We thank all the reviewers for their extensive review of our paper. This really helped to improve the manuscript! The response to the comments are given below.

Reviewer 1

General Comments

This is a well-written paper addressing scientific questions within the scope of HESS. It reports a study of an experimental treatment of a field in The Netherlands in which the operation of tile drains was restricted except during manure spreading and harvest (“controlled drainage”) in order to conserve water. The authors are interested in the effect of this on field hydrology and N and P export (other elements were measured but not reported here). As such the paper addresses an interesting and practically-relevant question. There is a 2-year reference period followed by a 2-year experimental period, though inevitably the meteorology is different. This is an unreplicated experiment, so results must be generalized with caution, though low frequency measurements were made on 3 individual tile drains in the field (showing considerable variation). The paper presents some novel data and some substantial conclusions are reached. I have however some reservations about the experimental design and whether the conclusions are justified by the data.
The Introduction states “This study aimed at quantifying the effects of controlled drainage on water and nutrient exports from an agricultural field to the surface water” and that they measured “all relevant parameters to assess the complete hydrological and hydrochemical response of the pilot field to the introduction of controlled drainage”. They criticise previous studies for failing to quantify “the changes of nutrient export via other flow routes, such as shallow groundwater flow and overland flow”. This is a valid criticism, but this study seems to do exactly the same, contrary to the statements above. The only nutrient fluxes reported are from the tile drains. The volume of water arriving in the adjacent ditch other than by the tile drains seems to have been recorded, though it is not reported in the paper. The chemical composition of this water is not reported either, though there are hints that it was measured. So the authors are not in a position to assess the “complete hydrochemical response of the pilot field to the introduction of controlled drainage”, as the composition of this water is apparently unknown. Yet this was surely an obvious and interesting question from the start of the experiment. Why build the sheet pile reservoirs otherwise? So I think the authors should either supply some estimate of the composition of this water so they can address the aims of the study, or if unable to do so should modify the aims of the study because the experimental measurements as described cannot achieve those aims stated in the Introduction.

1. *We agree that the introduction and statements like ‘all relevant parameters’ and ‘complete hydrochemical response’ may lead to too high expectations. Some of the fluxes (like groundwater discharge to surface water, overland flow, flow across the field boundaries) are notoriously hard or impossible to measure directly. Still, in the first monitoring period (2007-2008) we did manage to physically separate and measure the tile drain, groundwater and overland flow contributions (both flow and concentrations). These measurements have been reported by Van der Velde et al. (2010) and Rozemeijer et al. (2010a). Van der Velde et al. (2010) presented the field water balance based on these data. Rozemeijer et al. (2010a) reported the measured concentrations and load contributions from the different flow routes. During the second monitoring period after the introduction of controlled drainage (2009-2011), the monitoring setup was changed to focus more on the tile drain; we stopped the monitoring of the groundwater input and overland flow and introduced continuous concentration measurements for the combined tile drain effluent. However, to enable comparison between the water balances for both periods, we estimated the groundwater input and overland flow based on our continuous groundwater level data and their relation with the measured groundwater input and overland flow during the 2007-2008 period. Therefore, we do not agree*

that we did not consider all relevant fluxes, although we have not been able to measure them all for both periods.

To prevent too high expectations about what we were able to measure, we changed in the abstract "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." into "Our experimental setup enabled us to quantify changes in the field water and solute balance after introducing controlled drainage."

Also, we changed in the introduction "This combination yielded all relevant parameters to assess the complete hydrological and hydrochemical response of the pilot field to the introduction of controlled drainage." into "This experimental setup enabled us to quantify the changes in the field water and solute balance after introducing controlled drainage."

To be more clear about what was and what was not measured in the controlled drainage period, we changed in paragraph 2.3 (Experimental setup controlled drainage period) "After the reference period, the experimental setup was extended to study the effects of controlled drainage." into "For studying the effects of controlled drainage, the monitoring setup for the second period (2009-2011) was changed to focus more on the tile drains. The monitoring of the groundwater and overland flow contributions towards the in-stream reservoirs was stopped."

In general, the hydrological conclusions are based more soundly than the hydrochemical ones, and this is reflected in the Abstract, in which the final sentence "did not have clear positive effects" is about all that can be said about the nutrient fluxes.

2. *We agree that the hydrological results are more straightforward or less complex compared to the hydrochemical ones. We do not agree that "did not have clear positive effects" is all what can be said about the nutrient fluxes from our results. A lot more is mentioned in the paper, but not all findings were in the same direction (both positive and negative effects). The sentence "did not have clear positive effects" may be a too short summary of these results in the abstract. We changed this into: "The N concentrations and loads increased after introducing controlled drainage, which was largely related to elevated concentrations in one of the three monitored tube drains. The P loads via tube drains reduced due to the reduction in discharge. However, this may be counteracted by the higher groundwater levels and the larger contribution of N and P-rich shallow groundwater and overland flow to the surface water after introducing controlled drainage." In the conclusions we added: "The N concentrations and loads increased after introducing controlled drainage, which was largely related to elevated concentrations in one of the three monitored tube drains."*

The paper is entitled "High frequency monitoring of water fluxes and nutrient loads…" and does indeed report some high frequency monitoring. But surprisingly, the high frequency is not exploited to draw any conclusions. Annual means would have done just as well. Yet Fig. 6 shows some intriguing patterns – why do nitrate concentrations increase on imposition of controlled drainage, for instance, whereas P concentrations do not? Any interpretations based on processes must of course be speculative, but the authors could try to generate some hypotheses about what might be happening. The paper would fit much better within the Special Issue if some attempt was made to use the high frequency data, and I would recommend that the authors consider this.

3. *We agree that we did not fully exploit the continuous measurements in terms of interpretation of the variations. We focused on the longer term changes in water and solute fluxes rather than on short term variability. Still, the high resolution measurements enabled us to report detailed tube drain load patterns that could not have been measured by low-frequency grab sampling (this was already mentioned in the discussion). In addition, the HR measurements enabled us to measure the direct response of discharge, groundwater levels and nutrient concentrations to the changes in overflow levels of the drains water quality.*

   We added to the methods section:" The high resolution measurements enabled us to measure the direct responses of groundwater levels, drain discharges, and drain effluent nutrient concentrations after changing the overflow levels of the drains.
   We added to the discussion on the monitoring setup:"The changes in groundwater levels, tube drain discTogether with the continuous registration of discharge, the high resolution measurements enabled us to report detailed tube drain load patterns that could not have been measured by low-frequency grab sampling (see also Rozemeijer et al., 2010d). In addition, the direct responses of discharge, groundwater levels, and nutrient concentrations to the changes in overflow levels of the drains were measured. *These responses would not have been captured by conventional grab sampling."*

   To elaborate more on the concentration responses to changes in the overflow levels we've rewritten the section on Figure 6 in the results section into: "The NO3-N concentrations do not directly respond to changes in the overflow levels of the drains. However, the NO3-N concentrations increase upon the rewetting of the field and the increase of groundwater levels during November and December 2008. This increase in groundwater levels and NO3-N concentrations is a common seasonal pattern, although elevating the overflow levels of the tube drains further increases both the groundwater levels and NO3-N concentrations. The increase of NO3-N concentrations is related to the activation of near surface NO3-N rich groundwater flow routes towards the tube drains. The described autumn rewetting pattern is less clear in 2010, when a large precipitation event in August caused an immediate rewetting of the field and activation of NO3-rich tube drainage. For P, low concentrations were measured, both before and after the introduction of controlled drainage. Unlike NO3-N, the P concentrations did not increase during rewetting in autumn. The low P-tot concentrations are related to the P-immobilisation in the tube drains due to adsorption to iron-oxides (Van der Grift et al., 2014). During the 2010-2011 drainage season, the P-tot concentrations did increase after dropping the overflow levels with 50 cm and thereby increasing the drain flow velocities. This caused uptake and transport of the P-rich iron oxides and higher P concentrations in the tube drain effluent."

The paper is written in good English, is well-structured and contains few typographical errors. There a good number of appropriate references, showing that the authors know the literature well. There is no supplementary material.

Specific Comments

Abstract "Controlled drainage" needs to be defined in the Abstract for those unfamiliar with the concept.

4. *Agreed, we added "This is achieved by introducing control structures with adjustable overflow levels into subsurface tube drain systems."*

6280 l.16 What was the criterion for ionic imbalance (not "unbalance")? e.g. greater than 10% of the total anion concentration?

5. *We added “larger than 10%”.*

6280 l.21 “An evaluation of Sorbicells…was published…”. The reader here wants to know in a single sentence what the evaluation showed. e.g. did it produce comparable results to grab sampling?

6. *We added: “The SC-samplers proved to be capable of reproducing the NO3 concentration levels and the seasonal patterns that were observed with weekly conventional grab sampling and continuous water quality measurements.”*

Section 2.2 I found the description of the sampling setup rather confusing, though it becomes clearer on re-reading several times. A diagram as well as the existing photograph would help. I also wonder how the sampling tubes were attached to the ends of the tile drains and whether this significantly affected their hydraulic properties.

7. *A diagram and picture were provided (figures 1 and 2). For a more precise and elaborate description of the setup we’ve referred to Van der Velde et al., 2010. The largest problem with connecting the drain outlet to the collection vessel is that the flow rates may be affected; the drain can discharge freely in the vessels, while the drain outlet was below the surface water level. This was solved my attaching floaters to the connection tubes. About the attachment of the drains we’ve added: “The effluent from the tube drains was separated from the other flow routes by connecting each drain outlet to a 500 L vessel using a flexible tube (Figure 2). When tube drain outlets are below the ditch water level, the surface water pressure affects the flow rates. To imitate this effect, floaters were attached to the flexible tubes that connected the drains to the collection vessels. Thus, water leaving the drain had to flow up to the ditch level before being discharged into the vessel (Van der Velde, 2010).”*

Table 1 In Section 2.2, the Reference Period is defined as May 2007 to Dec 2008, and the Controlled Drainage Period as Nov 2009 to Sept 2011. For Table 1, however, the Reference Period suddenly changes to 2 Nov 2007 to 2 April 2008, and the Controlled Drainage period splits into two as Nov 2009 – 2 Apr 2010 and 2 Nov 2010 – 2 Apr 2011. There is no explanation given for this – these periods are certainly when most (but not all) the tile drainage takes place, but why only calculate the water balance for these periods? There may be a reason, but the authors need to justify it.

8. *We added: The water balances of Table 1 focus on the winter drainage periods when the differences between conventional and controlled drainage are most pronounced.*

Table 2 Periods 4 and 5. 944 mm precipitation in 10 weeks sounds more like the mountains of North Wales than the Netherlands! In Table 2, Period 5 (2 December 2009 to 12 Feb 2010) has more rain (944 mm) than the year that includes it (2 Nov 2009 to 2 Nov 2010; 910 mm, Period 2). Similarly Period 4 vs Period 1. The precipitation values for Periods 4 and 5 cannot possibly be correct. The authors need to review the values in this table and supply the correct values, and also review the conclusions drawn from the Table.

9. *We agree. The precipitation figures in Table 2 were wrong. We’ve updated the table with the correct values.The conclusions in the text were checked, but they were still correct.*

Fig.8 In Fig. 8, all the information is duplicated in the two graphs except the nutrient loads, which seems rather extravagant. Why not plot all the information on one graph so the nutrient loads can be more easily compared?

10. We agree that a lot of information is duplicated in both plots. However, we prefer to keep the N and P loads in separate plots. The N and P loads need to be plotted on a different y-scale, while the right side y-scale axis is already occupied for the water fluxes. The difference in scales would also make a comparison not straightforward.

Technical Corrections

p. 6276 l.23 “algal” not “algae”

11. Agreed and changed accordingly

6279 l.15 “farmer’s” not “farmers”

12. Agreed and changed accordingly

6279 l.17 170 kg N /ha. Is this per year? If not, what is the annual rate?

13. Yes, this is per year. We added “per year”.

6279 l.20 “tile drain effluent”. Are tile drains the same as tube drains at this site? There has been no mention of tile drains until this point. Best to stick to a consistent terminology throughout.

14. We’ve changed “tile” into “tube” throughout the paper.

6279 l.22 What materials were the sheet piles made from?

15. Pinewood. We added this.

6280 l.15 “analyze method” should be “analytical method”.

16. Agreed and changed accordingly

6282 l.19 “increases” should be “increased”

17. Agreed and changed accordingly

6285 l.9 ratios not ratio’s. Also in legend to Table 2.

18. Agreed and changed accordingly

6286 l.14 “reduced” should be “increased”

19. Agreed and changed accordingly

6286 l.17 needs a hyphen between “oxygen” and “containing”

20. Agreed and changed accordingly

6286 l.19 “are” should be “were”

21. Agreed and changed accordingly

6288 l.13 “maybe” should be “may be”.

22. Agreed and changed accordingly

Fig. 1 legend “Locations of groundwater level recording” – it should say these are the points labelled B1-B7 and D1-D7, as this is not immediately obvious.

23. We added to the figure caption “in transects at 5 m from the ditch (B1-B7) and at 80 m from the ditch (D1-D7).” To the main text we added: “in transects at 5 m from the ditch and at 80 m from the ditch (Figure 1).”

Fig. 2 On figure label “Fexible hose” should be “Flexible hose”

24. Agreed and changed accordingly

Figs 5 and 6 No scale is given for precipitation or discharge.
Fig. 7 No scale for precipitation

25. We are aware of this. The precipitation and discharge dynamics in these plots were just given for reference. The focus of figure 5 is on the groundwater levels and the focus of figure 6 and 7 on the concentrations. We prefer not to add an extra scale to these plots in order to keep them less complicated.

Reviewer 2

This manuscript describes experimental work in the Netherlands to investigate the usefulness of controlled drainage for water storage and nutrient transport mitigation. The manuscript is interesting, generally well written and adds to a body of work on applied water quality research. It fits, therefore, into the aims and scope of HESS.

General comments

While the work fits into the scope of the special issue on water quality and WFD related matters, the link to high-resolution nutrient monitoring is less clear. For example, what extra dimension does this give and could the work have proceeded without its use? This needs to be developed more in the justification for the experimental design, results (i.e. more descriptive stats on range of concs. found for example) and in the discussion

26. We agree. We refer to our response 1 to the first reviewer for the changes made.

Further to this, some quality assurance information needs to be provided (preferably) or referenced on both the P and N high-resolution data to enable readers to have confidence in the load estimates and general data. See Lloyd et al. 2015 Hydrological Processes (DOI: 10.1002/hyp.10574) for a critique of the method.

27. We agree. We've chosen to add reference with more details on the technology used in order to keep the methods section short and focused. We added: "More details on these technologies are provided by Van der Grift et al. (2015)."

The experiment is based on a reference period versus control period to assess the effect of changed conditions (controlled drainage). This is from one reference season and two controlled seasons. Clearly, the nuanced differences between annual and intra-annual rainfall patterns (magnitude, duration, wetting-drying etc.) can have significant influence on both runoff patterns and pollutant transport patterns. The authors need to justify the experimental design and how this could have been improved, for example, by a more parsimonious approach based on a synchronous control site and controlled site to eliminate the seasonal differences and influences in rainfall patterns.

28. We agree that a synchronous control site is a frequently used approach in many studies. However, the spatial variability in hydrology and water quality (drain effluent concentrations) is very large in this area. This prevents a proper comparison between a pilot and control site as was also experienced by Heinen et al. (2012,JEQ) in a nearby experiment studying the effects of buffer strips.

We added to the methods section:

"This approach enabled us to study the hydrological and chemical changes after introducing controlled drainage. We did not monitor a reference field were controlled drainage was not introduce. The large spatial variability in hydrology and nutrient concentrations (see also Rozemeijer et al., 2010a,2010c) would not allow for an appropriate comparison between the pilot field and a synchronous control site. This was also concluded by Heinen et al. (2012) who studied the field scale effects of buffer strips at a nearby experimental field. This involves that the differences in weather conditions during the reference and the controlled drainage periods have to be taken into account in the interpretation of the hydrological and hydrochemical differences."

Specific comments

Page 6276 line 16 amend to: "However, the introduction. . ."

29. This part of the abstracts was rephrased (see resonse 2)

Page 6276 line 22. These references need to be more up to date.

30. There are a lot of (recent) references that could be used here. We have chosen Foley et al., 2005 and Howarth, 2008 because they are the mostly cited review papers on this topic.

Page 6277 line 3. Needs referencing after ". . .Europe".

31. The reference after the subsequent sentence also refers to this statement (Seitzinger et al., 2010).

Page 6277 line 27 amend to: "This study aimed to quantify. . ."

32. Agreed and changed accordingly

Page 6278 line 11. Check the grid reference to be more precise – doesn't seem to locate to the site when checked in an online viewer.

33. The coordinates are correct; maybe a bit more precision helps. We've changed the coordinates into "(52°04'01.5" N 6°39'29.0" E)".

Page 6280 lines 15-16. Syntax issue with this sentence.

34. Agreed. We changed the sentence into: Samples with deviating results for ions measured by more than one analytical method as well as samples with an ionic unbalance larger than 10% were reanalyzed.

Page 6280 line 10. Should this be ". . .precipitation was higher. . ."? as compared with same info given on next page line 24.

35. Agreed and changed accordingly

Page 6282 lines 25-28. Syntax issue. Change to, for example: ". . .were lowered by (or to?) 50cm on two occasions (or instances). . ."

36. Agreed and changed as suggested

Page 6285 line 25 amend to ". . .load rates of change become steeper. . ."

37. Agreed and changed as suggested

Page 6286 lines 1-7. This is a conclusion. Delete from here.

38. Agreed and changed as suggested

Reviewer 3

General comments

This manuscript addresses the effects of controlled drainage on transport of nutrients, phosphorus and water for a small agricultural field. The field was monitored by groundwater head sampling, drain flow and precipitation measurements and water samples. The field setup was constructed so that surface/subsurface flow and groundwater flow was separated from the drain water at the outflow. The study shows that no significant effect of controlled drainage occurred in terms of reduced nutrient losses. However, the drain discharge was reduced resulting in a reduction of phosphorus loads.

The manuscript does address a topic relevant for the readership of HESS. However, it is not completely clear in what sense the study contributes with significant novel methods, results or conclusions. Generally the strongest part of the paper is found to be the considerations regarding how controlled drainage can be implemented and the different challenges with conducting controlled drainage in harmony with farming practice (for instance suggestions of larger manure storage capacity). Therefore, in order to strengthen the manuscript the discussion could be re-structured so that more focus is on the experiences gained from this study. For instance the discussion of the importance of also controlling drain overflow close to the stream/ditch as well as the timing of when to initiate and stop controlled drainage dependent on season, weather conditions and farming practice could be elaborated. Most of these issues are already mentioned, but they could be elaborated as this is the strongest part of the study. These issues could also be highlighted in the abstract.

39. We agree that these aspects of practical implementation deserve some more highlighting in the paper.

We've restructured the discussion in order to directly start with these experiences and insights. The discussion section now starts with: "Our monitoring results produced valuable insights in the hydrological and hydrochemical effects of controlled drainage and in some practical issues for implementing controlled drainage and optimizing its effects in agricultural practice." The experiences and considerations are then described in subsequent paragraphs and illustrated by figures.

We've also added the most important conclusion to the abstract and to the conclusions: "To achieve this, the overflow levels have to be elevated in early spring, before the drain discharge stops due to dryer conditions. The groundwater storage in the field would have been larger when the water levels in the adjacent ditch would have been controlled as well."

It seems as if the manuscript has been slightly rushed and it is strongly recommended that the entire manuscript is checked thoroughly for grammatical and general language mistakes as well as wrong sentence syntax.

40. The paper has been rechecked for language mistakes.

Specific comments

Generally throughout the manuscript there is an excessive use of the rather informal "we", and it is suggested that the authors rephrase sentences containing "we" to more proper formal language. Some examples are given below. The authors should be consistent in their use of past and present tense, especially in the results section. Some examples are given below, but the entire manuscript should be adjusted.

41. We agree. We've rephrased the sentences with "we" and "our" and checked the use of past and present tense.

Some parts of the results section rely on work already published (e.g. the SorbiCell results, hydraulic conductivity measurements and water balance issues), hence it is recommended that these parts and references are taken out of the results section, or used in a more direct way by referring specifically to results that can support this present study (examples given below).

42. See the responses below.

P 6276-line 13: In the abstract the term "all relevant hydrological and chemical parameters. . ." is somewhat confusing, since the reader will immediately ask which parameters are considered relevant? It is suggested that the authors rephrase this sentence so that it is precisely stated at least which type of hydrological and chemical parameters.

43. This was changed based on comments of reviewer 1 (See response #1)

P 6278 – line 6: The authors again use the non-specific term “all relevant parameters”. It is recommended to list the parameters instead, as it is most likely up for discussion which parameters are needed to accurately assess the complete hydrological and hydrochemical response.

44. This was changed based on comments of reviewer 1 (See response #1)

P 6278 – line 19: No need for the repeated reference to Wösten et al. (1985).

45. We agree. We’ve removed the second reference

P6279 – line 3 to 9: For some reason the text changes to past tense, please correct to present.

46. We agree. The entire paper was checked for the use of past and present tense.

P 6279 – line 21: Is the ditch 43.5 m wide or long? Please elaborate in the text.

47. We rephrased this into: “towards a 43.5 m long section of the ditch”

P 6279 – line 22: What is meant by the “eastern ditch”? From the figure is looks like there is only one ditch running more or less north – south? Do the authors mean the eastern side of the ditch? Please elaborate and change accordingly in the text.

48. We removed ‘eastern’ to prevent this confusion.

P 6279 – line 23 and 26: What is meant by “in-stream”? The reservoirs are built in the same ditch as where drain water is discharging to, right? not in a separate stream? Please clarify in the text.

49. We rephrased this into: “To separate the fluxes toward the ditch via different routes, three adjacent sheet pile reservoirs were built (Figure 2). These in-stream reservoirs were constructed around the outlets of drains 1, 2, and 3 and captured overland flow, interflow, direct precipitation, and groundwater inflow from the thin aquifer above the Miocene clay.”

P 6280 – line 2 to 5: The authors write that the drain flow is measured via the vessel when a maximum level is reached. During the drainage period, how long time does it in general take for this maximum level to be reached? Do you have flow measurements representing water discharging on average during an hour, a day, a week, or? I find this information important as it has a significant impact on the precision of the estimated flow rates.

50. The time it takes to fill up the vessels depends heavily on the discharges. It was also quite different for each drain. These discharge results (also for the individual drains) are published in Van der Velde et al, 2010). On an average day during the drainage season, the vessels were filled and emptied after 2 hours. We’ve added: ”On an average day during the drainage season, the vessels filled and emptied every two hours.”

P 6280 – line 5: Please refer to the locations on figure 1.

51. We added: “in transects at 5 m from the ditch and at 80 m from the ditch (Figure 1).”

P 6280 – line 17- 21: With which resolution do these SorbiCell-samplers give NO3-N concentrations? Is it hourly concentrations, composite sampling or something else? Generally if the authors wish to include the SorbiCell measurements, you should describe briefly in the manuscript how they are working and why you are using them. Why are the cells useful compared to the other drain water sampling you are performing? When referring to another paper for a test or comparison, it is recommended to refer to the specific results; otherwise the reference is not of much use for the reader. What did Rozemeijer et al. (2010) find? Where the cells better than conventional sampling? And is that why you chose to use them?

52. We agree. We've added to the methods section: "In addition to the grab sampling, SorbiCell-samplers (De Jonge and Rothenberg, 2005) were used for monthly time-average NO3-N concentration measurements of tube drain effluent. The SorbiCell-samplers were applied to measure average NO3-N concentrations for individual drains. An evaluation of SorbiCells based on duplicate analyses and comparison to conventional grab sampling and continuous measurements was published by Rozemeijer et al. (2010c). The SorbiCells proved to be capable of reproducing the NO3 concentration levels and the seasonal patterns that were observed with weekly conventional grab sampling and continuous water quality measurements."

P 6281 – line 5 to 6: Why do you write roughly instead of just showing the exact periods where the overflow levels were adjusted? Why are you using different overflow levels? Are you not concerned that changing the overflow levels also changes the hydrology? Is it for instance possible, that you lose water to neighboring fields when the levels are at the highest?

53. In this section we only aim at describing the reasoning behind the timing of the changes in overflow levels. The exact periods and levels are presented in the results section. The impact on hydrology, including the loss of water to neighboring fields is accounted for in the results section and in the water balances. Here, we've deleted "roughly" and added: "The exact adjustment moments are shown in the results section."

P 6281 – line 7: The sentence starting with "However,.. " seems somewhat disconnected or not finished. It is recommended to delete or rephrase it.

54. We rephrased this into: "However, the field had to be dry enough for manure spreading after the end of the winter ban on manure spreading on February 15th.

P 6281- line 9 to 12: You mentioned the different cases where the overflow levels were lowered. However, it is not really clear from the text how much you lowered it? I suppose you lowered it down to the original drain level? Please elaborate in text.

55. We added: "to the original drain outlet levels". More details on the levels are given in the results section.

P 6281 – line 14 to 16: It is recommended that this section is deleted, as the headings in the subsequent sections explain what the main content is.

56. Agreed and changed accordingly

P 6281 – line 19 to 23: It is suggested that this section is either deleted or rephrased as it just repeats what can be seen in the figure. Instead it is recommended that the authors explain the most important message that the figure illustrates.

57. We agreed and deleted this section.

P 6281 to 6282 – line 24 to 4: Here you touch the subject I addressed above regarding the reasoning behind the different drainage levels. However, it is not clear in the text how you chose these specific levels, and why you for instance changed the level from 20 cm to 50 cm in December 2009? Why did you not just use the same level, except when farming practice required a lowering?

58. We’ve worked with overflow level changes of 50 cm in the second controlled drainage season to be able to measure more distinct effects on hydrology and water quality. We added:”During the second drainage season with controlled drainage (2010-2011) we elevated and lowered the overflow levels with 50cm on each occasion in order to bring about more distinct changes in groundwater levels, drain discharges and nutrient losses compared to the first season (2009-2010).”

P 6282 – line 10 to 12: The importance of this sentence is not clear. You state that total precipitation was lower in the reference period than in the period of controlled drainage. Hence, I do not see how this indicates that the higher gw levels in the period of controlled drainage are due to the increased overflow level? As I understand it: If more precipitation fell in the period of controlled drainage and if you also see higher gw levels in that period, then the higher gw levels can both be due to more precipitation and the increased drainage level. So, that the less precipitation fell in the control period is not indicating that the higher gw levels in the drainage period are caused by the elevated overflow levels? Or do I misunderstand something? Could you please elaborate also in the text, or delete the section.

59. There was a mistake in this sentence. The total precipitation was higher instead of lower during the reference period (see also our response #35 to reviewer 2)

P 6282 – line 13: A groundwater (gw) level cannot be long? Do you mean that the gw levels are above land surface for longer time periods? Please correct and clarify in the text.

60. We rephrased this into: “The groundwater levels are above the land surface more frequently and for longer periods,”

P 6282 – line 14: Did you actually observe an increase in ponding and overflow water? You stated earlier that you measure overland flow, so could you please discuss whether these measurements support this?

61. Yes, we observed both ponding and overland flow. For the reference period (2008-2009) the overland flow towards the ditch was measured and reported by Van der Velde et al. (2010). We added:”Ponding and overland flow, as well as its relation with the groundwater levels, have been observed and reported by Van der Velde et al. (2010).”

P 6282 – line 5 to 19: The authors shift between using past and present tense. In general the figures show something, i.e. present tense when you refer to a figure. However, for instance when you refer to the gw levels then they were above the tube drain level, i.e. past tense. Please adjust to correct use of past and present tense.

62. We agree. The entire paper was checked for the use of past and present tense.

P 6283 - line 1 to 3: It is suggested that this section is rephrased, as the information is not important, the text just repeats the table. Instead write what the main message is, and then refer to the table in brackets. There is no need to repeat what can be directly seen in figures or tables instead help the reader deduce the main message from the table or figure.

63. We agree and rephrased this section into: ”Table 1 enables the comparison of the field water balances of the drainage seasons during the reference and the controlled drainage periods.”

P 6283 – line 17 to 19: You state that the net influx from regional gw flow is needed to close the water balance, but that it cannot be measured. So how did you solve this problem?

64. As all other input and output fluxes were measured accurately during the reference period, we assigned the water budget closure term to the groundwater flow across the field boundaries. More details on this were given in Van der Velde, 2010.

We rephrased the section into: "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 for which the other fluxes were accurately measured (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)."

P 6283 – line 19 to 21: Please delete this section or refer to some specific results of relevance for the present study.

65. We think these references are needed here to be able to accept the presented water balances without elaborating on their details within this paper.

P 6283 – line 25: Which "other differences" do you refer to? Please elaborate and be more precise.

66. We agree and changed this into "the differences in the discharges via groundwater, tube drains and overland flow"

P 6283 – line 26: You write that the gw levels rose during the reference period, but it is not clear how you come to this conclusion. In figure 5 it is seen that the gw levels both rise and fall in the reference period, so what do you mean by saying that the gw levels rose during the reference period? Do you mean the average gw level or? This issue also applies to the following section in the text.

67. This is the difference between the groundwater level at the start date and end date of the water balance period. This is the change of storage that has to be accounted for in the water balances.

P 6284 – line 4 to 9: Please rephrase this section. I assume you are making comparisons with the reference periods? However, when you for instance write that something is significantly lower, you need to write what you compare with.

68. We agree and added: "compared to the reference period"

P 6285 – line 6 to 8: Same comment as for P 6281 – line 19 to 23 (above).

69. *We agree and shortened this to prevent duplication of the info in the figure caption.However, we still want to introduce the figure and table in the text before starting the interpretation.*

P 6286-line 12: A reference to at least one example of "the frequently shown and modelled drainage concept" would be appropriate at this point.

70. We rephrased this into a "common " drainage concept and added a reference to De Vos et al., 2001.

P 6286 – line 18: Do you mean that the infiltrating water contains nitrate and oxygen? As it is written now it says that the nitrate and oxygen are containing infiltrating water. Please rephrase to correct English syntax.

71. We rephrased this into "nitrate- and oxygen-containing infiltrating water"

Figure 1: I do not see any explanation to the naming B and D and the dots they are placed next to, neither in the manuscript text nor in the figure text. I assume they represent the locations of gw level recordings? Please add an explanation at least in the figure caption.

72. We added this explanation to the figure caption and the text. See also our response #23 to reviewer 1

Figure 4. I find it somewhat misleading that you write “Drains up/down” on the figure, as it is not the drains you are moving up or down, but the overflow level. This could be changed in the figure.

73. We agree and changed “Drains” into “Overflow levels”

Figure 5: Generally avoid using the term “The figure shows. . .” or “The plot gives..” in figure captions, as it is obvious that the text is linked to the figure. Be short and concise and only elaborate on issues that are not already explained on the figure. It is recommended that the symbol for precipitation and drain flux/discharge is deleted on the figure, and just explained in the text, as the symbols coincide with the symbols for the gw levels. Please use the correct abbreviation for meters above sea level on the y-axis (m.a.s.l.).

74. We changed the caption into: “The time series shown are”. We prefer to use m +MSL as abbreviation for meters above mean sea level.

Figure 9: This figure could be considered left out, as it is already explained in the text. It is probably not very surprising the the gw head curvature between drains can vary significantly among individual fields due to soil type, drainage system, drainage depth, precipitation, hydraulic conductivity and connectivity with underlying gw reservoirs etc. The fact that more steep curvatures are the ones most often seen in connection with modelling studies is probably due to the difficulties that arise if small curvatures should be modelled, rather than evidence for steep curvatures occurring more often than the less steep ones.

Figure 10: This figure could be left out, as it does not really contribute with significant information. The figure just depicts the commonly known schematic response in the gw hydraulic head due to a change in gw level close to a gw gaining stream, with the largest effect observed furthest away from the stream.

75. We prefer to keep both figure 9 and 10 in the paper as a visual explanation of the text.

Technical corrections

P 6276 – line 14: Please delete “field” just before “water”.

76. Agreed and changed accordingly

P 6276 – line 15: Please delete “We” and rephrase to more formal sentence. Please avoid use of we as much as possible

P 6277 – line 28: Please rephrase to more formal language (avoid using “we”).

77. We’ve rephrased all sentences with “we” and “our”.

P 6278 – line 2: Use singular “period”.

78. Agreed and changed accordingly

P 6278 – line 4: Please avoid using “we”.

P 6278 – line 23: Please avoid using “we.

79. We’ve rephrased all sentences with “we” and “our”.

P 6278 – line 26: Please use correct abbreviation for meters above sea level (m.a.s.l.).

80. We prefer to use m +MSL as abbreviation for meters above mean sea level.

P 6279 – line 13: Please avoid using “we.

81. We’ve rephrased all sentences with “we” and “our”.

P 6279 – line 15: Please use the genitive correct: farmers’ if more than one farmer, farmer’s if only one farmer.

82. Agreed and changed into farmer’s

P 6280 – line 15: Please delete “analyze” before “method”.

83. Changed into “analytical”

P6282 – line 9: Please delete “the” before “transect”.

84. Agreed and changed accordingly

P6282 – line 22: Replace “ephemerally” with “ephemeral” or replace with for instance “for a shorter period”.

85. Agreed and changed accordingly

P 6282 – line 27: Improper sentence syntax, replace “taken down” with “lowered” and rephrase “at two moments. . .”, e.g. “..were lowered with 50 cm at two instances. . .”

86. Agreed and changed accordingly

P 8284 – line 26: improper use of “dropping”, replace with for instance “lowering”.

87. Agreed and changed accordingly

P 6285 – line 2: Rephrase sentence starting with “This figure shows”, it is not the figure that shows something, it is data.

88. Agreed and changed into: “The data show”

P 6285 – line 9: Please replace “ratio’s” with “ratios”. P 6285 – line 22: Improper use of the word “dropping”. Replace with for instance “lowering”. (the same goes for line 25).

89. Agreed and changed accordingly

P 6286 – line 13 to 15: Please rephrase sentence or replace “by” with another word, as “by” is used three times in the same sentence.

90. Agreed and changed accordingly

P 6288 – line 24: Please delete “of” before “continuous”.

91. Agreed and changed accordingly

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. This is achieved by introducing control structures with adjustable overflow levels into subsurface tube drain systems. A small scale (1 ha) field experiment was designed 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, auto-analysers for continuous records were combined with passive samplers for time-average concentrations at individual drain outlets. The experimental setup enabled the quantification of changes in the water and solute balance after introducing controlled drainage. The results showed that introducing controlled drainage reduced the drain discharge and increased the groundwater storage in the field. To achieve this, the overflow levels have to be elevated in early spring, before the drain discharge stops due to dryer conditions and falling groundwater levels. The groundwater storage in the field would have been larger when the water levels in the adjacent ditch would have been controlled as well by an adjustable weir. The N concentrations and loads increased, which was largely related to elevated concentrations in one of the three monitored tube drains. The P loads via the tube drains reduced due to the reduction in discharge after introducing controlled drainage. However, this may be counteracted by the higher groundwater levels and the larger contribution of N and P-rich shallow groundwater and overland flow to the surface water.

Keywords

Controlled drainage, Water conservation, Nutrients, Agriculture

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 algal 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 harbors. 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 (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 comes up that water and nutrients are still exported towards the surface water via enhanced overland or shallow groundwater flow.

This study aimed to quantify the effects of controlled drainage on water and nutrient exports from an agricultural field to the surface water system. A small scale (1 ha) field experiment was designed to investigate the changes in flow route contributions towards surface water after introducing controlled drainage. Precipitation rates and the response of water tables and drain fluxes were measured in the period before the introduction of controlled drainage (2007-2008) and after (2009-2011). For the N and P concentration measurements, auto-analysers for continuous records were combined with passive samplers for time-average concentrations at individual drain outlets. This setup enabled us to quantify the changes in the field water and solute balance after introducing 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 (Figure 1) (52°04'01.5" N 6°39'29.0" E). The surface elevations in the catchment range from 22-36 m above sea level (MSL) 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., (2010a, 2010b). 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. 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. See Van der Velde et al., (2010a) for a more detailed description of the Hupsel catchment.

For the field scale evaluation of controlled drainage, a 0.9 ha grass field in the northern part of the catchment was selected. Within this field, surface elevations range between 27.5 and 28.5 m +MSL. The subsurface consists of a 3-4 m thick unconfined 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 are present with spaces of 14.5 m between individual drains. The drains discharge into the ditch at 90 cm below the field surface level. Over their 200 m length the tubes slope 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 controlled drainage was introduced. This approach enabled us to study the hydrological and chemical changes after introducing controlled drainage. A reference field without controlled drainage was not included in the experimental setup. The large spatial variability in hydrology and nutrient concentrations (see also Rozemeijer et al., 2010c) would not allow for an appropriate comparison between a pilot and a reference field. This was also concluded by Heinen et al. (2012) who studied the field scale effects of buffer strips at a nearby experimental field.

The monitoring for the controlled drainage period was from November 2009 until September 2011. The farmer's 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 per hectare per year 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. (2010a). The tube drain effluent was physically separated from the groundwater and overland flow routes towards a 43.5 m long section of the ditch (Figure 1). To separate the fluxes toward the ditch via different routes, three adjacent sheet pile reservoirs were built (Figure 2). These in-stream reservoirs were constructed around the outlets of drains 1, 2, and 3 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%.

The effluent from the tube drains was separated from the other flow routes by connecting each drain outlet to a 500 L vessel using a flexible tube (Figure 2). In an undisturbed situation, the surface water pressure would affect the tube drain flow rates when the drain outlets are submerged. To imitate this effect, floaters were attached to the flexible tubes that connected the drains to the collection vessels. Thus, water leaving the drain had to flow up to the ditch water level before being discharged into the vessel (Van der Velde, 2010a). After reaching a maximum water level in the vessel, the water was pumped into the ditch and the flux was measured with digital water flux meters. On an average day during the drainage season, the vessels filled and emptied every two hours.

In addition to the discharge measurements, phreatic groundwater levels were measured weekly on 14 locations in transects at 5 m from the ditch and at 80 m from the ditch (Figure 1). The meteorological data were derived from the Royal Dutch Meteorological Institute (KNMI) weather station adjacent to the experimental field (Figure 1).

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. Sub-samples for ICP analysis were directly acidified with HNO3. All samples were transported and stored at 4^{o}C. The samples were analyzed within 48 hours 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 analytical method as well as samples with an ionic unbalance larger than 10% were reanalyzed.

In addition to the grab sampling, SorbiCell-samplers (De Jonge and Rothenberg, 2005) were used for monthly time-average NO_3-N concentration measurements of tube drain effluent. The SorbiCell-samplers were applied to measure average NO_3-N concentrations for individual drains. An evaluation of SorbiCells based on duplicate analyses and comparison to conventional grab sampling and continuous measurements was published by Rozemeijer et al. (2010c). The SorbiCells proved to be capable of reproducing the NO3 concentration levels and the seasonal patterns that were observed with weekly conventional grab sampling and continuous water quality measurements.

2.3 Experimental setup controlled drainage period

For studying the effects of controlled drainage, the monitoring setup for the second period (2009-2011) was changed to focus more on the tube drains. The monitoring of the groundwater and overland flow contributions towards the in-stream reservoirs was stopped. 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 (Figure 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 three drainage effluent vessels was collected in a combined reservoir (Figure 3b). This enabled continuous registration of NO_3-N and total-P concentrations of the combined drain effluent, for which a Nitratax-UV sensor and a Phosphax auto-analyser were used (both Hach, Germany, Figure 3c). More details on these technologies are provided by Van der Grift et al. (2015). Phreatic groundwater levels were monitored continuously using pressure sensors in all 14 piezometers in transects B and D. The high resolution measurements enabled us to measure the direct responses of groundwater levels, drain discharges, and drain effluent nutrient concentrations after changing the overflow levels of the drains.

The overflow levels of the drains were adjusted following the scheme in Figure 4. The exact adjustment moments are shown in the results section. To conserve as much water as possible, the overflow levels were elevated during most of the year. However, the field had to be dry enough for manure spreading after the end of the winter ban on manure spreading on February 15th. Like many farmers, the land owner has a limited storage capacity for manure, which forces him to apply manure as early as possible after February 15th. To enable manure spreading, the overflow levels were lowered to the original drain outlet levels 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

3.1 Water levels, flows, and water balances

The most important quantitative hydrological monitoring results are summarized in Figure 5. 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. During the second drainage season with controlled drainage (2010-2011) we elevated and lowered the overflow levels with 50cm on each occasion in order to bring about more distinct changes in groundwater levels, drain discharges and nutrient losses compared to the first season (2009-2010).

The groundwater levels were above the tube drain level during the winter drainage period (Figure 5). The differences between the individual piezometers in each transect were low, which indicates a minor groundwater level curvature between the drains. The winter groundwater levels were higher during the controlled drainage period compared to the reference period, especially in piezometers of transect D at 80 m from the ditch. The total amount of precipitation was higher in the reference drainage season compared to the controlled drainage period (see also Table 1). This indicates that the higher groundwater levels during the controlled drainage period cannot have been caused by weather conditions, but by the elevated overflow level of the drains.

During the controlled drainage period, the groundwater levels were above the land surface more frequently and for longer periods, which indicates that ponding and overland flow became more important. Ponding and overland flow at the experimental field, as well as its relation with the groundwater levels, have been observed and reported by Van der Velde et al. (2010a).

The groundwater levels at 5 m from the ditch in transect B were less affected by controlled drainage than the groundwater levels at 80 m from the ditch in transect D. The most evident difference between the responses of transects B and D was in November 2010, when the overflow levels were raised to +50 cm. Before this, the groundwater level difference between transects B and D averaged 15 cm. After elevating the overflow levels, the difference increased up to ca. 50 cm.

The tube drain fluxes were clearly affected by the changes in overflow levels during the controlled drainage period. During the reference period, the drains were active for several periods during the summer period of 2009. In the controlled drainage period, the tube drainage flow stopped after raising the overflow levels in spring 2010 and 2011. No drainage flow was registered during the subsequent summer periods. However, the drainage flow was immediately re-activated after lowering the overflow levels. This effect was most prominent in the 2010-2011 drainage period, when the overflow levels were lowered by 50 cm on two occasions, resulting in an immediate re-activation of the tube drain discharge.

Table 1 enables the comparison of the field water balances of the drainage seasons during the reference and the controlled drainage periods. The water balances of Table 1 focus on the winter drainage periods when the differences between conventional and controlled drainage were most pronounced. The precipitation and evapotranspiration data in the water balances 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 meter ditch transect were directly measured during the reference period (Van der Velde et al., 2010a). 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 for which the other fluxes were accurately measured (Van der Velde et al., 2010a). More details on the water balance for the reference period were reported in Van der Velde et al. (2010a) 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 differences in the discharges via groundwater, tube drains and overland flow 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 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 (+26mm).

The discharge via the tube drains was significantly lower in the controlled drainage periods compared to the reference period; -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, PO4) in tube drain effluent for the reference period and the controlled drainage period are shown in Figure 6. During the reference period, the NO_3-N concentrations varied between ca. 6 mgN/l in winter and 3 mgN/l in summer. During the controlled drainage period, higher NO_3-N concentrations of 8-10 mgN/l were recorded. The concentrations were well above the surface water quality standard of 2.3 mgN/l (Van der Molen et al., 2012). The NO3-N concentrations did not directly respond to changes in the overflow levels of the drains. However, the NO3-N concentrations increased upon the rewetting of the field and the increase of groundwater levels during November and December 2008. Although this increase in groundwater levels and NO3-N concentrations is a common seasonal pattern, elevating the overflow levels of the tube drains further increased both the groundwater levels and NO3-N concentrations. The increase of NO3-N concentrations is related to the activation of near surface NO3-N rich groundwater flow routes towards the tube drains. The described autumn rewetting pattern is less clear in 2010, when a large precipitation event in August caused an immediate rewetting of the field and activation of NO3-rich tube drainage.

For P, low concentrations were measured, both before and after the introduction of controlled drainage. Unlike NO3-N, the P concentrations did not increase during rewetting in autumn. The low P-tot concentrations are related to the P-immobilisation in the tube drains due to adsorption to iron-oxides (Van der Grift et al., 2014). During the 2010-2011 drainage season, the P-tot concentrations did increase after lowering the overflow levels with 50 cm and thereby increasing the drain effluent flow velocities. This caused uptake and transport of the P-rich iron oxides and higher P concentrations in the tube drain effluent.

The results of the SorbiCell average concentration measurements for the individual drains are shown in Figure 7. The data show 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 were between the concentrations measured in drain 1 and 2.

Cumulative plots of the nutrient loads from the three drains are shown in Figure 8, together with the cumulative precipitation and drain discharge. The NO_3-N and P loads for distinct periods are given in Table 2. 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 were 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 Figure 8 and by the lower loads and load/precipitation ratios during period 9 in Table 2. Lowering 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 figure 8, the cumulative discharge and load rates of change become steeper after lowering the overflow levels.

4 Discussion

The monitoring results produced valuable insights in the hydrological and hydrochemical effects of controlled drainage and in some practical issues for implementing controlled drainage and optimizing its effects in agricultural practice. First, the groundwater level monitoring revealed that on the 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 figure 9, the common drainage concept (e.g. De Vos et al., 2000) is compared with the situation at the experimental field. It is suggested that the groundwater discharge through the drains is limited due to an increased entrance resistance caused by the clogging of iron oxide around the drains. The formation of iron oxides around the water table and in tube 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 immobilization were studied for the same pilot site by Van der Grift et al., (2014).

From the groundwater level monitoring, a large difference was observed in the effect of controlled drainage between the piezometer transect at 5 m and at 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 Figure 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 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 Figure 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 became 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 February 15th, 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 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 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 may be less.

In the monitoring setup, continuous nutrient monitoring was successfully combined 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, the high resolution nutrient concentration measurements enabled us to report detailed tube drain load patterns that could not have been measured by low-frequency grab sampling (see also Rozemeijer et al., 2010d). In addition, the direct responses of discharge and nutrient concentrations to the changes in overflow levels of the drains were measured. These responses would not have been captured by conventional grab sampling. 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. The strategy of combining continuous water quality monitoring and passive samplers for individual sources is applicable for other monitoring studies as well.

5 Conclusions

The experimental setup produced valuable insights in the hydrological and hydrochemical effects of controlled drainage and in options to optimize the effects in agricultural practice. The introduction of controlled drainage effectively reduced the drain discharge and increased the groundwater storage in the studied field-site. To achieve this, the overflow levels have to be elevated in early spring, before the drain discharge stops due to dryer conditions. The groundwater storage in the field would have been larger when the water levels in the adjacent ditch would have been controlled as well. 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 tube drains NO_3-N concentrations and loads increased after introducing controlled drainage, which was largely related to elevated concentrations in one of the three monitored tube drains. 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. 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. 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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Tables

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

Table 2: Comparison of NO_3-N and P loads in the combined discharge of three drains between distinct periods. Precipitation and the ratios 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)	P load [g]	P load / Precipitation (g/mm)
1	Reference	02-Nov-07	02- Nov -08	812	17.6	0.022	284	0.35
2	Controlled (+0-50cm)	02- Nov -09	02- Nov -10	896	24.3	0.027	134	0.15
3	Controlled (+0-50cm)	21-Apr-10	21-Apr-11	861	18.2	0.021	127	0.15
4	Reference	03-Dec-07	12-Feb-08	175	15.1	0.086	240	1.37
5	Controlled (+0-50cm)	02- Dec -09	12- Feb -10	161	26.7	0.166	147	0.91
6	Reference	03-Sep-08	19-Nov-08	122	1.2	0.010	19	0.16
7	Controlled (+0 cm)	03-Sep-10	17-Nov-10	228	11.3	0.050	88	0.39
8	Reference	19-Nov-07	01-Feb-08	191	8.9	0.047	129	0.68
9	Controlled (+50 cm)	19-Nov-10	02-Feb-11	131	3.0	0.023	13	0.10

Figures

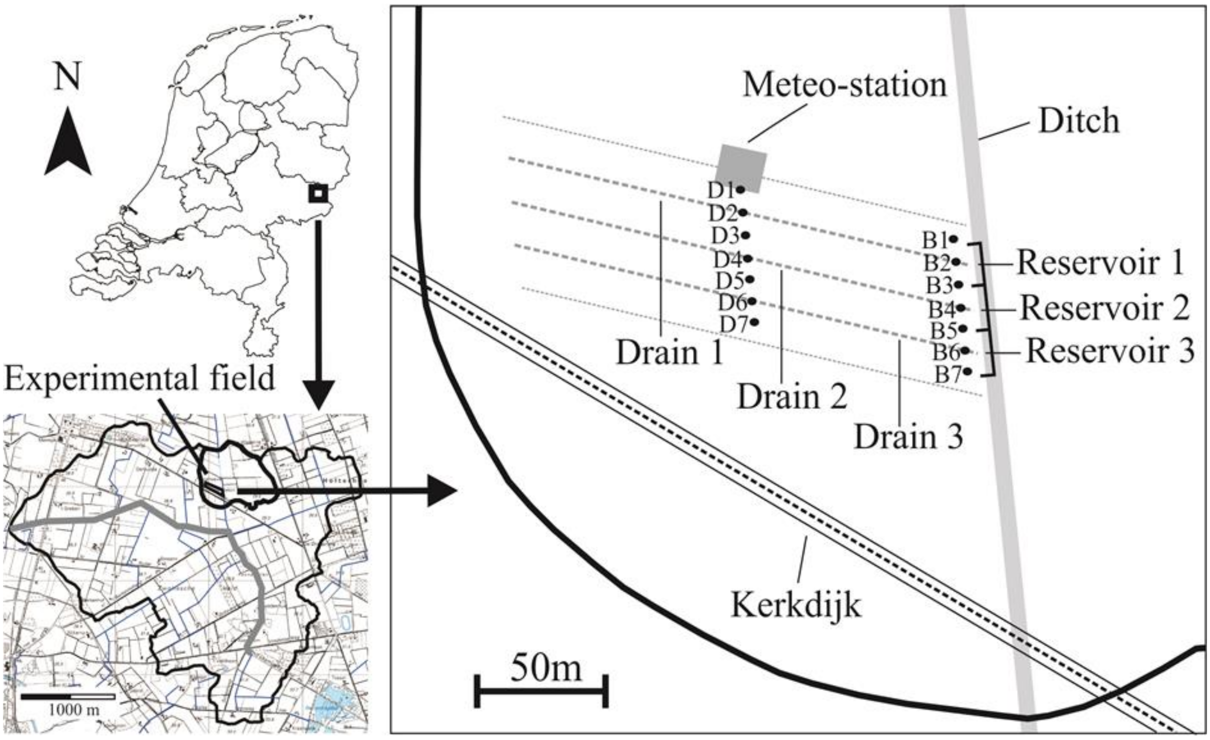

Figure 1: Location of the Hupsel Catchment and the experimental field. The field sketch shows the three measured tube drains, the location of the in-stream reservoirs, and the locations of the continuous groundwater level recording in transects at 5 m from the ditch (B1-B7) and at 80 m from the ditch (D1-D7).

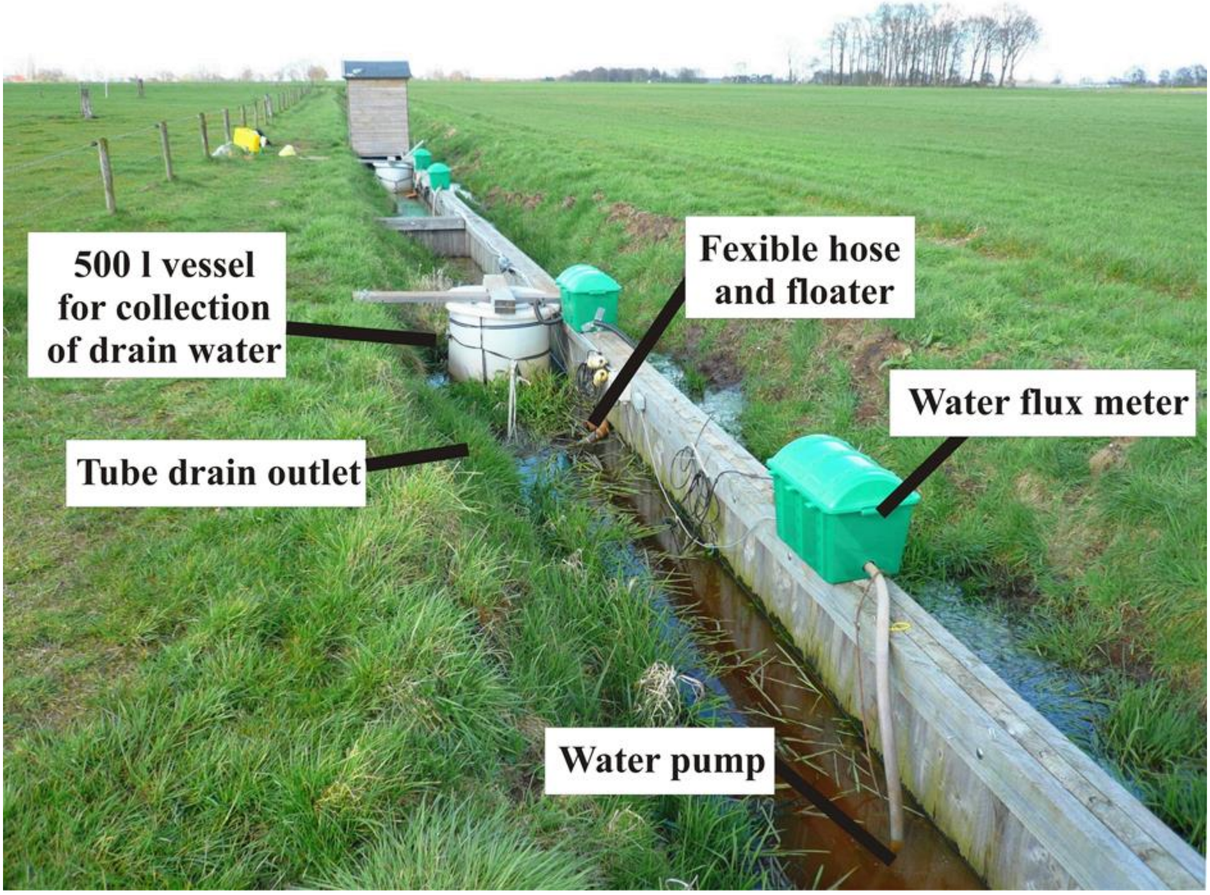

Figure 2: Picture of the complete setup with collector vessels for drain discharge, pumps and water flux meters. The shed in the back houses the data acquisition and control equipment.

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 tube 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).

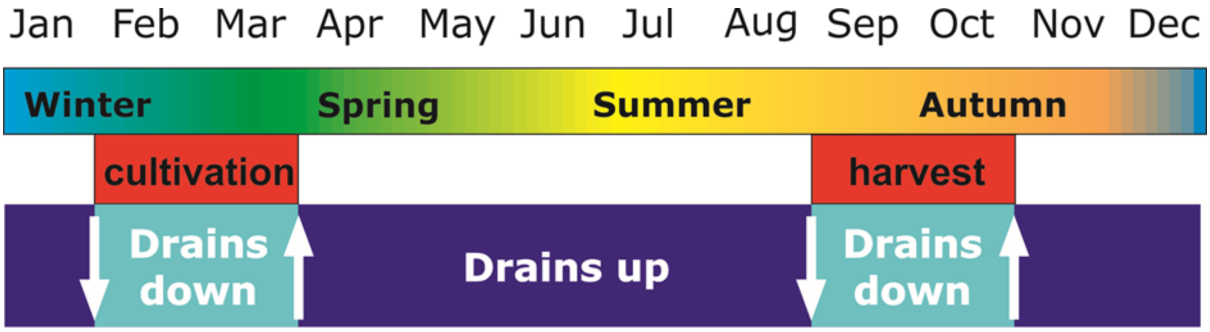

Figure 4: Drainage overflow level management schedule. The overflow levels were elevated most of the time, but were lowered in early spring and, if needed, in autumn to accommodate manure application and harvest.

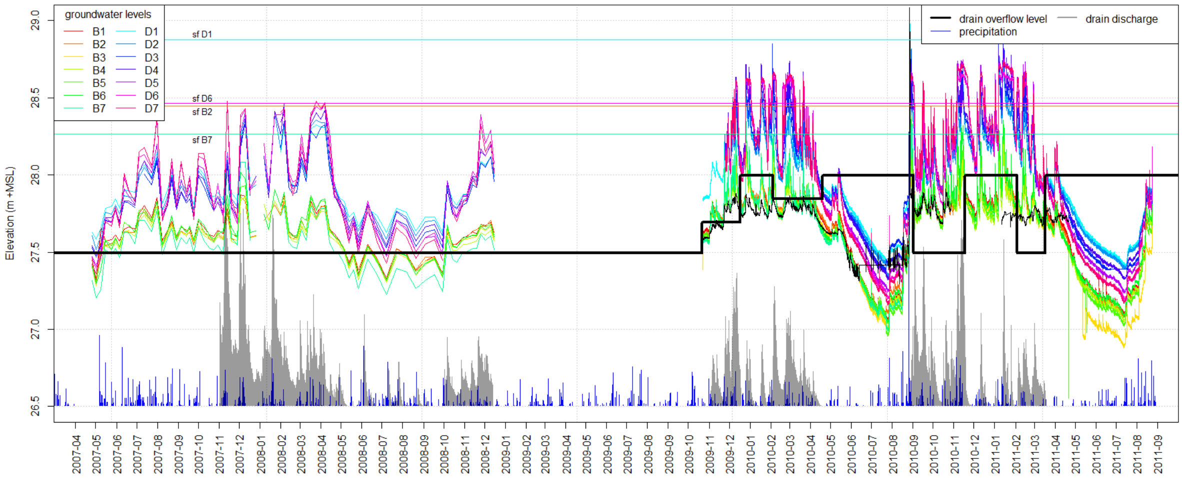

Figure 5: Combined results of hydrological measurements. The time series shown are (1) the overflow level of the drains (fixed at 27.5 in reference period, variable in controlled drainage period) in black, (2) the groundwater levels of the two transects B and D, (3) in the lower part the drainage flux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

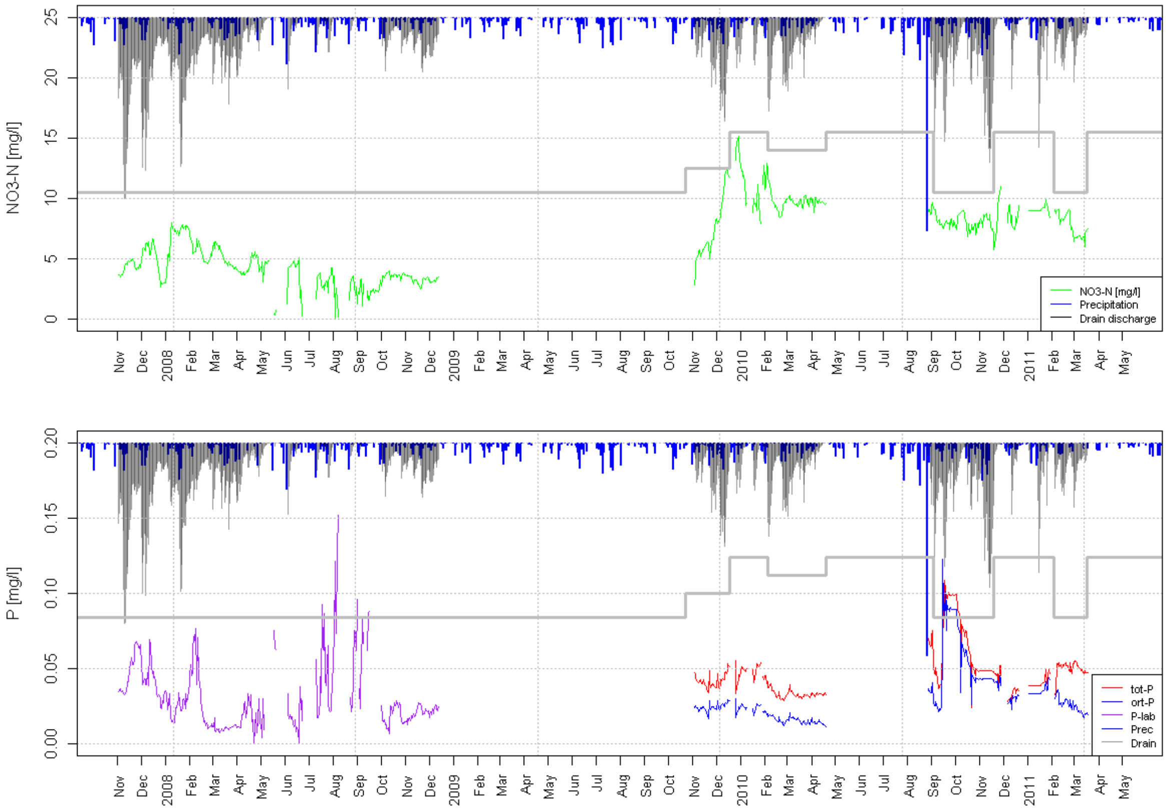

Figure 6: Measured nutrient concentrations in drain effluent. Precipitation (blue), drain discharge (grey), and the overflow levels are also plotted.

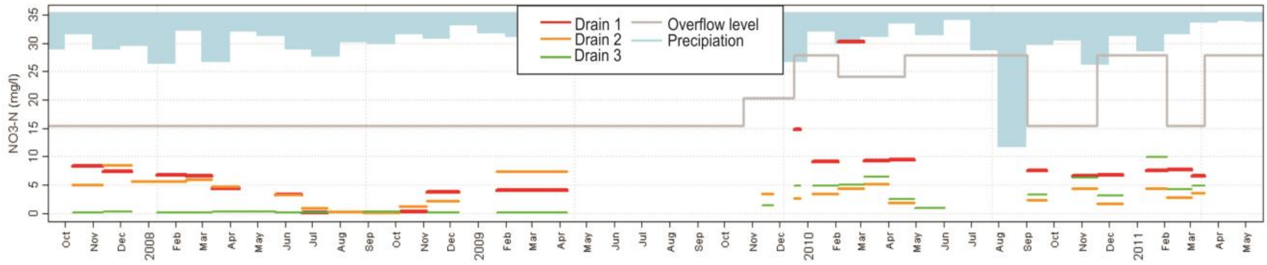

Figure 7: Results of the SorbiCell average NO_3-N concentration measurements for the individual drains.

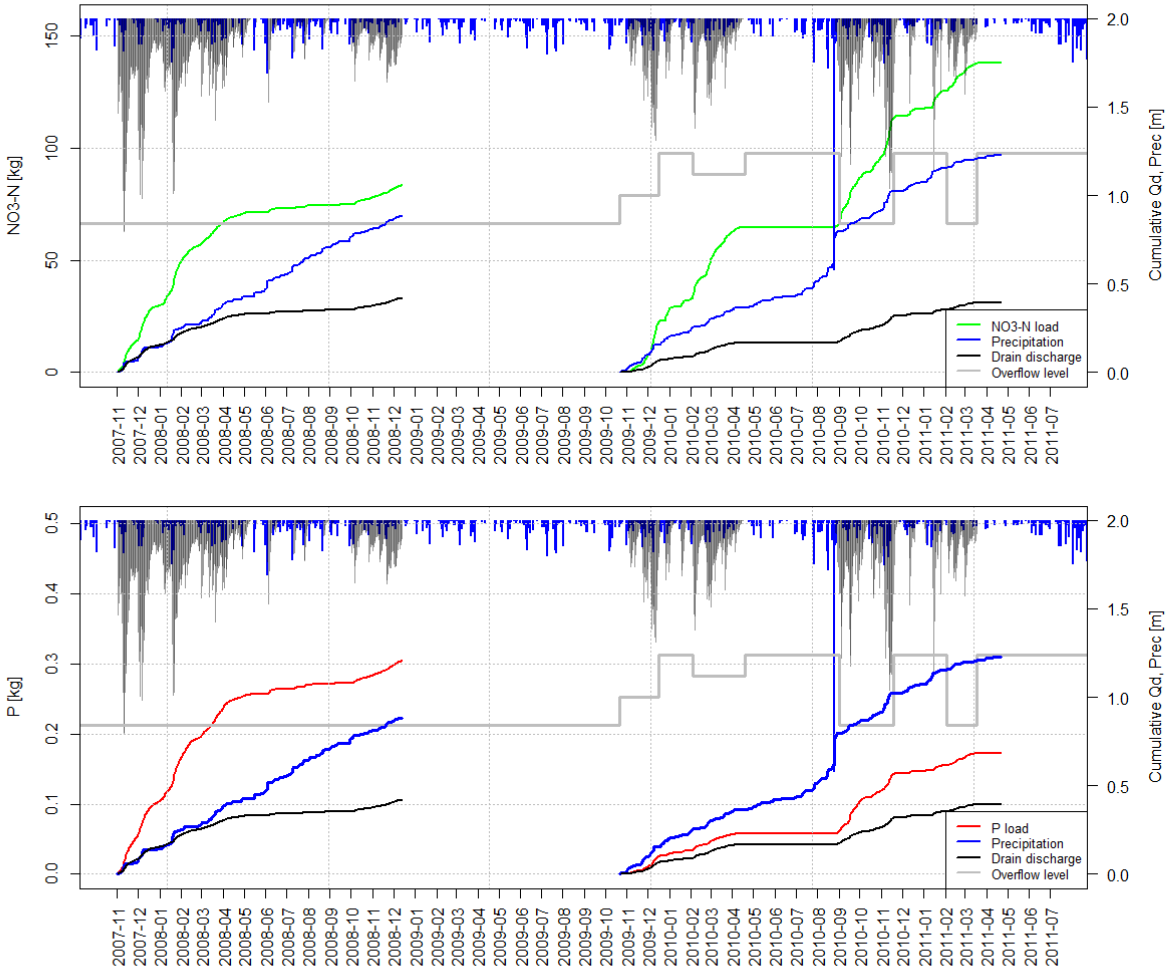

Figure 8: Cumulative precipitation, drain discharge, and drain NO_3-N and P-tot loads.

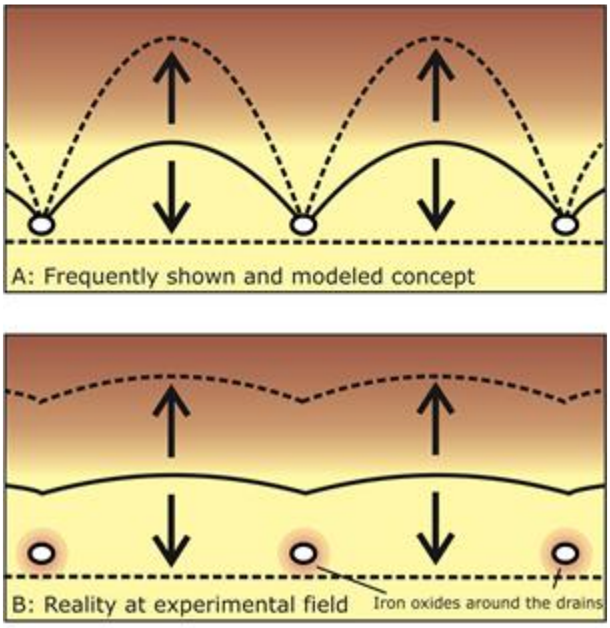

Figure 9: Comparison of (A) the common drainage concept with groundwater tables at the drain elevations and a large groundwater curvature between individual drains and (B) the situation at the experimental field with groundwater tables above the drains and a small groundwater curvature between the drains.

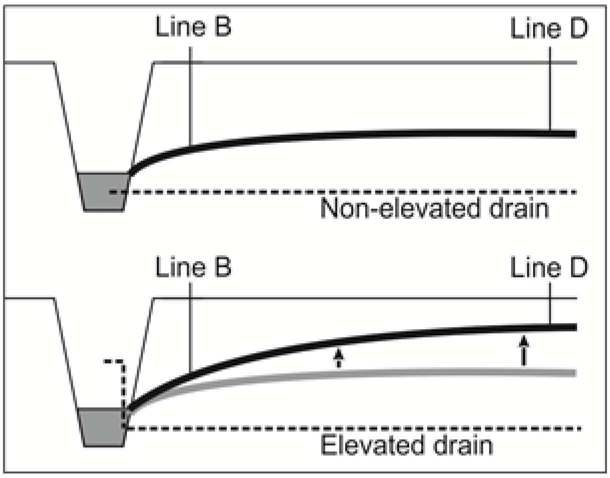

Figure 10: Transect-sketch of the effects of controlled drainage on groundwater levels in the experimental field.

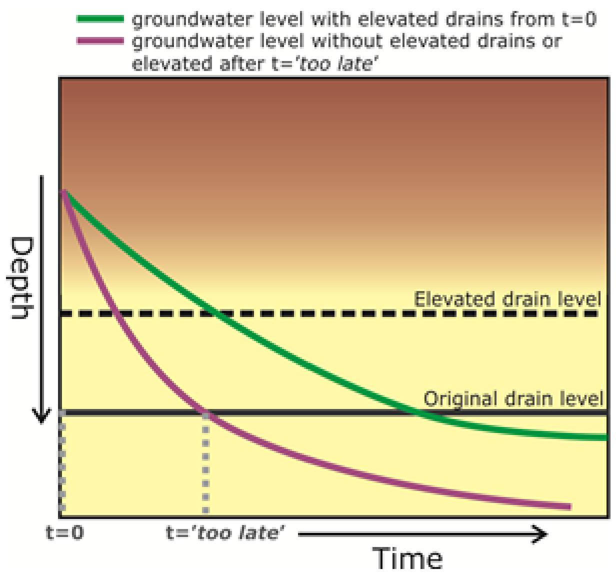

Figure 11: The crucial timing of elevating the overflow levels of controlled drainage at the end of the drainage season. Water can be conserved when the drain outlets are elevated before the groundwater levels are below the drains and the discharge has stopped.