Swedish University of Agricultural Sciences

Final report

Towards environmentally friendly Swedish agriculture
Mot ett miljövänligt svenskt lantbruk

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Anuschka Heeb, Johan Malgeryd and the students from SLU by the two-stage ditch in the study catchment. March 2020. Photo: M. Bieroza

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Part 1: Utförlig sammanfattning

Svenska lantbrukare, myndigheter och forskare arbetar tillsammans mot samma mål av Ingen Övergödning genom att minska förlusterna av näringsämnen och sediment från jordbruksmark till vattendrag, sjöar och Östersjön. Fokus på Fosfor-projektet genomfördes för att testa åtgärder för att minska fosforförluster från jordbruket. Bönder deltog frivilligt. Däremot har det inte funnits någon ekonomiskt stöd till ett uppföljningsprogram för att utvärdera de långsiktiga effekterna på vattenkvaliteten.

Projektet målsättning var att utvärdera effekten av genomförde åtgärder för att minska förluster av fosfor och jordpartiklar från jordbruksmark i pilotprojektet *Greppa Fosforn* (avrinningsområdet E23) genom att använda högtidsupplöst provtagning med våt-kemiska analysatorer och optiska sensorer. Vi utvärderade följande åtgärder för att minska belastningen av fosfor och jordpartiklar på vattendraget:

- Förbättrad dränering och strukturkalkning i jämförelse med ett parallellt fält som inte åtgärdats. Utvärdering av skördeutfallet ingår,
- Ett tvåstegsdike längs det öppna diket som berör fyra lantbrukare,
- En tvåstegs sedimentationsdamm för att fånga partiklar och sedimentbunden fosfor.

I det här projektet visade vi hur genomförandet av tre mer eller mindre oprövade åtgärder (strategiskt placerade the i område E23) har påverkat transporten av fosfor och jordpartiklar och hur processer i själva vattendraget styr koncentrationerna. Kalkfilterdike visade sig vara väldigt effektivt och minskade utsläpp av fosfor med 76% och jordpartiklar med 80% jämfört med fält utan kalkfilterdike. Å andra sidan ökade utsläppen av nitratkväve med 45%. Det kan bero på ökad infiltration eller mineralisering av kväve som kalkningen ger upphov till. Fosfordamm och tvåstegsdike visade sig vara mindre effektiva på att minska utsläpp, något som kan bero på många tillfällen av extremväder under försökstiden som påverkat dess funktionalitet. Vid stora regnoväder ökar vattenflödet och sedimenterade näringsrika partiklar rivs upp från botten och förs vidare nedströms. Den uteblivna effekten av tvåstegsdiket kan bero på instabila terrasser som även dem rivits upp av höga flöden, något som kan motverkas med tät och etablerad växtlighet.

Bekämpning av eutrofiering och klimatanpassning kräver kraftfulla åtgärder för att fördröja vattnet i landskapet och minska läckage och erosion från åkermark till omgivande vattensystem. Detta behov blir kritiskt i framtiden då ökad efterfrågan på mat och extrema väderändringar sannolikt kommer öka näringsförluster, torka och översvämningar. Vi behöver bättre vetenskaplig förståelse av faktorerna som styr deras effektivitet och påverkan på nedströms ekosystem och kunskap/verktyg om optimal val och placering av åtgärder.

Part 2: Report

Introduction

This project aimed to evaluate the effectiveness of mitigation measures for reducing phosphorus (P) and sediment losses, implemented in the pilot *Focus on Phosphorus* catchment E23, using high-temporal resolution sampling and modelling. We evaluated the following measures:

- Improved drainage and structure liming on fields throughout the catchment,
- Lime-backfill (**LF**) in selected field drains,
- Two-stage ditch (**SD**) along the main reach of the open stream (Photo 1) , and
- Two-stage sedimentation pond (**SP**) to capture sediments and sediment-bound P.

Photo 1 The two-stage ditch in E23 catchment during construction in November 2014 (left) and in March 2020 (right). It took 4 years before vegetation was fully established. Photos: A. Heeb & M. Bieroza

The key stakeholders and authorities (Jordbruksverket, LRF, Länsstyrelserna) initiated a project *Focus on Phosphorus* (2007-2014) in three pilot catchments in Västmanland (U8), Östergötland (E23) and Halland (N33) to implement and test different measures reducing P losses from agriculture. The implemented measures included several relatively 'new' measures with generally unknown long-term effects under Swedish conditions (structure liming, modernisation of field drainage, lime-filter ditches, construction of a 2 km two-stage ditch), along with traditional land and nutrient management methods (Malgeryd et al., 2015). The project invested in total 200 million SEK but without follow-up on the long-term effectiveness of the implemented measures. This project aimed to provide this information for the catchment E23.

Evaluation of the effects of these measures on water quality is scientifically difficult, both due to their cumulative effects observed in the stream and the importance of seasonally-changing precipitation and flow conditions on P and sediment transfers (Ulén et al., 2012). However, developments in high-temporal resolution sampling can provide improved understanding of P and sediment sources in relation to flow when compared with conventional grab (Bieroza et al., 2014) and flow-proportional sampling (Ulén et al., 2012). In the project, we used high-temporal resolution (15 min) P and sediment measurements at the catchment outlet and along the main stream. Our hypothesis was that there were significant differences in stream P and sediment concentrations between before and after building of the measures at the catchment outlet and between upstream and downstream of the individual measures.

Our project is the first comprehensive evaluation of the effectiveness of mitigation measures both at the catchment scale and for individual measures and provides scientific understanding of water quality controls in highly polluted catchments and practical recommendations on how individual measures could be implemented to enhance their effectiveness and avoid negative effects like pollution swapping (Stevens and Quinton, 2009). This knowledge is critical for land owners, farming advisors and authorities in Sweden and provides basis for a more targeted and cost-effective approaches in implementing mitigation measures.

Material and methods

Study catchment

Pilot catchment E23 in Östergötland covers an area of 748 ha of which 54% is arable land. The predominant soil type is heavy clay with a clay content of over 70% (Ulén et al., 2011). Livestock (0.6 LU/ha) is diverse with cattle, sheep, pig and chicken production. Mean P loading prior to 2010 was 0.39 kg per ha per year (Malgeryd et al., 2015). Phosphorus (TP) concentrations at the catchment outlet are high (mean 0.25 and standard deviation 0.15 mgl^{-1}, 1987-2014) compared to other small agricultural catchments monitored within the Swedish Agricultural Monitoring Programme (Kyllmar et al., 2014). The catchment is representative for other agricultural areas with dominant clay soils in south-eastern Sweden which cover approximately 60% of the Northern Baltic Sea water region (Geranmayeh and Aronsson, 2016).

Table 1 Mitigation measures implemented during the *Focus on Phosphorus* programme in three study catchments: E23, U8 and N33 (Malgeryd et al., 2015)

Mitigation measure	**Years built**	**Description and aim**
Farming advice	2006-2009	Advice included nutrient and fertliser management plans, crop and livestock management and improving soil conditions. On farms covering 55% of the arable land (30% of the catchment area). To increase awareness of SS and nutrient losses and available mitigation strategies
Buffer zones	2007-2013	10 m wide riparian buffer zones along the main stream and open ditches. To reduce losses of SS, P and N
Lime filter drains (LF)	2012-2013	New field drains with lime backfill over 32% of the arable land (18% of the catchment area). To improve field drainage, reduce ponding and reduce SS and P losses
Structure liming	2010-2014	Lime (burnt $CaCO_3$) was incorporated into field topsoil over 55% of the arable land (30% of the catchment area). To reduce P and SS losses and improve soil structure
Two-stage ditch (SD)	2014	A 2 km ditch with 7 m wide terraces rising at 0.65 m above the stream bed. To reduce stream flow during storm events and reduce losses of SS and P
Sedimentati on pond (SP)	2014	Consists of two ponds (0.15 ha): upstream 1.0-0.8 m deep and downstream 0.4 m deep. To reduce stream flow during storm events, increase water retention during baseflows and reduce stream transfer of SS, P and N

Approach

A novelty of our approach was to invest, thanks to the SLF funding, in the state-of-the art instruments for high temporal resolution measurements of water quality (Photo 2). These

Photo 2 The state-of-the-art instruments used in the project: S::can display unit (left, left), Hach Lange Sigmatax (left, middle), and Phospax (left, right) and an YSI EXO3 sonde (right). Photos: M. Bieroza

instruments allowed us to monitor water quality at the catchment outlet and along the stream at 15 min interval for three years, being the first study in Sweden providing such rich hydrochemical dataset. We used a wet-chemistry phosphorus analyser (Hach Lange) to measure stream total phosphorus (TP) and total reactive phosphorus (TRP) and an optical probe (S::can) to measure turbidity, nitrate nitrogen (NO_3-N), total and dissolved organic carbon (TOC and DOC) at the catchment outlet. Five optical sensors for measurements of turbidity (YSI EXO3) were installed in the stream at five locations to capture sediment transport in relation to flow conditions upstream and downstream of the mitigation measures. These measurements allowed us to assess current hydrochemical behaviour of the catchment. To evaluate the effectiveness of the measures before and after their implementation, we used data from the long-term water quality flow-proportional sampling at the catchment outlet (1988-) (Kyllmar et al., 2014).

Work packages (WPs) – brief overview

WP1 High-temporal resolution monitoring: at the catchment outlet (CA) to evaluate the cumulative effect of all mitigation measures implemented in the catchment on hydrochemical behaviour: improved drainage, structure liming, lime-backfill tile drain, two-stage ditch and two-stage sedimentation pond. For three mitigation measures (lime-backfill drain LF, two-stage ditch SD and two-stage sedimentation pond SP), upstream and downstream measurements of turbidity, specific conductivity, and temperature with YSI EXO sensors to evaluate their individual effect (Figure 1).

WP2 Evaluation of existing monitoring data

A comparison of pre- and post-implementation of measures water quality data to provide an assessment of their effectiveness. Synoptic water quality measurements (flow-proportional and grab samples) have been collected as part of the *Focus on Phosphorus* project for over 15 sampling points along the main stream (Figure 1) between 2007 and 2016 (~36 measurements for each point, for a range of determinands). The sampling points in this project were chosen to utilise the existing network of synoptic sampling points and to enable a statistical comparison of the data collected before and after the measures.

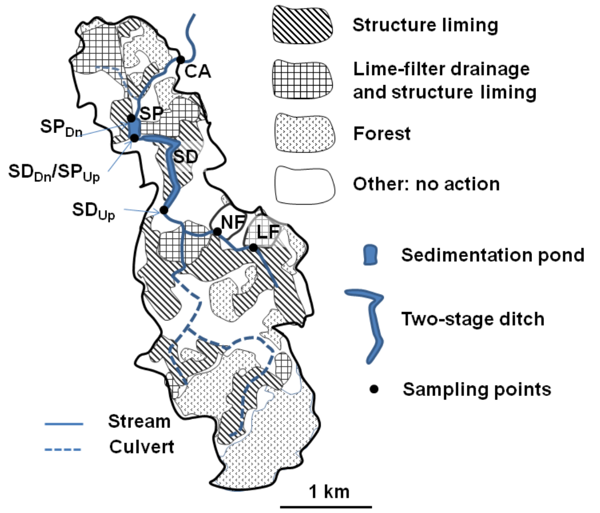

Figure 1 Location of the sampling points and extent of different mitigation measures implemented in the catchment

WP3 Evaluation of existing modelling data

An evaluation of previously calibrated models to understand catchment's behaviour included the HYPE model (SMHI) (Lindström et al., 2010). A good performance was achieved for the hydrological model, particularly using local precipitation data instead of national grid data (Milver, 2014). However, the model's performance was poor for different fractions of P (TP, SRP and particulate phosphorus). Source apportionment analysis based on oxygen isotopic composition of PO_4-P indicated that at flows <0.05 m^3s^{-1}, up to 90% of P was delivered from point sources in the catchment (septic tanks) and the diffuse P dominated in storm flows (Rönnberg, 2012). These results indicate that concentration-discharge mechanisms in the catchment are not represented properly by existing models and high-resolution data is need for to understand hydrochemical behaviour.

WP4 Phosphorus and sediment modelling

This work aimed at using high-resolution data to calibrate a new or re-calibrate existing models for the catchment. As setting up a new model can be challenging, we decided to use existing S-

HYPE model in collaboration with SMHI to provide a better understanding of switches in different hydrochemical regimes. This approach can provide a framework for modelling P losses from other small agricultural catchments in Sweden, for which S-HYPE models already exist (Arheimer et al., 2012). By comparing the model outputs for before and after the implementation of the mitigation measures and for different climatic conditions, this can be a useful tool for optimal placement of mitigation measures in the catchments.

WP5 Evaluation of effectiveness of mitigation measures

This work aimed at collating all monitoring and modelling data to provide assessment of cumulative (at the catchment outlet) and individual (at reach-scale) impact of the mitigation measures, using both quantitative (percentage change in concentrations and loads) and qualitative measures of effectiveness (changes in the effectiveness in relation to seasonally-changing flow and management). For individual measures, an analysis of concentration-discharge hysteresis was performed to provide information on sources of P and sediments (proximal and distal sources). Modelling work (WP4) is aimed at testing different scenarios for climate and flow conditions and evaluation of the changes in effectiveness of the measures.

WP6 Dissemination &communication

Our dissemination and communication plan involved meetings with the land owners and authorities involved in the *Focus on Phosphorus* project, news and short popular science summaries of our findings with practical recommendations, sharing findings during conferences and workshops for stakeholders and at least three scientific peer-reviewed publications.

Results and discussion

Hydrochemical regime controls diffuse losses of nutrients and sediments

High-temporal resolution water quality data has improved our understanding of diffuse pollution controls in the study catchment that was not possible with previous monitoring and modelling data (Milver, 2014; Rönnberg, 2012). Diffuse nutrient and sediment losses are controlled in the catchment by stream discharge (Figure 2). High flows generally lead to higher concentrations of pollutants compared to low flows. On a seasonal basis, winters are often wet leading to frequent pulsess of P and SS, whereas NO_3-N transport is more related to episodic inputs, e.g. from manure applications or related to prolonged drought. Drought (summer 2018) leads to accummulation of nutrients and SS and their rapid release during the first

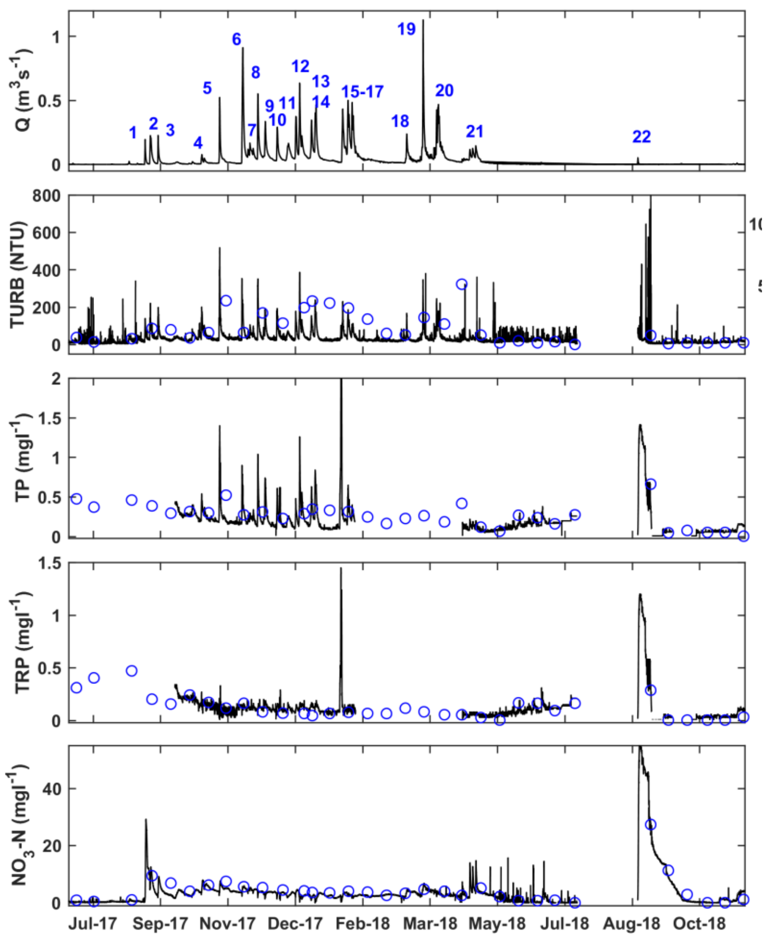

Figure 2 Time series of flow discharge (Q), total phosphorus (TP), total reactive phosphorus (TRP) and nitrate nitrogen (NO_3-N) measured at 15 min resolution at the E23 catchment outlet (black lines). Major storm events are numbered 1-22. Stream chemistry concentrations measured at low-frequency resolutions (fortnightly, flow-proportional samples) are given as blue circles. A gap in TP and TRP in Feb-Mar 2018 was due to freezing of sampling equipment. No measurements were taken in mid-Jul-Aug due to no flow

autumn storm event. Higher frequency of drought in the future climate will therefore negatively impact water quality and stream ecology, requiring strategies to further increase water retention.

The concentration-discharge relationships (Figure 3) show a variety of different responses: highly episodic, transport-limited response for particulate P and SS (TURB), a dilution, source-limitation pattern for TRP and a mixed chemostatic-episodic response for NO_3-N and DOC. These results indicate that: high flows are associated with high concentrations and loads of TP, SS, NO_3-N and DOC; low flows mobilise high TRP concentrations from point sources and desorbed P from bed sediments (Bieroza et al., 2019). With a higher magnitude of future storm events and longer periods of drough and low flows (Eklund et al., 2015; Woodward et al., 2016), both diffuse and point source pressures will become therefore enhanced leading to further water quality problems, despite all mitigation efforts in the catchment. To offset these negative impacts, further mitigation options including optimised nutrient and soil management will be needed to reduce leaching and soil erosion.

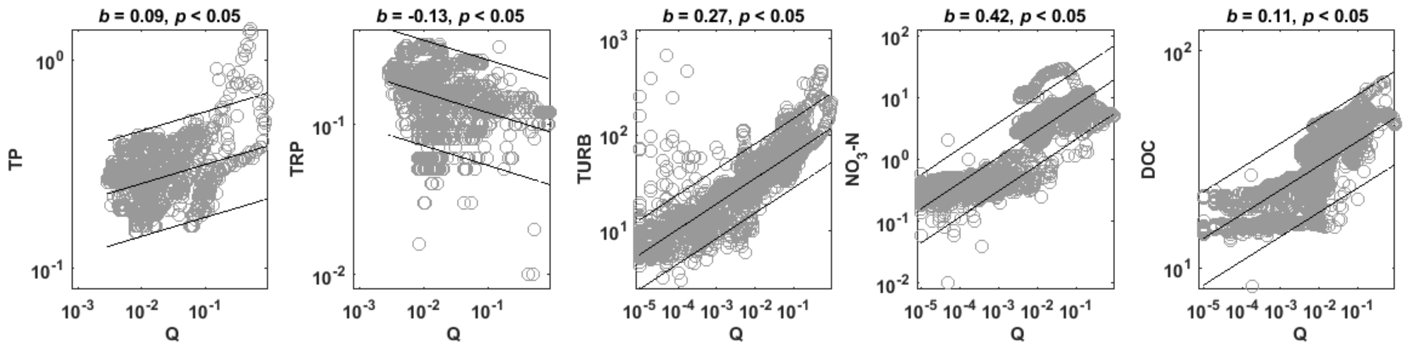

Figure 3 Concentration-discharge (*c*-*q*) relationship at the catchment outlet for total phosphorus TP, total reactive phosphorus TRP, turbidity TURB, nitrate nitrogen NO_3-N and dissolved organic carbon DOC. Slope of the *c*-*q* relationship *b* is given along with the *p* value. Both axes are in logarithmic scale

Cumulative effectiveness of mitigation measures at the catchment scale

The mitigation measures built in the catchment brought expected improvements in water quality measured as decrease in P and SS loads (Figure 4) by ~50% and 80% respectively with simultanous increases in TN and NO_3-N loads by 20%. However, these results need to be evaluated with care since, although not statistically significant, there was a clearly lower median flow discharge after building the measures compared to the period before by 40%. These results indicate that with the changing climate it might be difficult to distinguish the effect of the management vs. climate, as both control diffuse losses from agricultural catchments (Mellander et al., 2018). The increase in N loads can be driven by drier conditions in the period after the measures, since increased soil organic matter mineralisation and nitrification can cause increased nitrate leaching from agricultural soils (Castellano et al., 2019).

The impact of hydrology on loads can be illustrated by plotting a relationship between flow discharge and load (Figure 5), with strong influence for R^2>0.90. The importance of flow discharge on TP and SS loads has increased after building the measures, decreased for dissolved P (TDP and SRP), and has not changed for N forms. From Figure 5 it can be also seen that for a given flow discharge after builing the measures, the load is lower for P and SS but higher for TN and NO_3-N. This indicates that the pollution export regimes from the catchment have changed due to building measures and this change is positive for P and SS (lower load and concentrations) but negative for TN and NO_3-N (higher load and concentrations). Therefore, an increase in N export from the catchment cannot be solely explained by drier weather and other factors might also play a role, including pollution swapping mechanism (Stevens and Quinton, 2009).

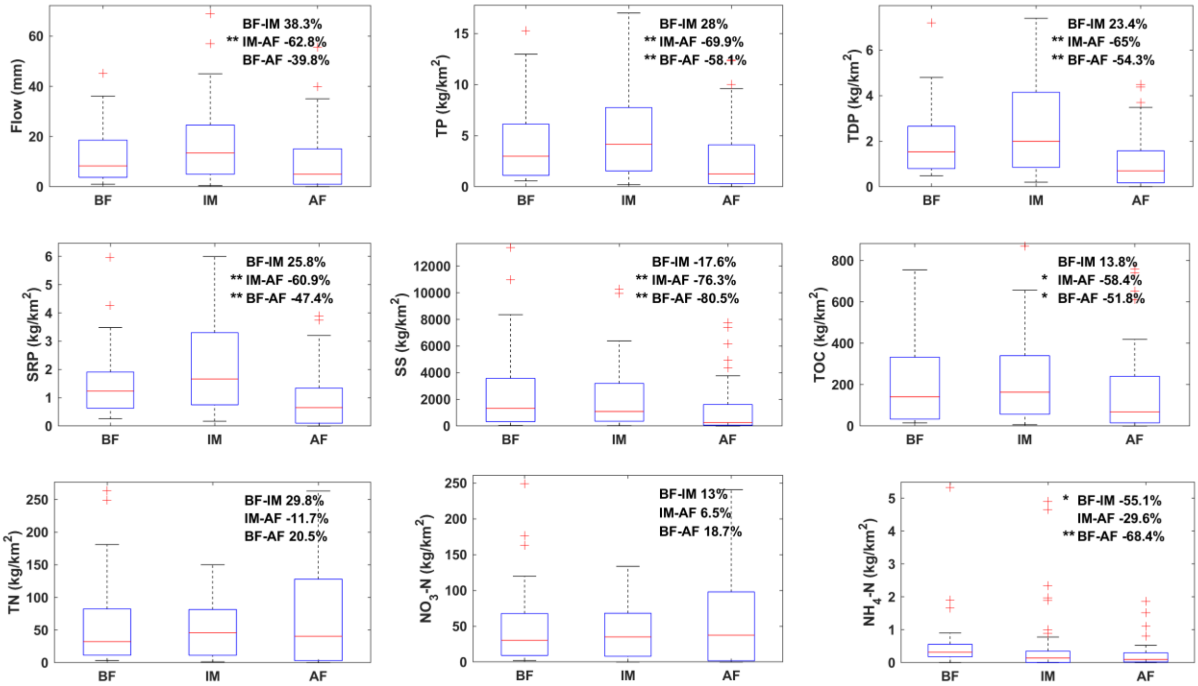

Figure 4 Median (red lines) loads (kg/km^2) in three periods: BF before measures (until 2010), IM during implementation (2011-2014) and AF after implementation of the measures (2015-2020). % change in loads between different periods, significant at ** 0.01 and * 0.05 level

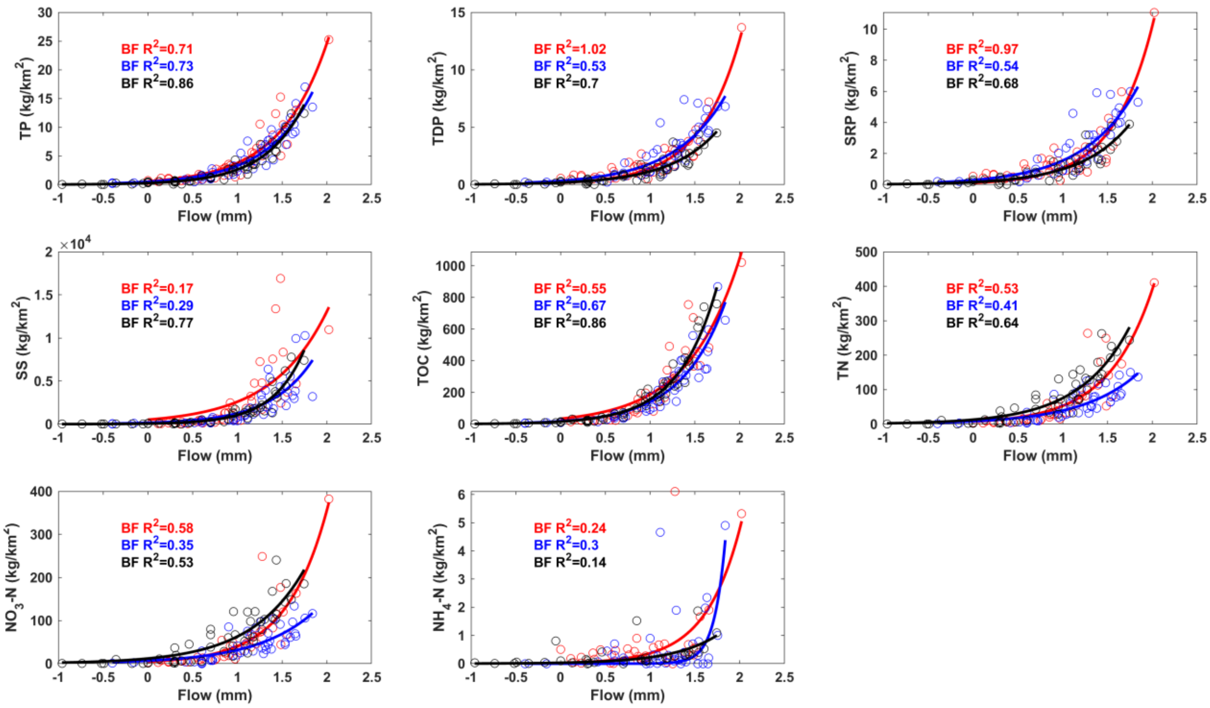

Figure 5 Monthly flow discharge (logarithmic scale) vs. load relationships for three periods BF, IM and AF with exponential regressions lines

Effectiveness of individual mitigation measures

The pollution swapping mechanism, in which decrease in concentrations of one pollutant can lead to increase in concentrations of another pollutant is corroborated when looking at the effectiveness of individual measures (Figure 6). Lime-filter drains significantly reduce SS (TURB) and TP concentrations by ~80% but increase NO_3-N by 45%. This could be a result of improved soil structure and infiltration capacity (Ulén and Etana, 2014) that can enhance mineralisation and nitrification (Castellano et al., 2019). As over 50% of arable land in the catchment was subjected to either structure liming or introduction of lime filter drains (Table 1), their cummulative effect can lead to observed increases in TN and NO_3-N loads and concentrations at the catchment scale.

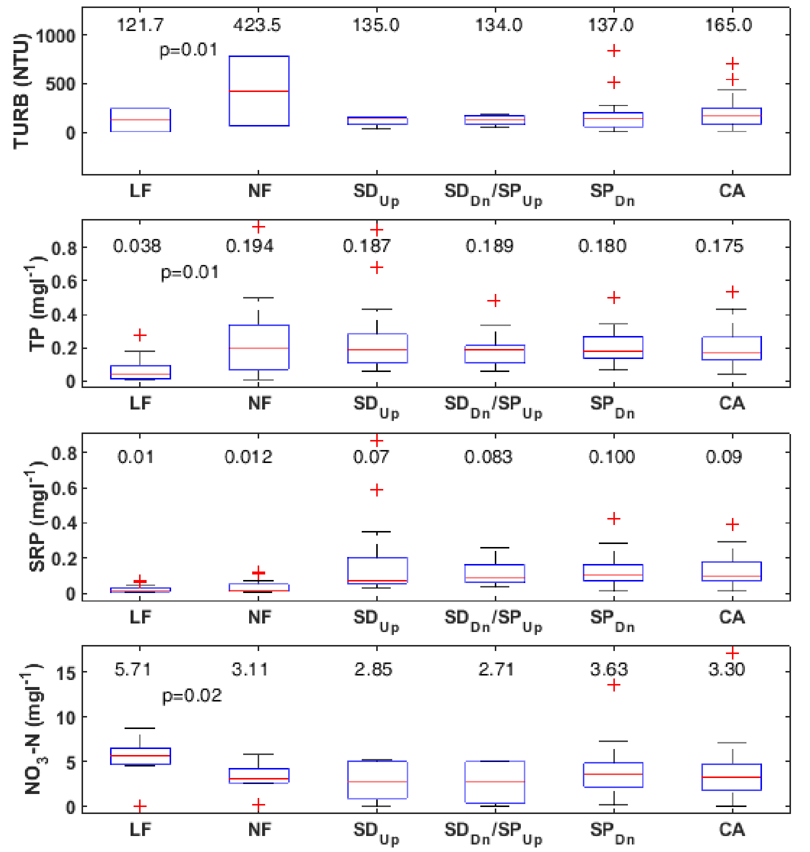

Figure 6 One-way analysis of variance (Kruskal-Wallis test with p values at 0.05 significance level) for monthly grab samples (*N*=20, 2017-2018). Pairwise comparisons are statistically significant if *p* value is given. For each sampling point, median value is given above the boxplot

High-frequency data clearly showed that lime-filter drain reduced turbidity concentrations (flow-weighted) compared to traditional drain (Figure 7) both during low flow conditions and storm flows. For example, a storm event at the beginning of Sep 2017 led to disproportionally higher concentrations in traditional drain (4050 NTU) compared with lime-filter drain (650 NTU). For both the two-stage ditch and sedimentation pond (Figure 7), the differences in concentrations between upstream and downstream sections were not evident and the measures acted both as a sink and source of SS. The variation in turbidity concentrations was higher for SD_{Dn} and SP_{Dn} indicating that resuspension of bed sediments plays an important role in SS export in the downstream sections of two-stage ditch and sedimentation pond.

Implications

A growing body of evidence shows that the efforts in combating eutrophication in North America and Europe (Bol et al., 2018; Jarvie et al., 2013) and specifically of the Baltic Sea are (Svanbäck et al., 2019) non-satisfactory. A greater use of mitigation measures is thus required to achieve good chemical and ecological status particularly in light of climate change (Ockenden et al., 2017). However, many studies show mixed effectiveness of these measures on water quality and considerable lags between treatment and response (Meals et al., 2010) that are increasingly difficult to communicate to stakeholders expecting instant improvements.

Therefore, our study adds value to the ongoing research on mitigation by analysing its impact for a headwater agricultural catchment with high diffuse losses of P and SS.

Our evaluation of the long-term hydrochemical data in E23 showed reductions in P and SS and increase in NO_3-N concentrations at the catchment outlet that could not be explained by changes in hydrological regime or land use management (production and fertilisation have not changed significantly after the measures; data not shown here). Therefore, mitigation measures are the likely cause of observed water quality trends. Similar trends in P and SS concentrations and flashiness were observed in two other *Focus on Phosphorus* catchments, with similar measures implemented: U8 and N33 (Bieroza et al., 2019). In the U8 catchment similar reductions in P and SS flow-proportional concentrations (17% and 43% respectively) but there was also a corresponding decrease in NO_3-N concentrations by 46% unlike in E23. In the N33 catchment, the observed patterns were similar (decrease in P and SS and increase in NO3-N) with lower flashiness and drier conditions (not statistically significant) after the measures. Therefore, longer hydrochemical time series are required to fully validate our results.

Lime-filter drains were particularly effective in reducing P and SS losses but they also contributed to leaching of NO_3-N. Two-stage ditch and sedimentation pond acted as both sink and source of P and SS depending on the antecedent meteorological and hydrological conditions and the availability of within-stream sources of P and SS. Mitigation of these secondary P and SS sources is critical for restoring good water quality status in the catchment. Further studies are also needed to determine if the increases in NO_3-N concentrations both for lime-filter drains and at the catchment scale are a result of dry weather conditions or pollution swapping.

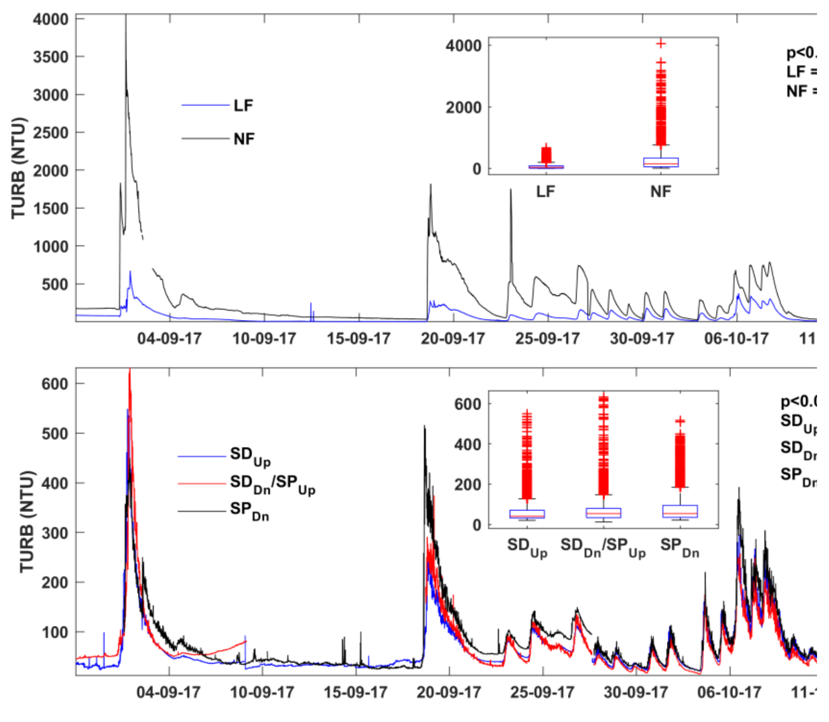

Figure 7 Time series of turbidity measured at 15 min resolution at two sampling points (LF in blue and NF in black, top panel) and at three sampling points (SDUp in blue, SDDn /SPUp in red, SPDn in black, bottom panel). Insert figures show pairwise comparisons (Kruskall-Wallis one-way ANOVA)

Conclusions

This project has resulted in publication of 2 scientific papers (Bieroza et al., 2019; Bieroza et al., 2018), 3 scientific papers based indirectly on the results (Bieroza et al., 2020; Bol et al., 2018; Heathwaite and Bieroza, 2020), 3 popular science summaries, 8 oral conference presentation, 1 conference poster, 1 meeting with stakeholders, 3 student projects and 4 awarded research grants (Part 3). There are also 3 further scientific publications in preparation and the ideas and knowledge obtained in this project will continue to generate further scientific insights and practical solutions. Thus, the long-term impact of the project is yet to be realised.

Benefits for agricultural industry and recommendations

There is a direct benefit of our study for the land owners and authorities who participated in the *Focus on Phosphorus* project as our results show reductions in P and SS loads and concentrations. We communicated these findings during a meeting with the stakeholders in E23 and through soon to be published two popular science reports in Swedish (Fakta blad, see part 3). To recommend two-stage ditches and sedimentation ponds as mitigation measures we need a comprehensive evaluation of the key processes responsible for reducing P, N and SS and their link to structural properties of these measures (how they are built and managed). We evaluate this through ongoing follow-up projects: Formas on two-stage ditches and Jordbruksverket on phosphorus ponds. The next step will involve evaluation of the cost-effectiveness of these measures and their role in providing multiple ecosystem services.

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Part 3: Communication of results

Scientific publications directly related to the project	Bieroza MZ, Bergström L, Ulén B, Djodjic F, Tonderski K, Heeb A, Svensson J & Malgeryd J, 2019, Hydrologic Extremes and Legacy Sources Can Override Efforts to Mitigate Nutrient and Sediment Losses at the Catchment Scale. Journal of Environmental Quality, doi:10.2134/jeq2019.02.0063. https://acsess.onlinelibrary.wiley.com/doi/full/10.2134/jeq2019.02.0063 Main publication showing project results: effectiveness of different measures and long-term trends.
	Bieroza MZ, Heathwaite AL, Bechmann M, Kyllmar K & Jordan P, 2018, The concentration-discharge slope as a tool for water quality management, Sci Total Environ, 630, 738-749. https://www.sciencedirect.com/science/article/pii/S0048969718306569 Publication showing hydrochemical functioning of the study catchment, key for mitigation.
Scientific publications indirectly related to the project	Heathwaite AL, Bieroza MZ, 2020, Fingerprinting hydrological and biogeochemical drivers of freshwater quality. Hydrological Processes, doi: 10.1002/hyp.13973. https://onlinelibrary.wiley.com/doi/full/10.1002/hyp.13973?af=R Publication related to another catchment but using knowledge generated in this project.
	Bieroza MZ, Dupas R, Glendell M, McGrath G, Mellander P-E, 2020, Hydrological and Chemical Controls on Nutrient and Contaminant Loss to Water in Agricultural Landscapes, Water, in press. https://www.mdpi.com/2073-4441/12/12/3379 Publication summarising diffuse pollution and mitigation, partly using knowledge generated in this project.
	Bol R, Gruau G, Mellander P-E, Dupas R, Bechmann M, Skarbøvik E, Bieroza M *et al*., 2018, Challenges of Reducing Phosphorus Based Water Eutrophication in the Agricultural Landscapes of Northwest Europe. Front. Mar. Sci. 5:276. doi: 10.3389/fmars.2018.00276. https://www.frontiersin.org/articles/10.3389/fmars.2018.00276/full Publication summarising eutrophication pressures and mitigation needs in Europe, partly based on the study.
Scientific publications in preparation	Bieroza MZ, Hallberg L, Ulén B, Djodjic F, Tonderski K, Heeb A, Svensson J, Malgeryd J, Lindström G, 202X, Nutrient and sediment exports from a small agricultural catchment. Publication summarising controls of nutrient and sediment export and modelling results.
	Bieroza MZ, Hallberg L, Ulén B, Djodjic F, Tonderski K, Heeb A, Svensson J, Malgeryd J, Lindström G, 202X,

	Agricultural streams are hotspots of biogeochemical transformations. Publication quantifying the rates of key biogeochemical processes responsible for reducing nutrient losses.
	Bieroza MZ, Bechmann M, Blicher-Mathiesen G, Kyllmar K, Rankinen K, 202X, Impacts of extreme hydrological events on water quality in boreal agricultural catchments. Publication using data for the study catchment, storm events and drought hydrochemical responses.
Popular science reports in Swedish	http://greppa.nu/arkiv/nyhetsarkiv/2019-11-05-tre-fosforatgarder-utvarderades-vid-samma-back.html
	Fakta blad: Utvärdering av tre miljöåtgärder för renare vatten i jordbrukslandskap. To be published on Greppa Näring or Jordbuksverket webpage in 2020. Hallberg L, Bieroza M, Heeb A, Malgeryd J.
	Fakta blad: Optimering av tvåstegsdikens design för förbättring av retention av näringsämnen och sediment. To be published on Greppa Näring or Jordbuksverket webpage in 2020. Englund S, Bieroza M, Heeb A, Malgeryd J.
Personal communication	***Oral conference presentations***
	Bieroza MZ, Ulen B, Geranmayeh P, Djodjic P, Heeb A. 2020, Combating eutrophication in agricultural catchments: factors controlling effectiveness and challenges of changing climate and nutrient legacies. EGU (Vienna, AT), 4-8th May.
	Bieroza MZ, 2019, Challenges in reducing nutrient and sediment losses in agricultural catchments, Catchment Science conference organised by Teagasc (Wexford, IE), 5-7th November.
	Bieroza MZ *et al*., 2019, Integrating high- and low-frequency water quality monitoring at the catchment scale, LuWQ2019 conference (Aarhus, DK), 3-6th June
	Bieroza MZ *et al*., 2019, Phosphorus mitigation at headwater catchment-scale: is increased hydrological flashiness overriding the management efforts? EGU (Vienna, AT), 7-12th April.
	Bieroza MZ, 2018, Making sense of the sensor data - from in situ sampling to understanding processes, 12-13th June during 3rd International Workshop on High Temporal Resolution Water Quality Monitoring and Analysis (TEAGASC, Ireland), Keynote.
	Bieroza MZ, 2018, Evaluation of eutrophication mitigation measures at fine spatial and temporal resolution, Society for Freshwater Science Annual Meeting (Detroit, US), 20-24th May.
	Bieroza MZ *et al*., 2018, Concentration-discharge slope as a robust tool for water quality management, EGU (Vienna, AT), 9-13th April.
	Bieroza MZ *et al*., 2017, Evaluation of the effectiveness of phosphorus and sediment mitigation measures with high-

	frequency monitoring, Phosphorus Workshop (Rennes, FR).
	Poster conference presentation
	Bieroza MZ *et al*., 2018, Evaluation of the effectiveness of the eutrophication mitigation measures with optical sensors. EGU (Vienna, AT).
	Meeting with stakeholders
	Meeting with land owners in Hestad catchment to discuss ways to reduce nutrient losses to the Baltic Sea. 6th March 2020. Anuschka Heeb (Vatten och växt), Johan Malgeryd and Emma Svensson (Jordbruksverket) and SLU students: Lukas Hallberg on Formas project Two-stage ditches in Sweden, Sofia Englund on MSc project optimising design of two-stage ditches, Andreas Matsson on MSc project Water quality in agricultural drainage and Adam Eriksson on MSc project Water quality in observational fields in Sweden.
	Letter to stakeholders
	Sent in February 2017 to the land owners in the study catchment informing them on the project objectives and measurements.
Student work directly related to the project	Matsson, Andreas, MSc, 2020. Subsurface drainage as hot-spot of water pollution in an agricultural catchment. In preparation.
	Englund, Sofia, 2020. Optimizing the design of two-stage ditches to improve nutrient and sediment retention. MSc thesis, Uppsala University, Department of Earth Sciences. http://www.diva-portal.org/smash/get/diva2:1450963/FULLTEXT01.pdf
	Larsson, Åsa, 2018. Nutrient concentrations before and after the Focus on Phosphorus project in E23 catchment. BSc thesis, SLU, Department of Soil and Environment. https://stud.epsilon.slu.se/13981/
Other awarded research grants related to the project	2019-2021 *Two-stage ditches in Sweden - from improving process understanding to reducing eutrophication*. Formas Research Council, Future Research Leaders Grant (3 mSEK). PI Bieroza, Co-Is: Jennifer Tank (University of Notre Dame), Barbro Ulén (SLU), Faruk Djodjic (SLU), Anuschka Heeb (Växt o vatten).
	2019-2021 *Do agri-environmental mitigation measures increase emissions of N2O?* Swedish Board of Agriculture (0.5 mSEK), PI Bieroza, Co-Is: Sara Hallin (SLU), Jennifer Tank (University of Notre Dame), Faruk Djodjic (SLU).
	2018-2019 *Denitrification in bed sediments of a two-stage ditch and a sedimentation pond*, Stiftelsen Carl Tryggers, (0.35 mSEK), PI Bieroza, Co-Is: Barbro Ulén, Faruk Djodjic, Anuschka Heeb, Karin Tonderski, Johan Malgeryd
	2017-2019 *Phosphorus ponds with and without sediment removal*, Jordbruksverket (0.7 mSEK), PI Bieroza, Co-Is: Lars Bergström, Pia Geranmayeh, Barbro Ulén