STØTTET AF

Promilleafgiftsfonden for landbrug


Drone image of saturated buffer in Ulvskov in December 2021 (photo: N. Ovesen)

Saturated Buffer Zones – Preliminary results
Innovationsplatform for Drænvirkemidler
Project Report 2021

Dominik Henrik Zak, Astrid Ledet Maagaard, Rasmus Jes Petersen, Brian Kronvang, Niels Bering Ovesen, Joachim Audet, Carl Christian Hoffmann.

Department of Ecoscience, Aarhus University

1. Background

Three billion people are expected to join the global population over the next two decades, thereby accelerating the degradation of natural resources (Scanlon et al. 2017) and along with this the increase in the global demand for clean water will likely exceed viable resources by 40% by 2030 in a business-as-usual scenario (WWAP, 2015). In Europe, an increasing demand for water and a major pressure on aquatic ecosystems coming from the still-growing agricultural sector coincides with reduced water availability as a consequence of climate change, with higher evapotranspiration and reduced water storage during more extreme precipitation events. Despite substantial efforts to reduce fertiliser application and adopt best land use and management practices (Lam et al., 2011), nutrient pollution problems persist, and are now aggravated by effects of climate change on landscape hydrology. From year 2003, the Water Environment Plans was implemented to fulfil the EU Water Framework Directive (WFD), that aims to protect all terrestrial surface waters and sets environmental goals for all water bodies to achieve good ecological status (Chave, 2001). According to WFD all waters including surface and ground waters should achieve good quality by year 2027. However, it can be challenging as these targets may potentially impact agriculture, industries, an the household sector, since compliance with the WFD can result in costly investments. In Denmark the awareness towards the deterioration of the aquatic environment started to raise in the 1980's amongst others pushed by a medially staged event: A group of fishermen sailed into a port with their catch – dead Norway lobsters. Four decades later, still a large share of the Danish coastal water bodies fails to meet the requirement of good ecological status (Peterson et al, 2021). According to Danish "Agreement on green conversion of Danish agriculture" published 4th of October 2021, around 1,500 t of total nitrogen reduction it is planned to achieve using collective methods, such as afforestation, natural and constructed wetlands (Hoffmann et al. 2020). According to this, an increase in the number of constructed wetlands in Denmark is expected within the next couple of years. The saturated buffer zone (SBZ) is a new mitigation measure in a Danish context. This edge of the field technology has been tested in USA since 2010 (Jaynes & Isenhart, 2014), showing that a simple design of water saturating a riparian zone can have promising effects on nutrient removal (Jaynes & Isenhart, 2019). In following, the monitoring results of a Danish pilot site will be reported.

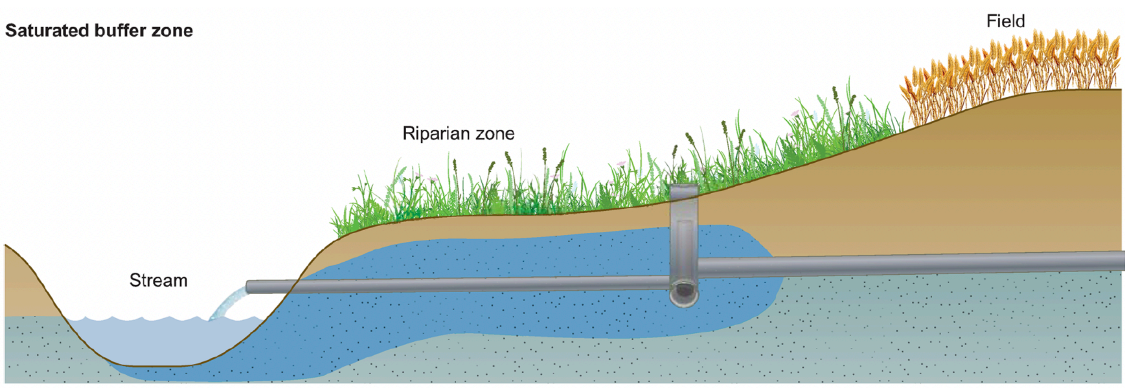

Figure 1. Conceptual scheme of a saturated buffer zone. The drainage pipe is diverted into a distribution pipe charging the SBZ until water saturation depending on the amount of infiltrating water during the year. Surplus of water is directed to the stream over a vertical bypass pipe in the distribution well presenting the old drainpipe (image from Carstensen et al. 2020)

2. Material and Methods

The investigation of two SBZ started in September 2019 which included water flow and water table measurements, water sampling of the inlet, stream and piezometer transects, soil analysis, bromide tracer experiments, slug tests, vegetation survey and plant harvesting (for details see Table 1 and sections below). The investigation in the SBZ 'Gylling' was suspended end of the year 2020 since high groundwater tables in addition to presumed low water infiltration capacity of strongly degraded peat at the soil surface (down to 1 m) prevented an ongoing charging of the IBZ with drain water. Instead, a new SBZ was fully instrumented from October to December 2021 near Odder called 'Bondesvad' (see section 4).

Table 1. Overview of investigations conducted in the two project sites Gylling and Ulvskov.

Type of Action	Target	Site (Time)
Continuous water flow measurements	Quantification of drain water inflow on the daily basis	Gylling (10/2019 – 12/2020) Ulvskov (09/2019 – 12/2021)
Water table measurements (every three weeks, continuously for selected piezometer)	Temporal and spatial changes of groundwater tables	Gylling (10/2019 – 12/2020) Ulvskov (09/2019 – 12/2021)
Soil analysis	Elemental composition (metals, nutrients, and carbon); phosphorus fractions (water soluble phosphorus and redox-sensitive phosphorus); water extractable organic carbon; soil texture	Gylling (03/2019 – 02/2020) Ulvskov (09/2019 – 12/2021)
Water analysis (on the daily basis for the inlet from ISCO samplers and for all sampling spots every three weeks grab samples)	Dissolved N and P species (nitrate, nitrite, ammonium, total dissolved nitrogen, soluble reactive phosphorus, and total dissolved phosphorus); dissolved organic carbon, physico-chemical parameters (electrical conductivity, pH, oxygen, temperature)	Gylling (10/2019 – 12/2020) Ulvskov (09/2019 – 12/2021)
Tracer experiment with bromide over 2 to 4 weeks (hourly to weekly sampling)	Determination of subsurface water flow paths and to estimate the water residence time	Gylling (12/2019) Ulvskov (11/2019; 11/2020)
Slug test (one day)	Determination of hydraulic conductivity and water flow	Ulvskov (12/2021)
Vegetation survey and plant harvesting	Plant species analysis and determination of nutrient (nitrogen and phosphorus) and carbon uptake	Ulvskov (10/2021 – 11/2021)

2.1 Study site

The saturated buffer zone is located at the forest Ulvskov, near Odder, and named hereafter. Drainage water is received from an upland of 4.5 ha of agricultural field. Firstly, the drainage water runs into a distribution well at the inlet containing a flow meter and a raised bypass pipe. The water is led to the SBZ through an 80 m long distribution pipe running parallel to the stream at ca. 20 m distance. Hereby, the distribution pipe located about 0.5 m below soil surface charges the SBZ to raise the soil water table ideally up to the surface. The SBZ has 4 transects installed, whereas 'transect 4' is a control transect placed in a naturally wet part of the buffer zone as the soil surface is about 0.5 lower than in the managed SBZ. All transects consists of

4 piezometers (e.g., 1-1, 1-2, 1-3, 1-4), and the first piezometer is placed between the edge of the field and the distribution pipe to account for input of shallow groundwater (Figure 2).

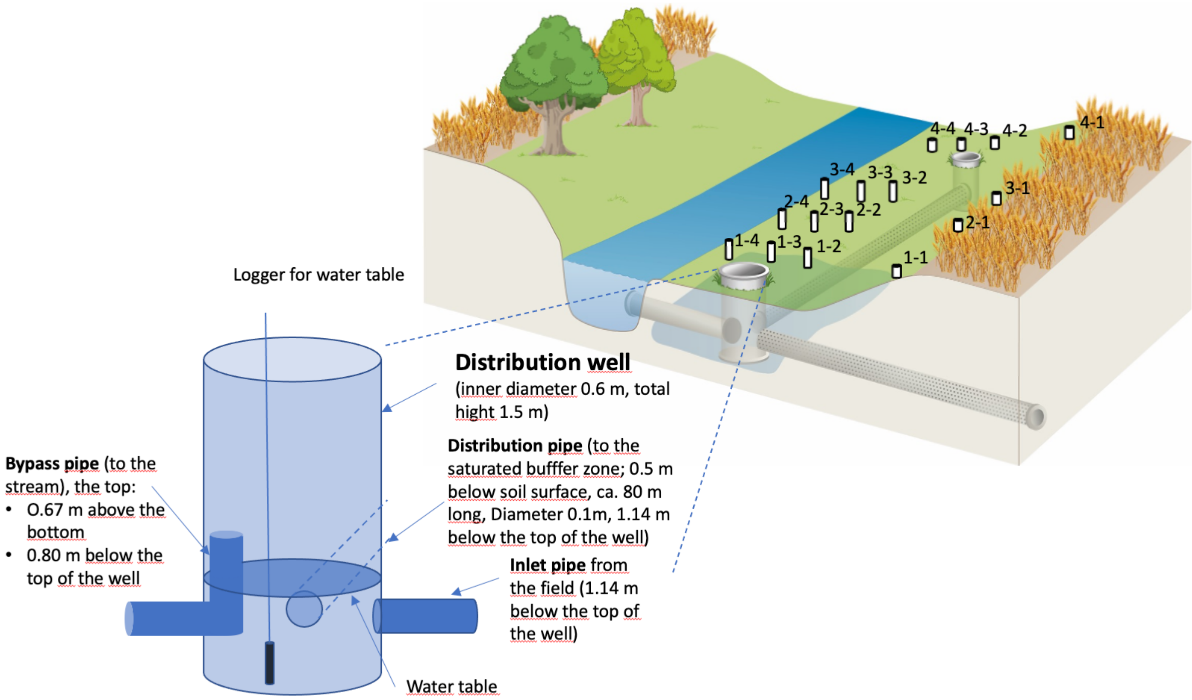

Figure 2. Layout of the instrumented saturated buffer zone (SBZ). Three transects with piezometer are in the SBZ and one control transect (4-1, …, 4-4) in a natural wetter part of the riparian zone.

2.2 Water flow, sampling, and analysis

The buffer zone is instrumented with a solar-charged water flow meter (Krohne) at the inlet to achieve a continuous flow measurement of the drainage water. In addition, the water table in the distribution well is logged continuously to detect periods of water loss to the stream via the bypass pipe (Figure 2). Bypass flow was found taking the water level when above the height of the bypass pipe and comparing these occurrences with the flow rate. Over time the amount of drain water charging the SBZ was decreasing to about 1 l/s either due to lowered water uptake capacity of the soil in the buffer zone and/or a clogging of the distribution pipe with fines soil particles. The distribution pipe was rinsed on 2nd of December 2021 to increase infiltration of drainage water and thereby decrease the bypass flow. Since the effect was minor a clogging of the distribution pipe seems to be currently negligible.

Water samples were taken continuously by automatic ISCO samplers at the inlet every 30 minutes and pooled to daily samples. Furthermore, grab samples were taken in every 3 weeks in the inlet, outlet, stream, and the piezometer tubes. All water samples are handled and analysed in the laboratory according to Danish Standard/ European Standard for total nitrogen (TN), total dissolved phosphorus (TDP), soluble reactive phosphorus (SRP), nitrate (NO_3-N), and ammonium (NH_4^+). For mass balance calculations for P and N species only grab samples were considered since both phosphate and nitrate might decline in the Isco bottles due to sorption or denitrification, respectively.

2.3 Hydraulic conductivity

For the Ulvskov site hydraulic conductivities were measured using slug tests (falling head) in all saturated piezometers according to the method described by (Bouwer & Rice, 1976). Hydraulic heads were measured manually in all piezometers every 3-4 weeks, while hourly values were measured in piezometers U3-4-60 and U4-4-47 using ventilated AquiLite ATP00 pressure sensors (AquiTronic, Germany). Subsurface water flow between selected piezometer nests was calculated on a daily basis according to Darcy using daily values of hydraulic head interpolated between manual measurements. However, data calculations need further validation and are thus omitted here.

2.4 Vegetation survey and plant nutrient uptake

At each piezometer point in the saturated buffer zone and in the control transect, all plant species were recorded within 1x1 m quadrats in October 2021 (see Appendix) and the total aboveground biomass of all vascular plants was harvested from this 1 m^2 area afterwards. Biomass samples were dried at ambient air temperature over 7 days (Figure 3) and a larger subsample (50-90 g) was dried afterwards for 24 hours at 45°C until mass constancy in an oven to determine dry biomass. The survey of plant species was completed for the remaining area but might be incomplete due to seasonal constraints.

Net nutrient uptake was calculated from nutrient concentrations and biomass data (Jabłońska, et al., 2021). The nutrient and C uptake by plants were calculated using the following equation (Eq. 1).

$$NUP = PLN/P/C \times DM \times 10000 \qquad (1)$$

where NUP is nutrient and carbon uptake by plants (kg ha^{-1}), $PL_{N/P/C}$ is the concentrations of nitrogen, phosphorus, or carbon, respectively, in dried plant litter (kg kg^{-1} dry mass) and DM is the dry mass of the aboveground biomass of plants (kg ha^{-1}) sampled from an area of 1 m^2 (see above). Due to possible litter loss before biomass yield, the data refers to the net production of aboveground biomass and the net nutrient uptake, respectively.

Figure 3. Harvesting of above ground plants in the three transects of the saturated buffer and the control transect. Note that the piezometer points at the edge of the field (Figure 2) were not harvested.

3. Results and Discussion

Results of this 2-year monitoring unravel a high performance of the investigated SBZ as nitrate and phosphate removal efficiency was as high as 87% and 76 %, respectively. However, these high efficiencies must still be interpreted with caution since subsurface water flows turned out be rather heterogenous varying by two orders of magnitude within the investigated transects leading to uncertainties of the current removal estimates. Furthermore, it was shown that the water infiltration capacity was reduced over three draining seasons which must be considering both for the dimensioning or construction of SBZ, respectively as well as for their maintenance.

Drain water inflow, hydraulic conductivity, and soil water table

The distribution well at Ulvskov has received drain water of 0-8.6 L/s (daily average) during the project period of 29.09.2019 – 29.11.2021, however the maximum amount of water infiltrating the SBZ became substantially lowered over time (Figure 4).

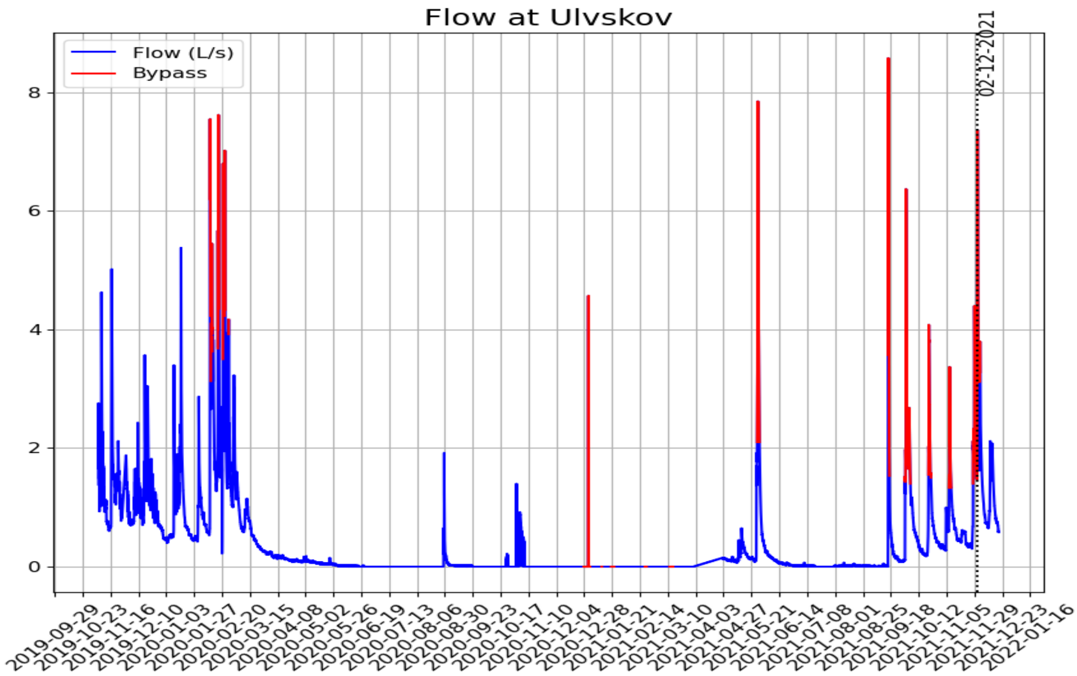

Figure 4. Flow and bypass flow for Ulvskov for the entire project period. The blue line shows the flow, while the red indicates when bypass flow has occurred. The dashed line shows the date (02-12-2021) when the distribution pipe was rinsed to decrease bypass flow.

Already after a couple of months within the first draining season (September 2019 - March 2020) the maximum amount of water infiltrating the buffer zones was lowered from 5 L/s to about 4 l/s and dropped down to approximately 1L/s in the third drain period starting in September 2021. Since fine particles settled down in the distribution well and in the well at the end of the distribution pipe a clogging effect was suspected as demonstrated for other constructed wetlands (Wang et al., 2021). Rinsing the distribution pipe with a high-water pressure tube helped increase the infiltration and decreasing the bypass flow (Figure 4). Before rinsing, the bypass flow would begin when the inlet flow reached 1.3-1.5 L/s, while an inlet flow of 2.1 L/s a few days after didn't result in bypass flow. It is, however, obvious that the infiltration is not fully restored to the start capacity. Either the clogging could be not fully removed, e.g., in the outer sphere of the distribution pipe and/or a higher water saturation of the buffer zone is currently reducing the water infiltration capacity. Accordingly at high flow condition (>> 1 L/s) a substantial proportion of drain water is bypassed to the stream without becoming purified in the SBZ (Figure 4).

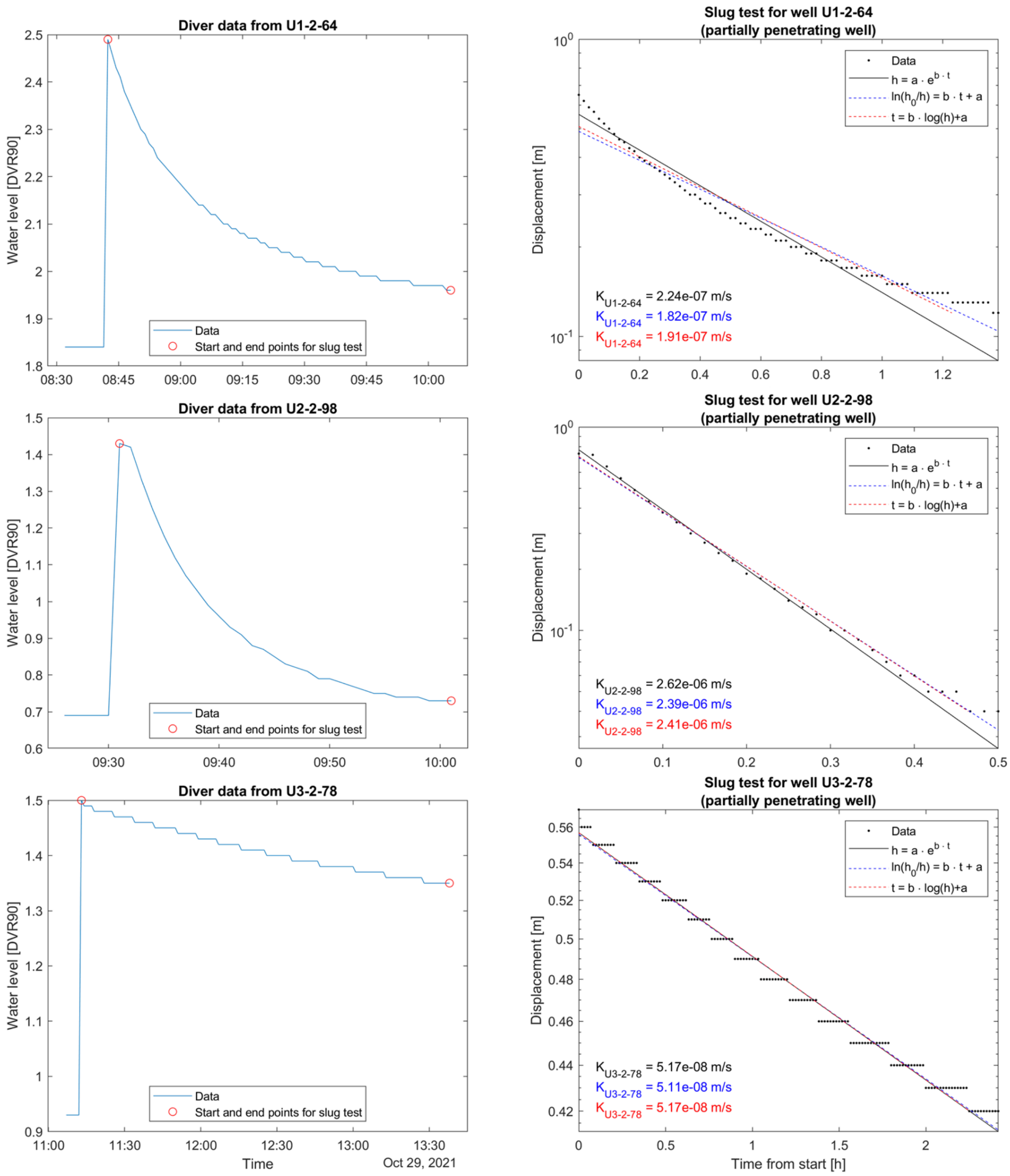

Figure 5. Demand of time for water tables to decrease after water addition (slug tests) to determine the hydraulic conductivity (HYC) in the middle of the saturated buffer zones: piezometer points 1-2, 2-2, 3-2 (left column). Different models were applied for calculating the HYC (right column).

Likewise, the hydraulic conductivity (HYC) was highly differing by two orders of magnitude in the SBZ (Figure 5). For example, for the Transect 2 the highest HYC was found in the middle of the SBZ (20.66 cm/day) almost 50 times higher than the middle of transect 3 (0.46 cm/day). Depending on water table difference subsurface water fluxes can be calculated which will also vary by orders of magnitude (calculations are in progress).

Since water inflow was highly variable within the draining seasons and ceasing to zero flow over a couple of months afterwards the soil water table is likewise changing over the year by several decimetres. However, water table fluctuation was somewhat more pronounced in the the upper zone of the SBZ closed to the field (Figure 6). At the other hand, a full water saturation of soils up to slight inundation of few centimetres took place only in the lowest part of the SBZ. High water tables occurred in 2021 in the entire transect 3 of the SBZ. As mentioned before, this situation could partly explain the lowered infiltration capacity in this monitoring period. Differences in the soil water table are accompanied with different redox conditions (not measured in this study) which determine biogeochemical processes controlling the nutrient removal (see below).

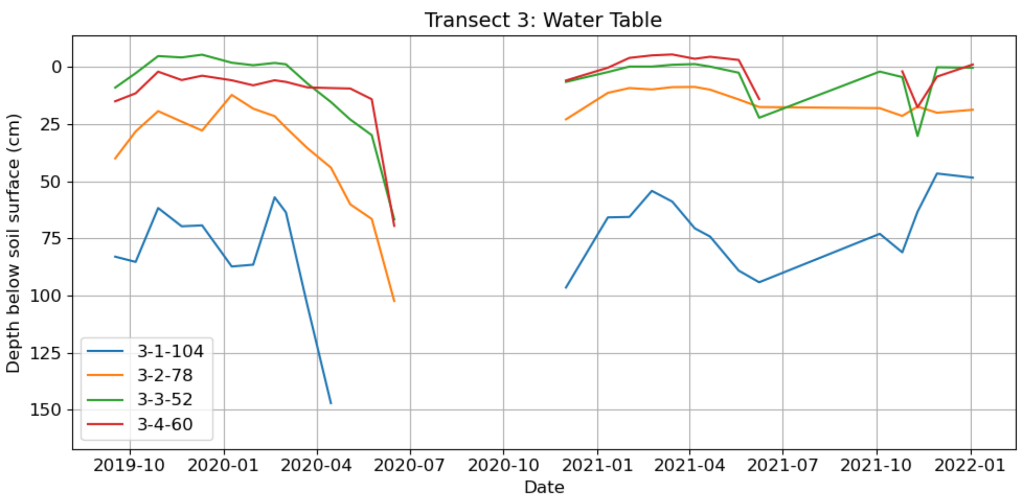

Figure 6. Temporal changes of water tables in relation to the soil surface in transect 3. The first point (3-1-104) is located at the edge of field (see Figure 2) not influenced by the drain water but by shallow groundwater

Water quality changes

Overall, a distinct pattern for water quality changes and eventually a water quality improvement was found for the investigated SBZ both for nitrogen and phosphorus species (Figures 7 and 8). The proportion of nitrate on total nitrogen (TN) was higher than 90% for most of the water samples and phosphate (measured as SRP) widely equated with total dissolved phosphorus (only occasionally analysed) so that dissolved organic phosphorus is negligible in the site under investigation. Specifically, for most of the sampling occasions the concentrations of nitrate where highest in the shallow groundwater coming from the neighboured field ranging between 1.1 and 22.7 mg N/L (Table 2). The average nitrate concentrations in the drain water ranged between 0.9 and 10.5 mg N/L. Interestingly, in the beginning of the SBZ in the proximity of the distribution pipe (< 3 m) the nitrate concentrations were about two times higher than in the drain water for some sampling occasions (Figure 7). Although not investigated in detail those results can be probably interpreted just as mixing effect of similar proportions of ground water and drain water (see transect 1 and 2 in Figure 7). The water tables in this initial part of the SBZ were mostly several decimetres below the soil surface implying that denitrification should be less important compared to the lower part of the SBZ having water tables closed to the surface at least over most of the draining season (Figure 6). Indeed, nitrate concentration is substantially declining to values much lower than 1 mg N/L with few exceptions at the last point of the SBZ transects (Table 2). Eventually 3-to-10-fold higher nitrate concentrations were recorded in the adjacent stream so that water from the SBZ dilute rather than pollute the stream. Higher ammonium concentrations (> 1 mg N/L) in some sampling points of the SBZ imply the importance of N mineralization processes but not overwhelming the decline of nitrate concentration.

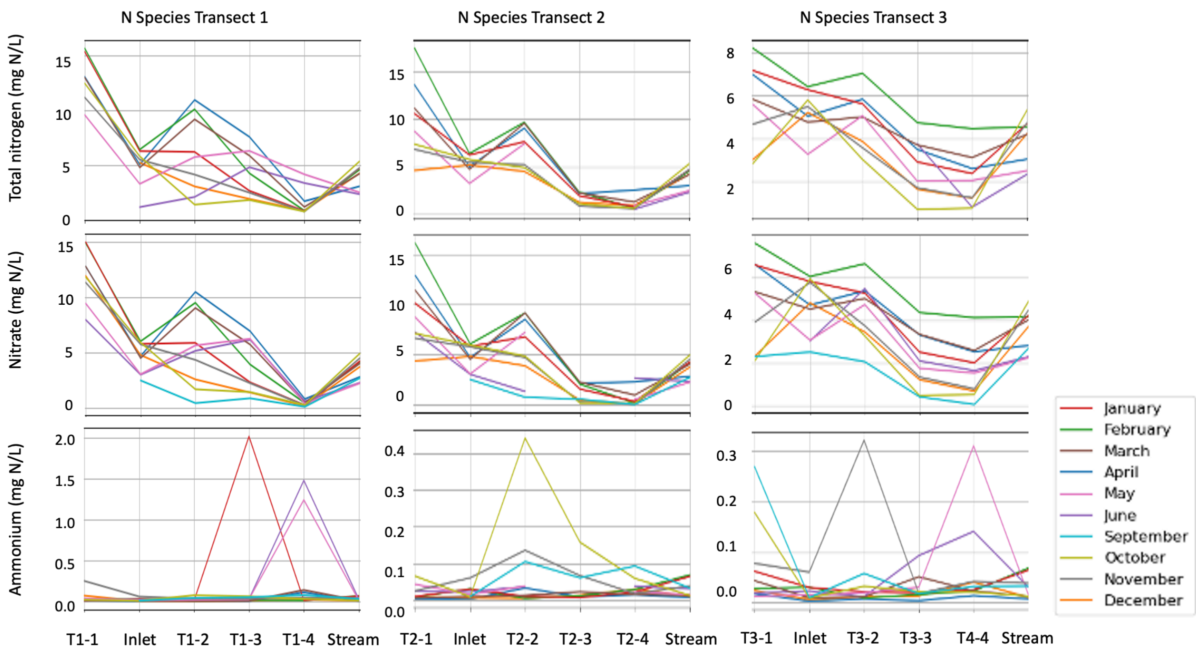

Figure 7. Total nitrogen (TN), nitrate and ammonium as monthly mean concentrations in the three transects of the saturated buffer zones, in the inlet and in the stream. The first transect point represent the shallow groundwater before of the distribution pipe, the inlet represents the drain water, and the stream was sampled upstream before the saturated buffer zone.

Contrary to nitrogen the phosphorus concentrations in the ground water were mostly lower than in the drain water, however being highly variable throughout the monitoring period (Table 2). In most cases phosphorus concentrations reached lowest values already in the beginning of the SBZ and raised again afterwards in the lower part of the SBZ (Figure 8). This phenomenon can be again related to difference in water tables or redox conditions, respectively. While lower water tables in the beginning favor the sorption of phosphorus on metal oxides higher water tables or water saturation of soils, respectively promote the reductive dissolution of iron (III)-phosphorus compounds (Zak et al., 2018). Despite of this internal P release again the water from the SBZ dilutes the stream water having phosphorus concentrations up to 10-times higher than the last sampling points of the SBZ transects (Table 2).

Table 2. Nutrient concentrations taken as grab samples for the 4 transects as mean (minimum - maximum) in mg/L (for location of sampling points see Figure 2).

	1-1	**Inlet**	**1-2**	**1-3**	**01. Apr**	**Stream**
TDP	0.013 (0.003-0.025)	0.033 (0.007-0.054)	0.006 (0-0.011)	0.006 (0.001-0.017)	0.072 (0.004-0.446)	0.051 (0.033-0.081)
PO_4-P	0.016 (0.002-0.049)	0.026 (0.005-0.069)	0.006 (0.002-0.015)	0.006 (0.002-0.013)	0.041 (0.003-0.473)	0.057 (0.031-0.125)
TN	13.343 (7.133-17.580)	5.100 (1.140-10.820)	6.079 (0.708-12.240)	4.201 (0.920-8.747)	1.523 (0.472-5.738)	4.063 (2.275-6.638)
NH_4-N	0.073 (0-0.871)	0.022 (0-0.182)	0.027 (0-0.228)	0.242 (0-6.000)	0.249 (0.005-2.400)	0.030 (0-0.181)
NO_3-N	12.642 (6.350-17.340)	4.910 (0.918-10.459)	5.626 (0.171-11.877)	3.814 (0.635-8.608)	0.381 (0.131-1.151)	3.753 (1.993-6.411)
	2-1	**Inlet**	**2-2**	**2-3**	**2-4**	**Stream**
TDP	0.006 (0.002-0.012)	0.033 (0.007-0.054)	0.013 (0.007-0.018)	0.010 (0.009-0.011)	0.014 (0.001-0.047)	0.051 (0.033-0.081)
PO_4-P	0.009 (0.002-0.049)	0.026 (0.005-0.069)	0.021 (0.004-0.167)	0.010 (0.002-0.042)	0.005 (0.002-0.010)	0.057 (0.031-0.125)
TN	10.929 (4.634-23.940)	5.100 (1.140-10.820)	7.462 (2.165-10.880)	1.693 (0.780-2.532)	1.072 (0.239-3.461)	4.063 (2.275-6.638)
NH_4-N	0.023 (0-0.206)	0.022 (0-0.182)	0.107 (0.004-0.875)	0.055 (0.007-0.274)	0.030 (0.002-0.110)	0.030 (0-0.181)
NO_3-N	9.984 (4.351-22.725)	4.910 (0.918-10.459)	5.796 (0.654-10.211)	0.949 (0.079-2.399)	0.717 (0-5.256)	3.753 (1.993-6.411)
	3-1	**Inlet**	**3-2**	**3-3**	**3-4**	**Stream**
TDP	0.064 (0.015-0.159)	0.033 (0.007-0.054)	0.008 (0.002-0.016)	0.005 (0.002-0.010)	0.007 (0.001-0.022)	0.051 (0.033-0.081)
PO_4-P	0.045 (0.004-0.116)	0.026 (0.005-0.069)	0.009 (0.001-0.040)	0.006 (0.001-0.068)	0.005 (0.001-0.015)	0.057 (0.031-0.125)
TN	5.571 (1.905-10.600)	5.100 (1.140-10.820)	4.902 (1.852-8.893)	2.697 (0.584-5.875)	2.207 (0.388-6.264)	4.063 (2.275-6.638)
NH_4-N	0.076 (0.003-0.598)	0.022 (0-0.182)	0.065 (0.002-1.119)	0.027 (0-0.128)	0.066 (0.006-0.846)	0.030 (0-0.181)
NO_3-N	4.701 (1.102-9.743)	4.910 (0.918-10.459)	4.570 (1.973-8.346)	2.142 (0.155-5.544)	1.720 (0.020-5.930)	3.753 (1.993-6.411)
	4-1	**Inlet**	**4-2**	**4-3**	**4-4**	**Stream**
TDP	0.170 (0.007-1.390)	0.033 (0.007-0.054)	0.015 (0.004-0.038)	0.005 (0.001-0.011)	0.008 (0.003-0.017)	0.051 (0.033-0.081)
PO_4-P	0.079 (0.005-1.210)	0.026 (0.005-0.069)	0.011 (0.002-0.030)	0.005 (0-0.018)	0.007 (0.002-0.016)	0.057 (0.031-0.125)
TN	5.418 (1.982-11.000)	5.100 (1.140-10.820)	2.880 (0.981-5.282)	1.232 (0.245-2.213)	0.669 (0.334-2.064)	4.063 (2.275-6.638)
NH_4-N	0.067 (0-1.160)	0.022 (0-0.182)	0.045 (0.003-0.235)	0.024 (0.003-0.192)	0.054 (0.005-0.130)	0.030 (0-0.181)
NO_3-N	5.080 (0.615-10.206)	4.910 (0.918-10.459)	2.469 (0.937-5.104)	0.894 (0.192-1.834)	0.098 (0-0.287)	3.753 (1.993-6.411)

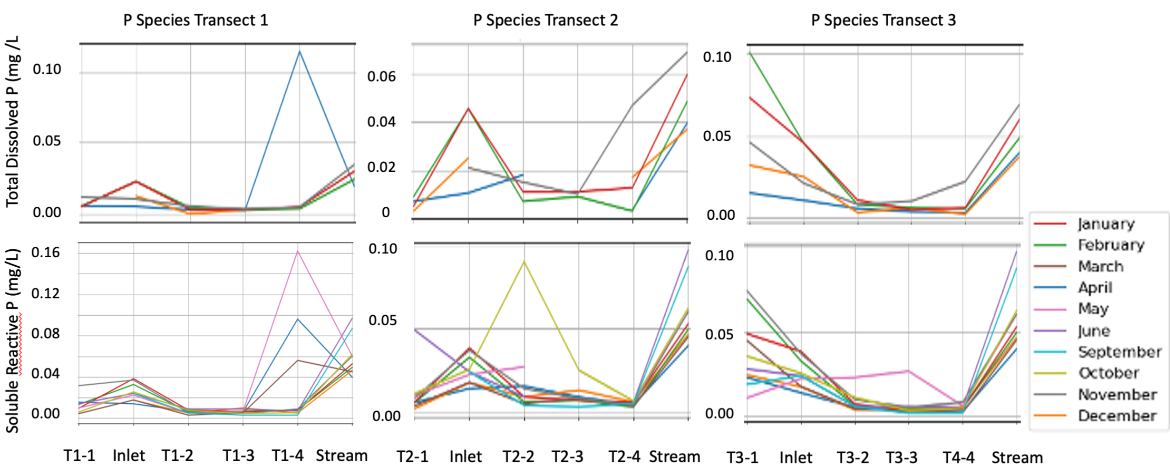

Figure 8. Total phosphorus and phosphate as monthly mean concentrations in in the three transects of the saturated buffer zones, in the inlet and in the stream. The first transect point represent the shallow groundwater before of the distribution pipe, the inlet represents the drain water, and the stream was sampled upstream before the saturated buffer zone.

Nutrient removal

According to mass balance calculations the SBZ was acting as effective sink for nitrogen and phosphorus. The TN import via drain water over the whole monitoring period of about 2 years was 130 kg and for phosphate it was 0,9 kg P. During this time 105 kg nitrate-N and 0.7 kg phosphate-P was removed equating to removal efficiencies of 87% and 76%, respectively. These removal efficacies are higher than any other drainage or nutrient mitigation measures in Denmark (see SWS abstract in the Appendix; Hoffmann et al. 2020). Beside of former discussed biogeochemical processes (dentification, sorption/desorption) a major part of nitrogen and phosphorus removal can be explained by plant uptake. The nutrient uptake by plants was in average 14.9 g N/m^2 and 1.6 g P/m^2 in comparison to the annual nutrient removal in the SBZ of about 52 g N/m^2 and 0.4 g P/m^2 (SBZ size: about 1000 m^2). That means that about 30% of the N removal and all of the P removal could be explained just by plant uptake. It must be noted for this comparison that the SBZ was not removing nutrients alone from the introduction of drain water via the distribution pipe but also receiving groundwater directly from the adjacent field, however the latter input could be not quantified so far.

4. Conclusions and Outlook

Overall, the results of this study highlight that SBZ are effective sinks for nutrients. However, these preliminary results need further approval by considering different flow paths and velocities of infiltrating drain and ground water. Furthermore, it needs to be assessed how the SBZ must be ideally sized, and which technical improvements may be implemented to capture most drain water over longer time periods (> 10 years). Another SBZ was instrumented near Odder (named 'Bondesvad') to improve our understanding of the limitations and advantages of SBZ as drainage mitigation measure in riparian buffer zones. Eventually we do need better knowledge where SBZ are an optimal choice to be installed rather than other constructed wetlands taking aspects like soil type, slope, size and possibly vegetation into account.

5. Acknowledgements

We gratefully acknowledge Marlene Venø Skjærbæk, Henrik Stenholt, Carsten Brian Nielsen, and Dorte Nedergaard for the great support with field sampling and comprehensive water and soil analysis. Many thanks to Tinna Christensen for valuable graphical assistance. The project is funded by PAF drænfilterprojekt "SEGES innovationsplatform for drænvirkemidler".

6. Dissemination of Results

The results of the project became presented during two international meetings in 2021 (see abstract and proceeding in the appendix). Currently, a scientific publication is drafted from the comprehensive data obtained in this project.

7. References

Bouwer, H., & Rice, R. C. (1976). A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. *Water Resources Research*, *12*(3), 423–428. https://doi.org/10.1029/WR012i003p00423

Carstensen, M. V., Hashemi, F., Hoffmann, C. C., Zak, D., Audet, J., & Kronvang, B. (2020). Efficiency of mitigation measures targeting nutrient losses from agricultural drainage systems: A review. AMBIO, 49(11), 1820-1837.

Chave, P.A. (2001). The EU Water Framework Directive, an introduction. IWA publishing, 208 p.

Hoffmann, C. C., Zak, D., Kronvang, B., Kjaergaard, C., Carstensen, M. V., & Audet, J. (2020). An overview of nutrient transport mitigation measures for improvement of water quality in Denmark. Ecological Engineering, 155, [105863].

Jabłońska, E., Winkowska, M., Wiśniewska, M., Geurts, J., Zak, D., & Kotowski, W. (2021). Impact of vegetation harvesting on nutrient removal and plant biomass quality in wetland buffer zones. Hydrobiologia, 848(14), 3273-3289.

Jaynes, D. B., & Isenhart, T. M. (2014). Reconnecting Tile Drainage to Riparian Buffer Hydrology for Enhanced Nitrate Removal. *Journal of Environmental Quality*, *43*(2), 631–638. https://doi.org/10.2134/jeq2013.08.0331

Jaynes, D. B., & Isenhart, T. M. (2019). Performance of Saturated Riparian Buffers in Iowa, USA. *Journal of Environmental Quality*, *48*(2), 289–296.

Lam, Q. D., Schmalz, B., & Fohrer, N. (2011). The impact of agricultural best manage¬ment practices on water quality in a North German lowland catchment. Envi¬ron. Monit. Assess. 183:351–379. https://doi.org/10.2134/jeq2018.03.0115

Petersen, R. J., Blicher-Mathiesen, G., Rolighed, J., Andersen, H. E., & Kronvang, B. (2021). Three decades of regulation of agricultural nitrogen losse: Experiences from the Danish Agricultural Monitoring Program. Science of the total Environment, 787, [147619].

Scanlon, B. R., Ruddell, B. L., Reed, P. M., Hook, R. I., Zheng, C., Tidwell, V. C., Siebert, S. (2017). The food-energy-water nexus: Transforming science for society. Water Resour. Res. 53: 3550-3556.

Wang, H., L. Sheng, & J. Xu, (2021). *Clogging mechanisms of constructed wetlands: A critical review.* Journal of Cleaner Production, 295, 126455.

WWAP, (2015). The United Nations world water development report 2015. Water for a sustainable world. United Nations World Water Assess. WaProgr., Paris.

Zak, D., Kronvang, B., Carstensen, M., Hoffmann, C. C., Kjeldgaard, A., Larsen, S. E., Audet, J., Egemose, S., Jorgensen, C. A., Feuerbach, P., Gertz, F., & Jensen, H. S. (2018). Nitrogen and Phosphorus Removal from Agricultural Runoff in Integrated Buffer Zones. Environmental Science & Technology, 52(11), 6508-6517.

8. Appendix

11th INTECOL
international wetlands
conference

10 – 15 OCTOBER 2021 | Christchurch, New Zealand

„Saturated and integrated buffer zones as novel drainage mitigation measures in Denmark"

Dominik Zak, Mette Vodder Carstensen, Sofie Gyritia Madsen van't Veen, Rasmus Jes Petersen, Brian Kronvang

Department of Bioscience, Aarhus University, Vejlsøvej 25, 8600 Silkeborg, Denmark

Vegetated buffer strips (VBSs) along watercourses have been introduced in many European countries to mitigate impacts on water quality and ecological quality of watercourses by reducing inputs of sediment and nutrients from surface runoff on intensively managed agricultural land. However, the effectiveness of VBSs was proven to be low for the retention of dissolved nutrients (NO_x, PO_4^{3-}), especially when agricultural drainage water was directly discharging to streams via tile drainage pipes. Therefore, two new drainage mitigation measures namely saturated and integrated buffer zones (SBZs and IBZs) have been implemented at test sites and studied during the last five years in Denmark for their retention efficiency for nitrogen and phosphorus. Tile drain pipes were disconnected at the sloping field margin to the riparian zone by diverting drainage water either to a buried, lateral distribution pipe running parallel to the stream (SBZ) or charging a pond combined with a sub-surface flow infiltration zone planted with vegetation (IBZ). Altogether, six sites were intensively monitored over a period of 2-5 years to evaluate the nutrient removal efficiency of SBZs and IBZs. Depending on the water inflow, physical soil characteristics, water saturation of soils and dominant vegetation type, a substantial fraction of the water can infiltrate the soil before reaching the watercourse. While the results on total nitrogen removal were promising for both systems with mean removal efficiencies between 31% and 76 % of the load, a risk of phosphorus release occurred at higher summer temperatures or if the buffer zone had organic soils.

About smaller and bigger kidneys: riparian zones as nutrient buffers in Denmark

Dominik Zak[a,b], Carl C Hoffmann[a,b], Brian Kronvang[a,b], Mette V Carstensen[a], Sebastian P Zacho[c], Joachim Audet[a,b]
[a] Dep. of Bioscience, Aarhus University, Denmark
[b]Aarhus University, WATEC, Denmark
[c] SEGES, Crops and Environment Innovation, Denmark

INTRODUCTION

In Denmark, measures reducing nitrogen (N) and phosphorus (P) losses from fields are divided into two main categories "source mitigation measures", e.g. catch crops and fertiliser norms as well as set-a-side and afforestation, and "nutrient transport mitigation measures", e.g. restored wetlands and a number of drainage mitigation measures (Figure 1). This paper deals with nutrient transport mitigation measures to reduce diffuse pollution from agriculture. It treats already approved measures, such as restoration of riparian wetlands, larger lowlands areas including fens and swamps, re-establishment of shallow lakes, constructed wetlands (surface flow and subsurface flow), as well as drainage mitigation measures not yet approved and still under development such as integrated buffer zones, saturated buffer zones and controlled drainage.

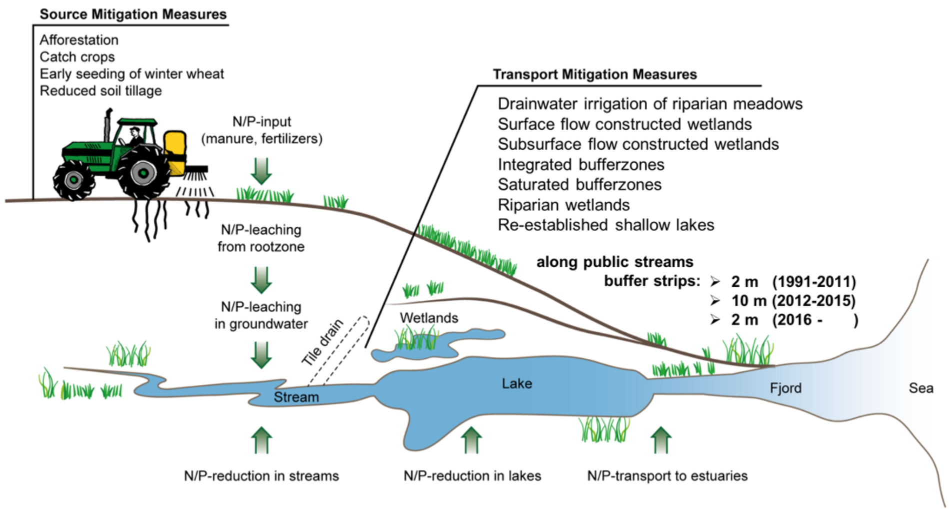

Fig. 1. Nutrient reduction efforts in Denmark since 1985.

METHODS

New nutrient transport mitigation measures cannot be implemented in Denmark until after completion of a series of steps. Whenever a new measure is proposed for use by Danish farmer advisors, it must be scientifically tested and thoroughly described. Thereafter, guidelines and national maps showing how and where to implement the measures must be made. A web-based support system for the funding of nutrient transport mitigation measures, including construction criteria, guidelines and maps, is run by the Danish Ministry of Environment and Food (lbst.dk/tilskudsguide).

RESULTS and DISCUSSION

Wetland restoration measures have proved to be efficient at removing N, whereas the results regarding P are more variable; in fact, some sites have been observed to act as P sources, especially in the first years following rewetting (Walton et al., 2020). Overall nutrient removal rates and efficiency vary strongly for all of the studied nutrient transport mitigation measures (Table 1). It is important to note that this variation not only reflect differences in efficiency of the mitigation measures but also differences in nutrient loading and local characteristics of the sites used for implementation (e.g. soil type, vegetation, climate) (Carstensen et al. 2020).

Table 1. Overview of absolute and relative nutrient removal efficiency (mean ± sd) of Danish nutrient transport mitigation measures (from Hoffmann et al. 2020)

	Sites (n)	Years	Removal rate (kg ha^{-1} y^{-1})		Removal efficiency (%)	
			TN	TP	TN	TP
Restored riparian wetlands	9	9	144±73	3±5	37±31	12±15
Restored shallow lakes	11	12	159±53	4±6	45±21	-2±83
Restored swamps and fens	5	5	209±77	2±3	44±12	11±26
Drain water irrigation	10	10	139±91	-0.3±0.3	45±22	-51±49
Surface flow constr.wetland	13	44	472±372	31±26	23±10	45±20
Subsurface flow constr. wetland	3	15	7771±241	34±6	50±13	12±4
Controlled drainage	4	8	8.8±6.5	2.2±2.4	33±13	5±29
Integrated buffer zones	3	6	1661±605	17±15	45±12	29±60

CONCLUSIONS

The Danish strategy to mitigate agricultural nutrient losses has resulted in a substantial decrease in the nutrient export to fresh waters.Yet, more efforts are still required to reach the "good ecological status" stipulated in the EU Water Framework Directive. Furthermore it is recognized that other aspects, for example, biodiversity or greenhouse gas emissions, needs to be included in montirong schemes to support the implementation of mitigation measures.

ACKNOWLEDGEMENTS

We are grateful for Nordic Centre of Excellence BIOWATER, funded by Nordforsk under Project no. 82263, by the Ministry of Environment and Food of Denmark (33010-NIFA-16-649) and by PAF drænfilterprojekt "SEGES innovationsplatform for drænvirkemidler". SupremeTech Sustainable nutrient remediation technologies grant no. 09-067280, Danish Strategic Research Council; iDRAIN-Optimised Drainage Filter Technologies grant no 3405-10-0142, GUDP (Green development and demonstration programme) also supported the work.

REFERENCES

Carstensen, M.V., et al. 2020. Efficiency of mitigation measures targeting nutrient losses from agricultural drainage systems: A review. *Ambio* 49(11): 1820-1837.

Hoffmann, C.C., et al. 2020. An overview of nutrient transport mitigation measures for improvement of water quality in Denmark. *Ecological Engineering*: 105863.

Walton, C., et al., 2020. Wetland buffer zones for nitrogen and phosphorus retention: Impacts of soil type, hydrology and vegetation. *Science of the Total Environment*:138709.

Table A1. Plant species in the saturated buffer zone of site "Ulvskov" in October 2021.

Latin name	Danish name
Epilobium hirsutum	Lådden Dueurt
Scirpus sylvaticus	Skovkogleaks
Filipendula ulmaria	Almindelig Mjødurt
Geum rivale	Eng-Nellikerod
Urtica dioica	Stor nælde
Equisetum arvense	Ager-Padderok
Equisetum fluviatile	Dynd-Padderok
Alopecurus pratensis	Eng-rævehale
Phalaris arundinacea	Rørgræs
Juncus conglomeratus	Knop-siv
Juncus effusus	Lyse-siv
Poa trivialis	Almindelig Rapgræs
Lathyrus pratensis	Gul fladbælg
Deschampsia cespitosa	Mose-Bunke
Alnus glutinosa	Rød-El
Corylus avellana	Hassel
Lolium perenne	Alm. Rajgræs
Ranunculus repens	Lav Ranunkel
Angelica sylvestris	Angelik
Dactylis glomerata	Hundegræs
Cirsium palustre	Kær-tidsel
Cirsium arvense	Ager-Tidsel
Rubus sect. Rubus	Brombær
Mentha aquatica	Vand-Mynte
Galium aparine	Burre-Snerre
Chrysosplenium alternifolium	Almindelig Milturt
Dryopteris filix-mas	Almindelig Mangeløv