. The comparison of water balances before and after the introduction showed that the reduced drain discharge was partly compensated by more overland flow and shallow groundwater flow, both to the surrounding fields and directly to the ditch. Controlled drainage did not have clear positive effects for nutrient losses to surface water. The P loads via tube drainage decreased due to the lower drain discharge. However, this may be compensated by more P-rich overland flow and shallow groundwater flow. The tube drains NO_3-N concentrations and loads increased after introducing controlled drainage. In areas with dense networks of open ditches, the effectiveness of controlled drainage for water conservation may be increased by also controlling the ditch water levels and discharges using flexible weirs. In livestock areas, the pressure on manure application on dry fields directly after the end of the winter ban on manure spreading limits the optimal use of controlled drainage systems to conserve water in early spring.

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Table 1. Water balances for a reference drainage season (2007–2008) and two controlled drainage seasons (2009–2010 and 2010–2011).

Water balance period	Reference	Controlled drainage	
	2 Nov 2007 – 2 Apr 2008	2 Nov 2009 – 2 Apr 2010	2 Nov 2010 – 2 Apr 2011
Precipitation (mm)	+387	+331	+300
Evapotranspiration (mm)	−51	−47	−50
Discharge via drains (mm)	−303	−163	−127
Discharge via groundwater (mm)	−51	−63	−68
Discharge via overland and biopore flow (mm)	−28	−20	−34
Compensation groundwater storage change (mm)	−108	−46	+26
Net inflow from surroundings (mm)	+154	+8	−47

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Table 2. Comparison of NO_3-N and P loads in the combined discharge of three drains between distinct periods. Precipitation and the ratio's between loads and precipitation are also shown. The first 3 periods cover total years, the others compare shorter periods within the drainage season.

Period	Drainage level	Start	End	Precipitation [mm]	NO_3-N load [kg]	NO_3-N load/ Precipitation [$kg\,mm^{-1}$]	P load [g]	P load/ Precipitation [$g\,mm^{-1}$]
1	Reference	2 Nov 2007	2 Nov 2008	812	17.6	0.022	284	0.35
2	Controlled (+0–50 cm)	2 Nov 2009	2 Nov 2010	910	24.3	0.027	134	0.15
3	Controlled (+0–50 cm)	21 Apr 2010	21 Apr 2011	861	18.2	0.021	127	0.15
4	Reference	3 Dec 2007	12 Feb 2008	802	15.1	0.019	24	0.30
5	Controlled (+0–50 cm)	2 Dec 2009	12 Feb 2010	944	26.7	0.028	147	0.16
6	Reference	3 Sep 2008	19 Nov 2008	129	1.2	0.0091	19	0.15
7	Controlled (+0 cm)	3 Sep 2010	17 Nov 2010	252	11.3	0.045	88	0.35
8	Reference	19 Nov 2007	1 Feb 2008	198	8.9	0.045	129	0.65
9	Controlled (+50 cm)	19 Nov 2010	2 Feb 2011	151	3.0	0.200	13	0.086

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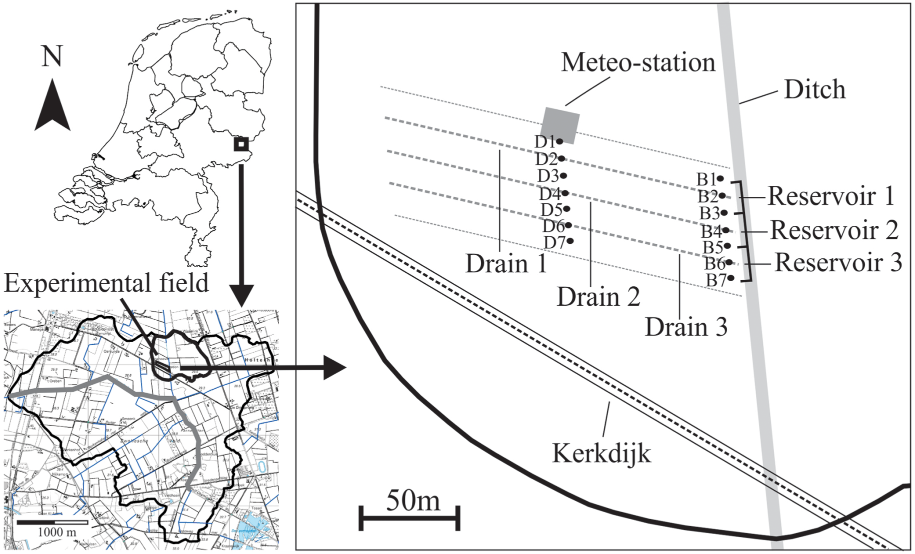

Figure 1. Location of the Hupsel Catchment and the experimental field. The field sketch shows the three measured tile drains, the location of the in-stream reservoirs, and the locations of the continuous groundwater level recording.

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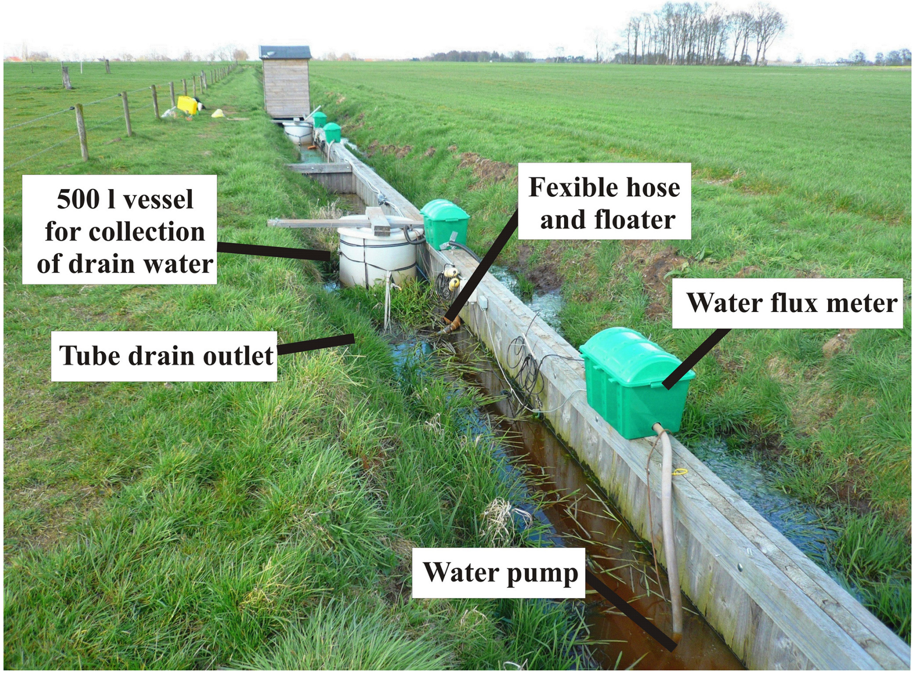

Figure 2. Picture of the complete setup with collector vessels for drain discharge, pumps and water flux meters. The shed in the back houses the data acquisition and control equipment.

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Figure 3. Pictures of the controlled drainage period setup, **(a)** the drainage overflow levels were adjusted by attaching the flexible connection tube (with a SorbiCell socket between the black fasteners) at the desired level, **(b)** the tile drain effluent was pumped to a collection vessel to enable continuous monitoring of NO_3-N and total-P concentrations using a Nitratax-sensor and a Phosphax autoanalyser **(c)**.

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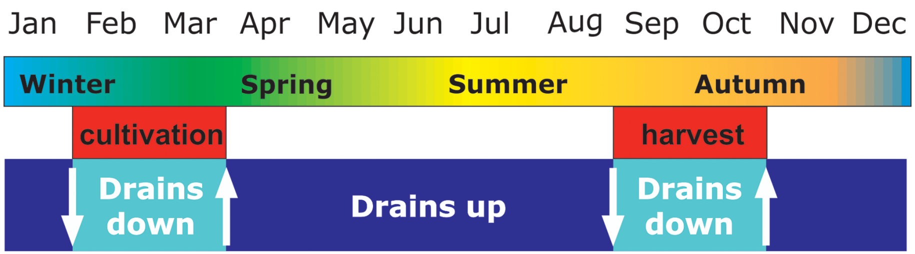

Figure 4. Drainage overflow level management schedule. The overflow levels were elevated most of the time, but were lowered in early spring and, if needed, in autumn to accommodate manure application and harvest.

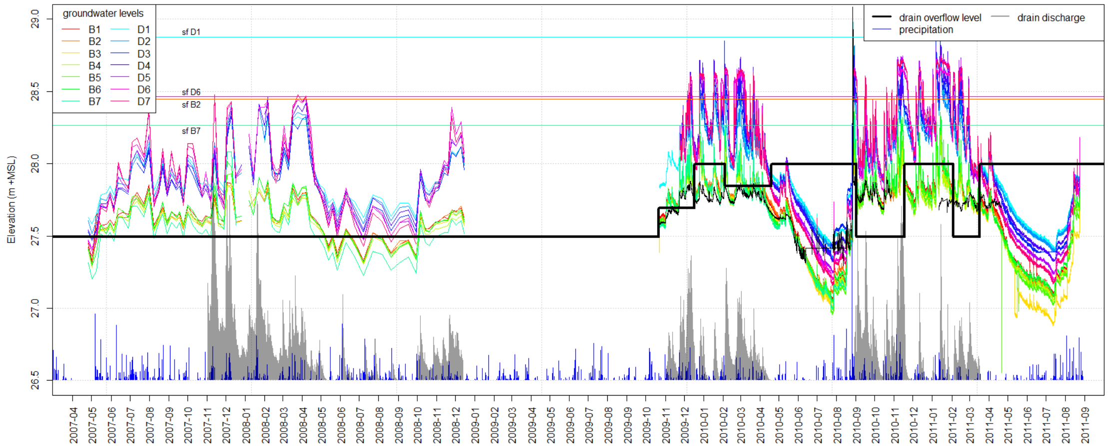

Figure 5. Combined results of hydrological measurements. The plot gives (1) the overflow level of the drains (fixed at 27.5 in reference period, variable in controlled drainage period) in black, (2) the groundwater levels of the two transects B and D, (3) in the lower part the drainage flux (grey) and precipitation (blue). The surface elevation levels at the lowest and highest groundwater monitoring locations of transects B and D are shown in coloured horizontal lines.

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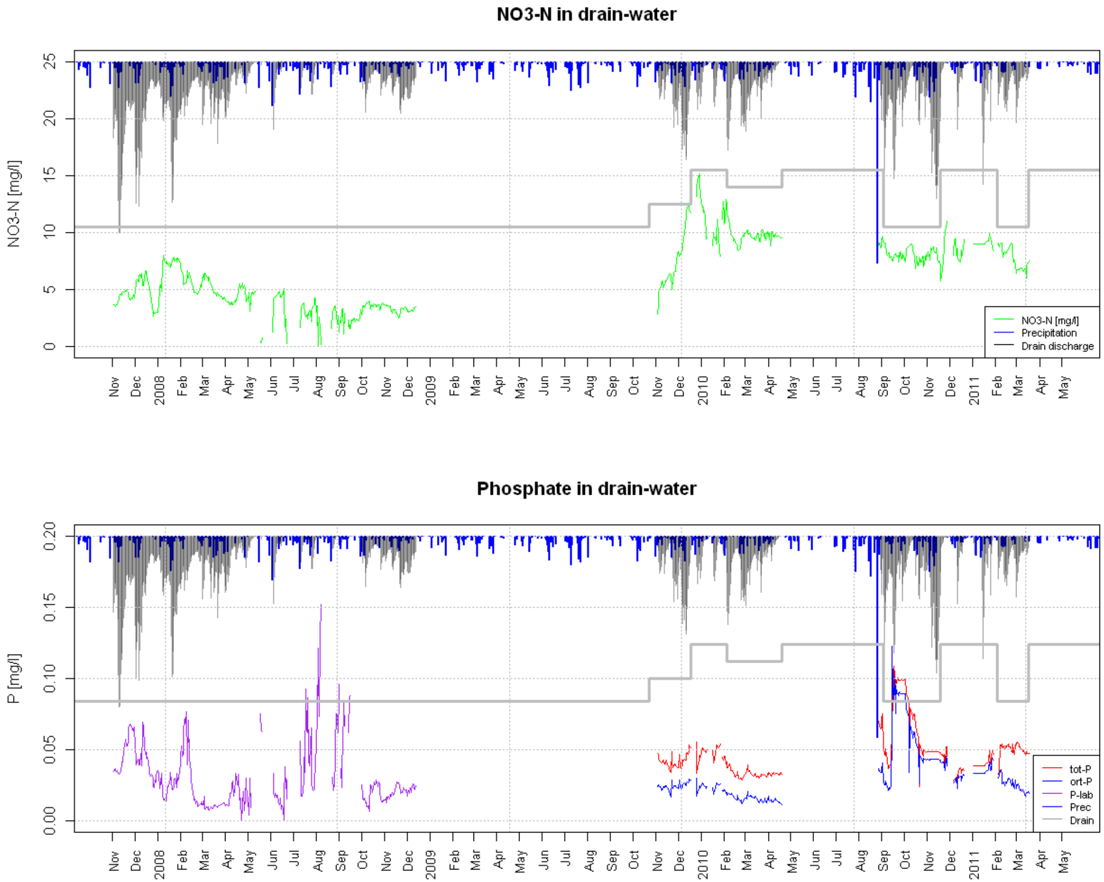

Figure 6. Measured nutrient concentrations in drain effluent. Precipitation (blue), drain discharge (grey), and the overflow levels are also plotted.

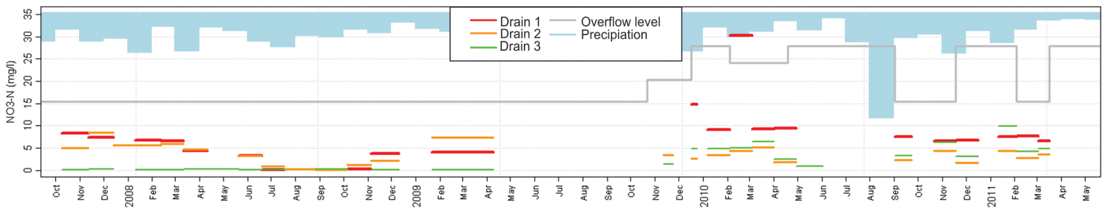

Figure 7. Results of the SorbiCell average NO_3-N concentration measurements for the individual drains.

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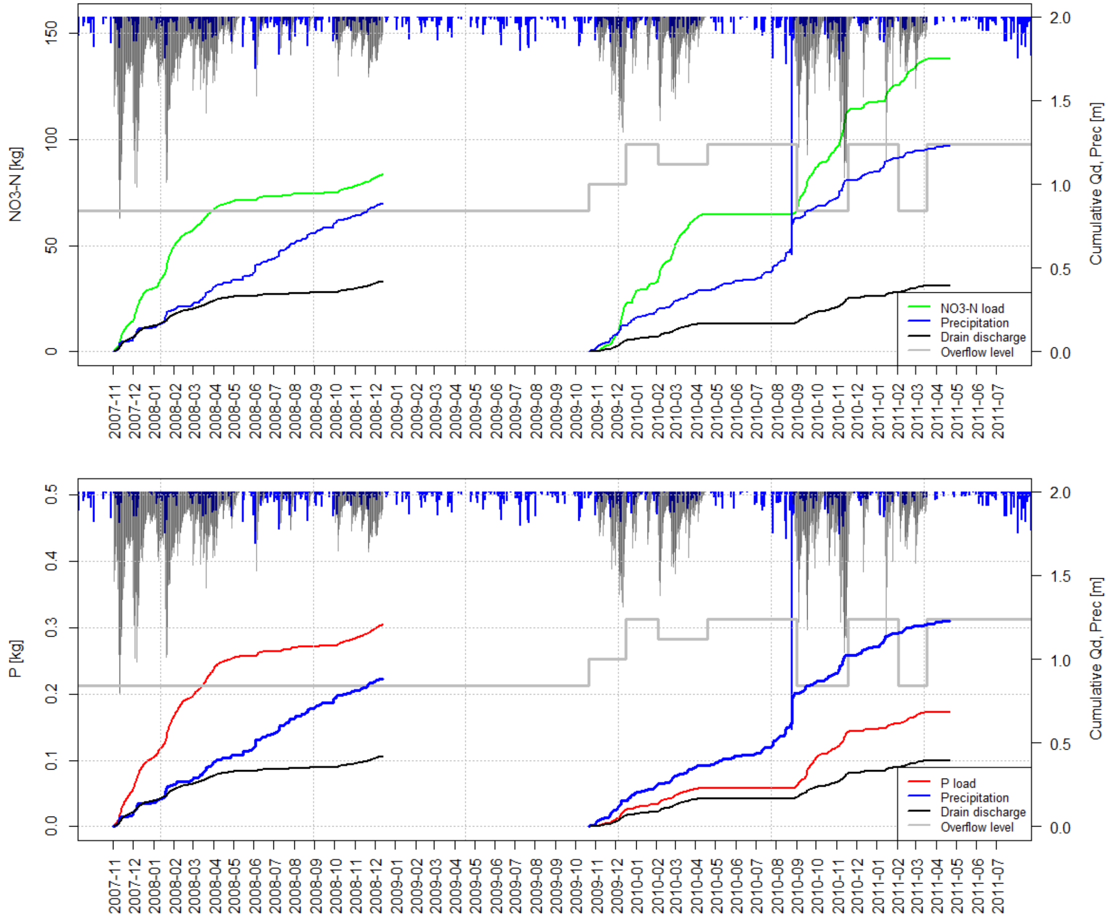

Figure 8. Cumulative precipitation, drain discharge, and drain NO_3-N and P-tot loads.

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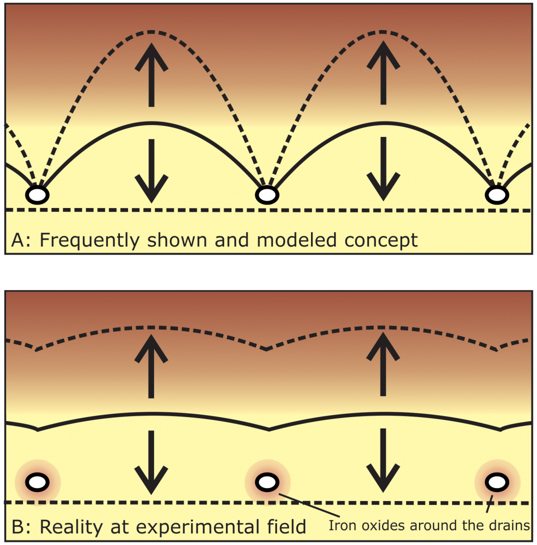

Figure 9. Comparison of **(a)** the frequently modelled concept with groundwater tables at the drain elevations and a large groundwater curvature between individual drains and **(b)** the situation at the experimental field with groundwater tables above the drains and a small groundwater curvature between the drains.

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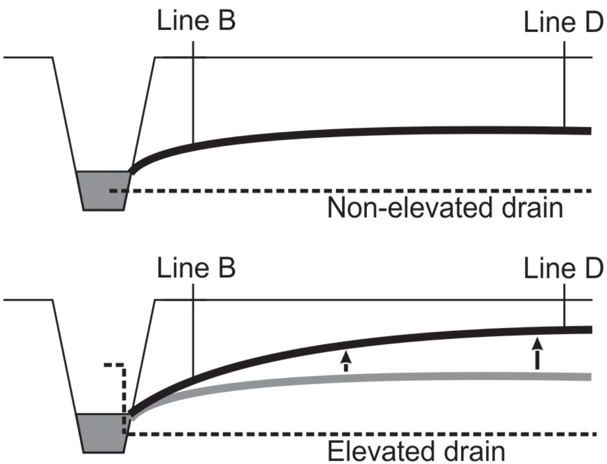

Figure 10. Transect-sketch of the effects of controlled drainage on groundwater levels in the experimental field.

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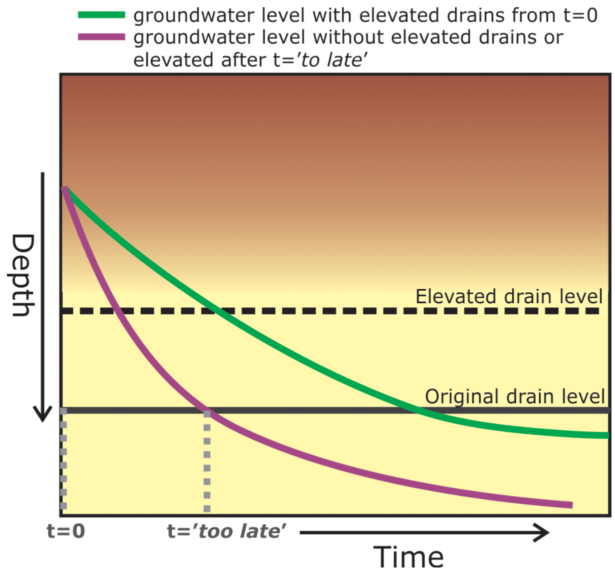

Figure 11. The crucial timing of elevating the overflow levels of controlled drainage at the end of the drainage season. Water can be conserved when the drain outlets are elevated before the groundwater levels are below the drains and the discharge has stopped.

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