STØTTET AF

Promilleafgiftsfonden for landbrug

Saturated Buffer Zones to lower nutrient pollution of streams in Denmark – A survey of three contrasting edge of field systems

Final Project Report 2023

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Summary
Three pilot sites, designated as saturated buffer zones (SBZ), were established in Denmark between 2019 and 2022 to assess their effectiveness in removing nutrients, specifically nitrogen and phosphorus, from agricultural drainage water. While these represent the first SBZ test sites in Europe, the concept has been in use in the USA since 2010. A comprehensive monitoring program was executed across all sites, encompassing measurements of water inflow, water tables, water quality at the inlet, soil water transects within the SBZ, and soil characteristics, including structure and chemistry. The performance of the three pilot sites exhibited significant variability. Despite of high potential nitrate removal monitoring was discontinued at the ”Gylling site” due to the inability to achieve a sufficient rise in groundwater table and water inflow, attributed to the high water table of inflowing groundwater. In contrast, the ”Ulvskov site” yielded promising results in terms of water flow, water tables, and nutrient removal. The nutrient removal efficiency averaged 77% for nitrate and 72% for phosphate, surpassing the efficacy of any other transport mitigation measures in Denmark. A one-year monitoring of the last established ”Bondesvad site” showed once again, that only a comparatively small proportion of drainage water of about 10% of the annual water flow can be captured by this new system. This limitation is attributed to unfavorable site characteristics, such as excessively high clay content in the topsoil and a relatively low slope of the buffer area (ca. 1-2%), coinciding with a low hydraulic gradient compared to the well-performing Ulvskov site (slope ca. 5-10%). To conclude if SBZ’s are placed under favorable site conditions they can perform as high-cost efficient drainage mitigation measure.

Resume
Tre pilotområder, betegnet som mættede bufferzoner (SBZ), blev etableret i Danmark mellem 2019 og 2022 for at vurdere deres effektivitet med hensyn til at fjerne næringsstoffer, især kvælstof og fosfor, fra drænvand fra landbruget. Det er de første SBZ-teststeder i Europa, men konceptet har været i brug i USA siden 2010. Der blev udført et omfattende overvågningsprogram på alle steder, som omfattede målinger af vandtilstrømning, vandspejl, vandkvalitet ved indløbet, jordvandstransekter i SBZ'en og jordegenskaber, herunder struktur og kemi. Resultaterne fra de tre pilotanlæg udviste betydelige variationer. På trods af det store potentiale for nitratfjernelse blev overvågningen afbrudt på "Gylling site", fordi det ikke var muligt at opnå en tilstrækkelig stigning i grundvandsspejlet og vandtilstrømningen, hvilket skyldtes det høje grundvandsspejl i det tilstrømmende grundvand. Derimod gav "Ulvskov-grunden" lovende resultater med hensyn til vandgennemstrømning, vandspejl og fjernelse af næringsstoffer. Effektiviteten af næringsstoffjernelsen var i gennemsnit 77 % for nitrat og 72 % for fosfat, hvilket overgår effektiviteten af alle andre transportbegrænsende foranstaltninger i Danmark. Et års overvågning af det sidst etablerede "Bondesvad site" viste endnu en gang, at kun en forholdsvis lille del af drænvandet på omkring 10% af den årlige vandgennemstrømning kan opfanges af dette nye system. Denne begrænsning tilskrives ugunstige forhold på stedet, såsom et for højt ler indhold i overjorden og en relativt lav hældning på bufferområdet (ca. 1-2%), hvilket er sammenfaldende med en lav hydraulisk gradient sammenlignet med det velfungerende Ulvskov-område (hældning ca. 5-10%). Konklusionen er, at hvis SBZ'er placeres under gunstige forhold, kan de fungere som en omkostningseffektiv afvandingsforanstaltning.

1. Background and project objectives

Agricultural losses of nitrogen (N) and phosphorus (P) have widespread detrimental effects on ecosystem functioning and the state of aquatic systems globally (Fowler et al., 2013; Galloway et al., 2008; Smith, 2003). The EU Water Framework Directive 2000/60/EC (WFD) mandates that all waters, including surface and ground waters, must achieve at least a good ecological status by 2027 (European Union, 2000). However, compliance with the WFD can be challenging, entailing costly investments and imposing limits on agricultural and industrial production. Despite these challenges, there is an urgent need to enhance actions taken by Member States, as a majority of EU water bodies have yet to attain a good ecological status (European Commission, 2021). Agriculture, as reported by the European Environmental Agency, stands out as a key driver for the failure to achieve good ecological status in EU water bodies (European Environmental Agency, 2018). Intensively farmed agricultural land faces significant nutrient losses through drainage, soil leaching, ditches, and surface runoff (Mellander et al., 2012).

Denmark's awareness of the deterioration of aquatic environments began in the 1980s, partly prompted by a media event where a group of fishermen brought in a catch of dead Norway lobsters. However, even after four decades, a substantial portion of Danish coastal water bodies fails to meet the requirements for good ecological status (Peterson et al., 2021). Denmark, boasting 59% arable land (FAO, 2019) and an estimated 50% of agricultural land being tile-drained (Møller et al., 2018), faces subsurface tile drainage with reported nitrogen losses ranging from 8 to 50 kg N/ha/year (Hoffmann et al., 2020). Artificial drainage pipes disrupt natural soil processes that would otherwise remove or retain nutrients before reaching adjacent water bodies (Dinnes et al., 2002; Hunt et al., 2008). Consequently, various mitigation measures have been developed and improved, including controlled drainage, constructed wetlands, and vegetated or integrated buffer zones (Carstensen et al., 2020; Schipper et al., 2010; Zak et al., 2018). The Danish political agreement "Agreement on green conversion of Danish agriculture," published on October 4, 2021, aims to achieve approximately 1,500 t of total nitrogen reduction annually using collective methods such as afforestation and the use of restored natural and constructed wetlands (Hoffmann et al. 2020).

The saturated buffer zone (SBZ) represents a novel drainage mitigation measure, untested in a Northern European context. The fundamental principle involves reconnecting drain water from the field to the non-cropped riparian zone. This is achieved through a buried, lateral perforated distribution pipe running parallel to the stream (0.5-1 m below the soil surface), redirecting drainage water into the riparian zone (Jaynes and Isenhart, 2019) (Fig. 1). Also known as 'saturated riparian buffers,' this edge-of-the-field technology was first established and monitored in Iowa, USA, in 2010 (Jaynes & Isenhart, 2014). Investigations in the USA revealed nitrate (NO_3^-) removal efficiencies ranging widely from 8 to 84%. Based on these results, SBZs could still be considered rather cost-efficient, with costs approximately equating to \$2.94 kg^{-1} N removed. However, existing data on SBZs are sparse compared to other edge-of-field technologies, leading to their exclusion from a recent statistical meta-analysis on nutrient mitigation measures due to only one study with multiple sites being published thus far (Carstensen et al., 2020).

This report summarize the performance of three pilot-scale SBZs established in Denmark between 2019 and 2022. Specifically, we investigated: 1) site hydrology, including water inflow and spatial differences in soil water fluxes, hydraulic conductivity, and groundwater table changes, 2) effects on water quality and nutrient removal (total nitrogen (TN), nitrate (NO_3^--N), ammonium-N (NH_4^+-N), dissolved organic N (DON), total phosphorus (TP) and phosphate), and 3) assessed long-term performance regarding P sorption and cost efficiency. Our hypothesis was that SBZ would emerge as a competitive drainage mitigation measure, offering favorable conditions for retaining both nitrogen and phosphorus in a well-chosen environmental setting.

2. Study sites

The three SBZs —Gylling, Ulvskov, and Bondesvad—are situated in East Jutland between Aarhus and Horsens, within the Odder municipality (Figure 1). The region experiences a cold temperate climate, characterized by an annual precipitation of 718 mm and mean daily temperatures ranging from 1.6°C in January to 16.6°C in July. All three SBZs are situated along small streams affected by agricultural activities, receiving nutrient-polluted water from intensively cultivated catchment areas.

The SBZs share a consistent layout and size, determined by an approximately 50-meter distribution pipe length, however 100 m in Bondesvad, and a distance of about 15 to 30 meters to the adjacent stream. Construction involved diverting the main drain, which would have otherwise discharged directly into the nearby stream. Initially, drainage water flows into an inlet distribution well equipped with a flow meter and a raised bypass pipe (see Figure 1). The water is then directed to the SBZ through a parallel distribution pipe, positioned approximately 0.5 meters below the soil surface, facilitating SBZ saturation and raising the soil water table.

Each SBZ incorporates 4-6 transects, each containing 4-6 piezometer tubes. A control transect is installed outside the SBZ, solely influenced by groundwater. It's important to note that the control transect in Gylling and Ulvskov has a soil surface up to 0.5 meters lower than other drain water-treated transects. Consequently, a substantial portion of the Ulvskov control transect represents a naturally wet section of the meadow buffer zone, unlike Gyllinga and Bondesvad, where the control transect reflects a naturally drier area due to elevated soil levels. The first piezometer of each transect (excluding the control transect) is positioned between the field edge and the distribution pipe, accounting for the input of shallow groundwater (Figure 1).

All sites under investigation exhibit significant variations in terms of soil type, composition, slope, buffer width, and other site characteristics (Tab. 1)

Table 1 Selected site characteristics of investigated saturated buffer zones east of Jutland, Denmark (see Fig. 1)

SBZ characteristics	Gylling	Ulvskov	Bondesvad
Vegetation	Perennial grasses, rushes	Reed canary grass, rushes, tussock grass	Perennial grasses, thistle, arctium
Soil type	Hydro-morphic soil (degraded peat at the upper 0.5 m below less decomposed sedge-reed peat until 3 m deth and clay at the bottom)	Sandy soil with increasing clay content at depth (ca. 2 m clay dominates)	Clay with sand underlain by sand with large stones below 1.5 m under soil surface (>0.5 m)
Hydrology	Drained peatland	Vegetated dry buffer with smaller floodplain areas	Vegetated dry buffer with narrow floodplain at the river margin
Catchment size	23 ha	4.5 ha	30 ha
Buffer width	30-50 m	20-25 m	10-15 m
Slope	1-2%	5-10%	1-2%

3. Material and Methods

To evaluate the nutrient removal capabilities of the SBZ the following investigation were carried out with different emphasis in the three pilot sites:

1) Water inflow (continously)
2) Water quality inflow (3-hourly)
3) Water quality buffer zone and stream (3-weekly)
4) Ground water table changes (hourly to 3-weekly)
5) Groundwater flow pattern (bromid tracer experiment)
6) Saturated hydraulic conductivity (slug test)
7) Soil quality (texture and chemical composition)
8) Nutrient uptake plants (N, P)

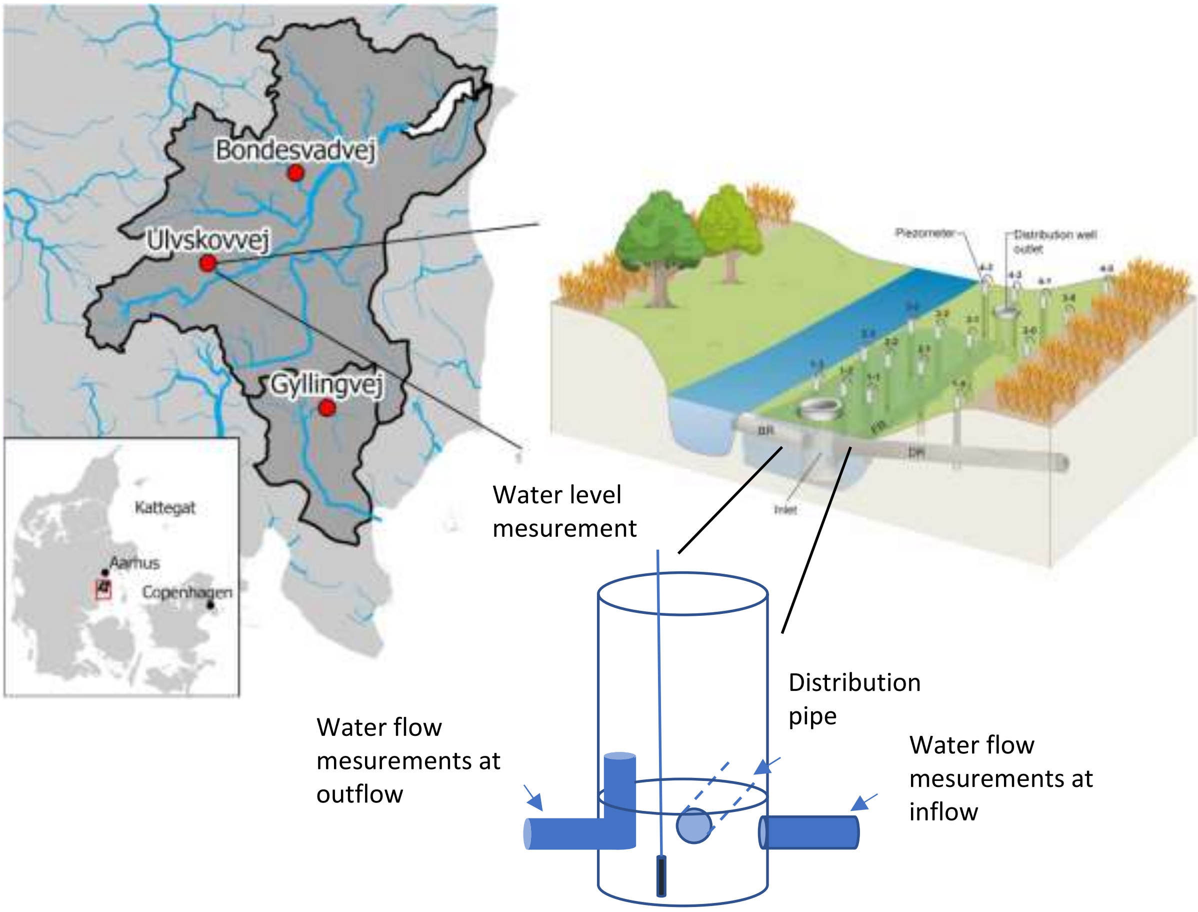

Fig. 1 Map of three pilot sites in a river basin (Nordsminde Fjord) east of Jutland (Denmark). At the example of Ulvskov the water discharge system (DR: drainpipe, BR: bypass pipe, FR: distribution pipe) and piezometer transects are shown which have been used to assess the removal of nutrient from agricultural drain water. Note that in Gylling and Bondesvad the inflow and outflow was measured continuously but in Ulskov only the inflow and the outflow was calculated based on automated water level measurements in the distribution well (see Fig. 2)

A detailed description of the monitoring programme and the methods applied for analysing water flow, water quality, and soil characteristics can be found in Maagaard et al. (2022). In the following two sections the monitoring results from Ulskov for the last full four drain periods will be presented (2019-2023) and first results from Bondesvad for one monitoring year from 2022-2023. In Gylling, the water discharge into the SBZ predominantly exhibited negativity or approached zero throughout most of the monitoring period (see Fig. 2). This was attributed to the distribution pipe functioning akin to a drainpipe. Consequently, the findings from Gylling are omitted in subsequent discussions, however, see Lynga et al. (202) for further details.

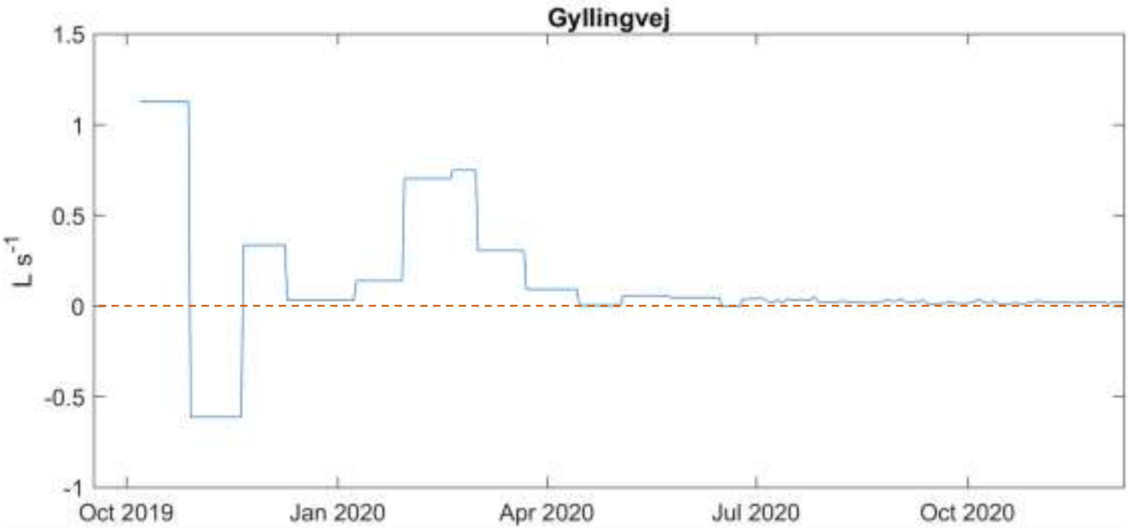

Fig. 2 Water inflow for the investigated saturated buffer zones Gylling. Due to technical issues with flow meter and data logger water flow was averaged for always three weeks.

For the water flow measurements, it must be notified that in Ulvskov only the drain water flow from the field was measured directly. To calculate the water infiltration in the SBZ continuous (logged) water table measurements in the drain water inlet and total water discharge at the inflow of the drain well were used. A water inflow function was generated from this data showing at which water table water was either completely charging the SBZ or partly leaving the bypass directly into the stream (Fig. 3). Whereas in Gylling and Bondesvad the volume of water inflow into the SBZ could be calculated by the difference of continuous water flow measurement from the drain water and the bypass water (Fig. 1)

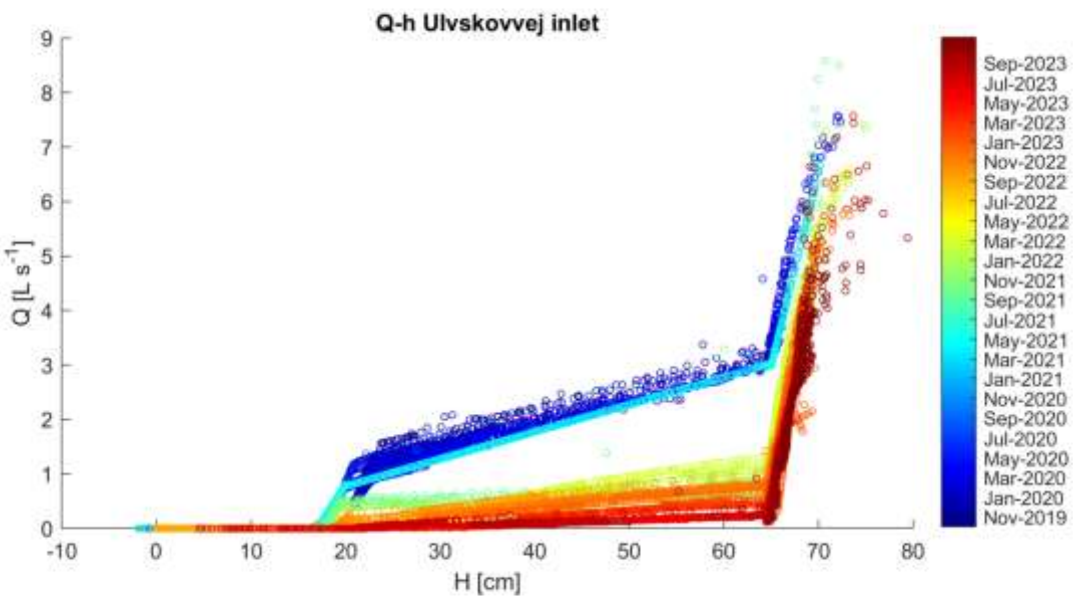

Fig. 3 Relation between water table in the drain water inlet and the drain water discharge which was used for calculation of water inflow into the SBZ.

4. Ulvskov

Water flow and water tables

There was a strong decline of water infiltration in the first drain season in 2019/2020 from more than 3 L/s down to about 1 L/s in 2021 (Fig. 4) which was first supposed to be related to a clogging of the distribution pipe. However, cleaning of the pipe in December 2021 had only minor effects and the water infiltration has not been further declining in the following year, but it dropped down to 0.5 L/s at few high discharge events in 2023. This imply that the higher water infiltration was related to a higher water uptake capacity of the project site in the beginning, however being reduced over time due to higher groundwater tables closed or above the soil surface in the SBZ (Fig. 5).

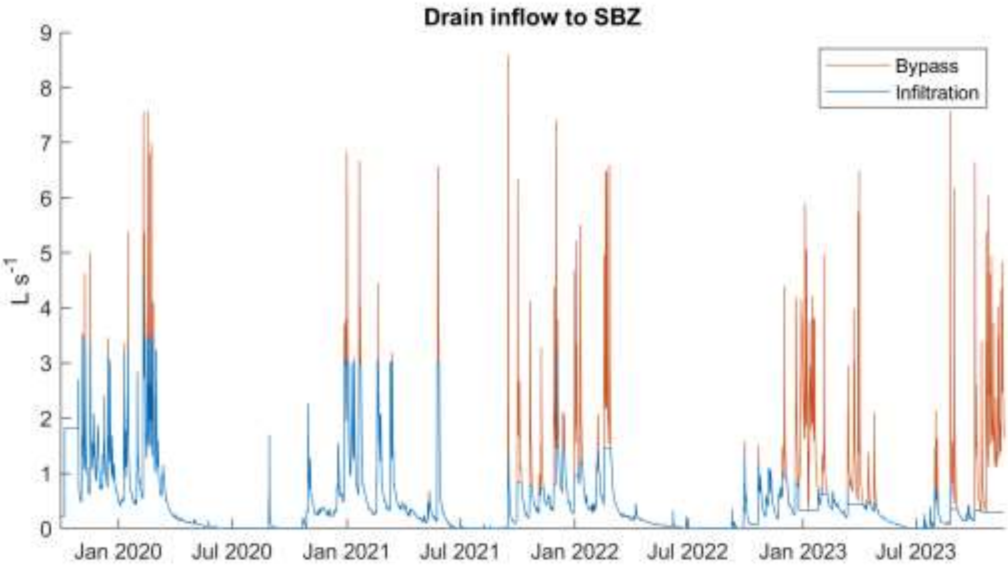

Fig. 4 The total water inflow from agricultural drain water in Ulvskov divided into the amount which was flowing into the SBZ (blue line) and the amount which was bypassed directly into the stream (red line).

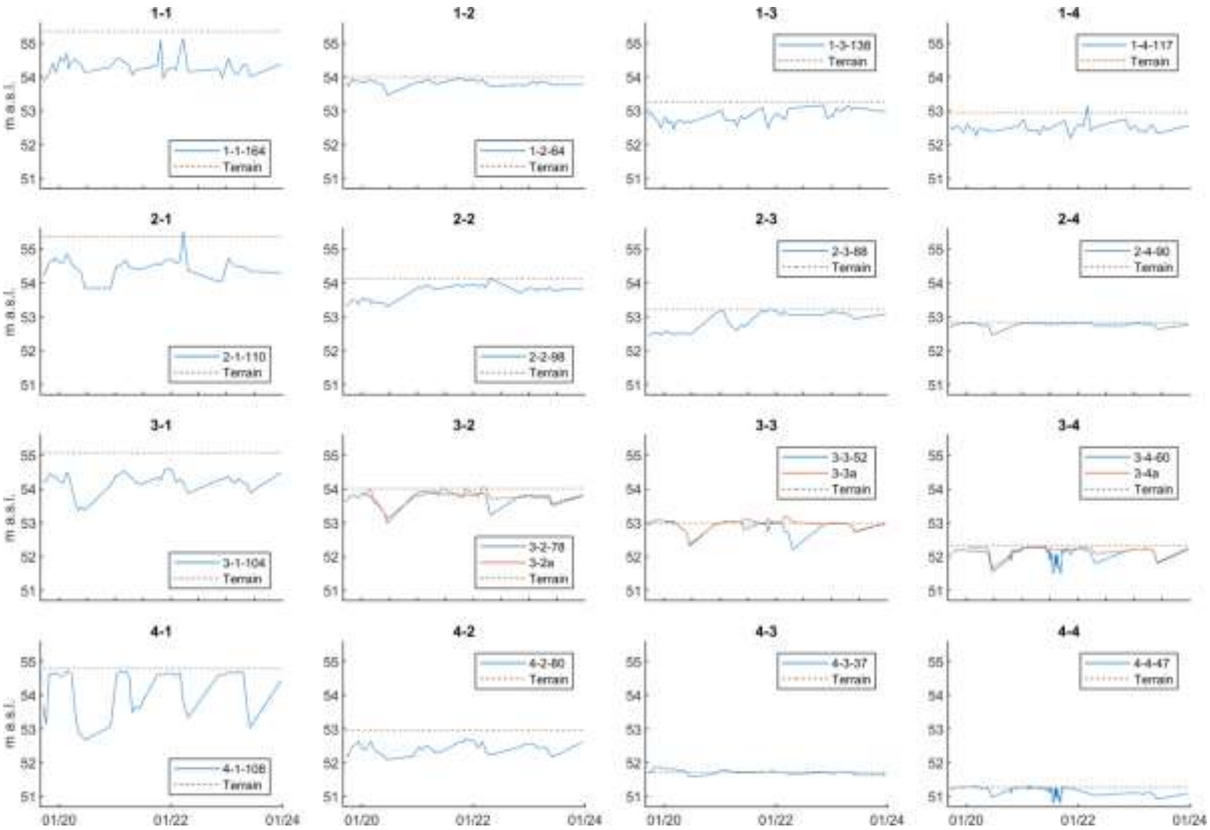

Fig. 5 The position and change of water tables (above sea level) in the four piezometer transects from the edge of the field down to stream (from left to the right) (the dashed brown line refers to the soil surface)

Water quality changes and nutrient removal

In a prior study by Maagaard et al. (2022), it was demonstrated that nitrate and phosphate concentrations exhibited a consistent decline across all transects, spanning from the onset of the SBZ near the distribution pipe to the stream's periphery (Fig. 1). Notably, nitrate concentrations in the incoming drain water displayed pronounced fluctuations throughout the monitoring duration, ranging from approximately 1 mg/L to 10 mg N/L, with the highest concentrations observed during the colder winter period. Comparison of nitrogen (N) and phosphorus (P) concentrations in the drain water with the groundwater at the transects' terminus highlights a substantial enhancement in water quality facilitated by the SBZ throughout the drainage period (see Fig. 6).

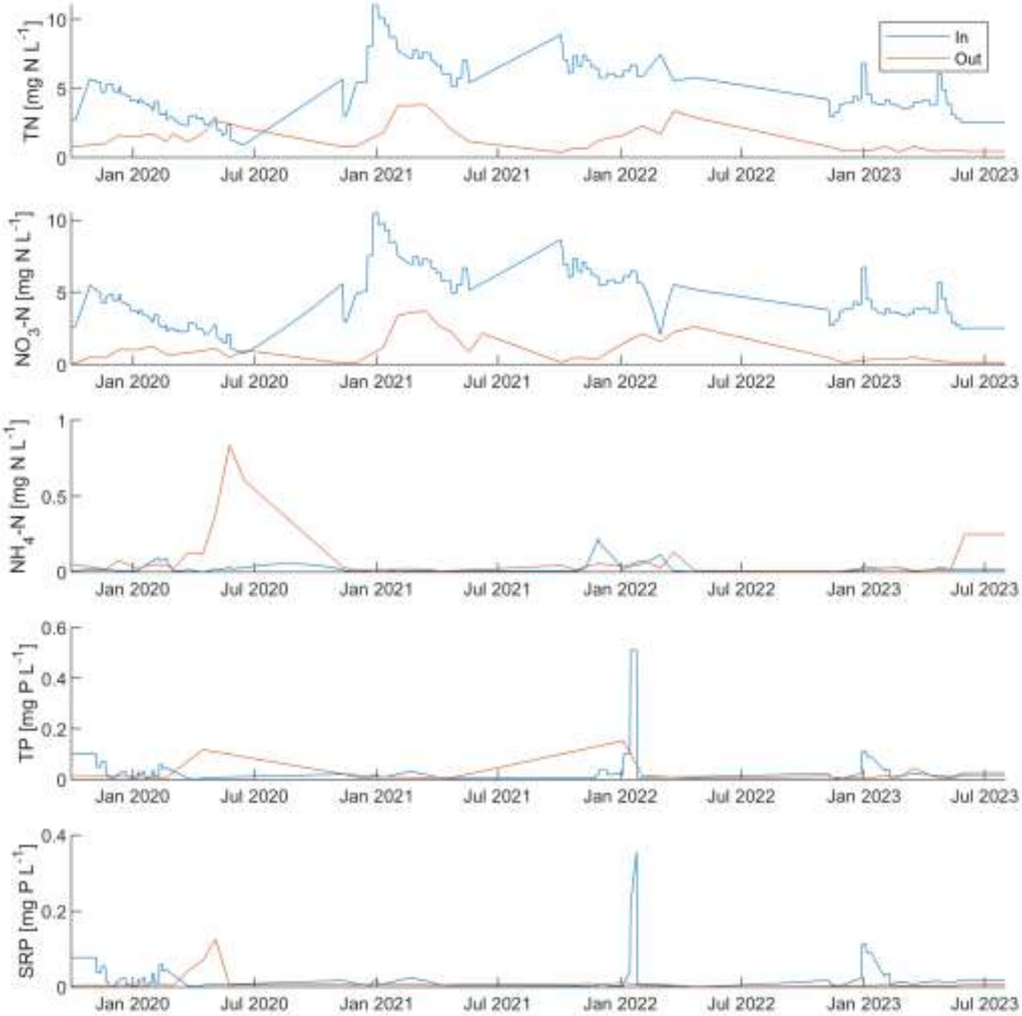

Fig. 6 A comparison of nutrient concentration in inflowing drain water ("In") compared to the ground water at the lower end of the SBZ (near the stream) (TN = total nitrogen, NO_3-N = nitrate-N, NH_4-N = ammonium N, TP = total phosphorus, SRP = soluble reactive phosphorus). Note that total dissolved N and total dissolved P were used at the outflow as estimate for TN and TP as water sampling in piezometer might be biased by particles.

The observed reduction in nutrient concentrations is attributed to various removal processes within the SBZ, rather than mere dilution of incoming groundwater, as suggested by Maagaard et al. (2022). Despite occasional elevations in ammonium concentrations within the SBZ's soil water during warmer summer periods, these instances do not compromise the overall positive impact on total nitrogen removal, as detailed in Table 2.

Table 2 Total removal and removal efficiencies for total dissolve nitrogen (TDN), nitrate-N (NO3-N), ammonium-N (NH_4-N), organic N (Norg), soluble reactive phosphorus (SRP) during three drainage seasons in the Site Ulvskov.

		Sum in [kg]	Sum out [kg]	Removal [kg]	Removal [%]
TN	01/10-2019 – 31/07-2020	79.1	25.5	53.6	68
	01/08-2020 – 31/07-2021	110.6	32.4	78.2	71
	01/08-2021 – 31/07-2022	75.5	17.8	57.7	76
	01/08-2022 – 31/07-2023	36.3	5.7	30.6	84
	Average	**75.4**	**20.4**	**55.0**	**73**
NO_3-N	01/10-2019 – 31/07-2020	72.0	14.3	57.7	80
	01/08-2020 – 31/07-2021	106.0	27.4	78.6	74
	01/08-2021 – 31/07-2022	64.2	14.2	50.0	78
	01/08-2022 – 31/07-2023	34.3	3.2	31.1	90
	Average	**69.1**	**14.8**	**54.4**	**79**
NH_4-N	01/10-2019 – 31/07-2020	0.54	0.98	-0.43	-79
	01/08-2020 – 31/07-2021	0.13	0.29	-0.16	-117
	01/08-2021 – 31/07-2022	0.78	0.53	0.25	32
	01/08-2022 – 31/07-2023	0.14	0.17	-0.03	-25
	Average	**0.40**	**0.49**	**-0.09**	**-23**
N_{org}	01/10-2019 – 31/07-2020	6.6	10.2	-3.6	-55
	01/08-2020 – 31/07-2021	4.5	5.4	-0.9	-20
	01/08-2021 – 31/07-2022	10.5	3.1	7.4	70
	01/08-2022 – 31/07-2023	1.9	2.3	-0.41	-21
	Average	**5.9**	**5.2**	**0.6**	**10**
TP	01/10-2019 – 31/07-2020	0.94	0.34	0.60	64
	01/08-2020 – 31/07-2021	0.22	0.20	0.02	10
	01/08-2021 – 31/07-2022	0.43	0.94	-0.52	-121
	01/08-2022 – 31/07-2023	0.23	0.11	0.11	47
	Average	**0.45**	**0.40**	**0.06**	**12.3**
SRP	01/10-2019 – 31/07-2020	0.77	0.15	0.62	80
	01/08-2020 – 31/07-2021	0.18	0.09	0.09	48
	01/08-2021 – 31/07-2022	0.17	0.07	0.10	59
	01/08-2022 – 31/07-2023	0.19	0.03	0.16	85
	Average	**0.33**	**0.09**	**0.24**	**74**

The comprehensive findings from this 4-year monitoring initiative unveil the exceptional performance of the SBZ, demonstrating impressive nitrate and phosphate removal efficiencies of 79% and 74%, respectively. Notably, these removal rates surpass those achieved by alternative drainage mitigation measures such as surface flow constructed wetlands, with a notable margin of two to three times (Hoffmann et al., 2020).

While nitrate removal exhibited minimal variation across the monitoring years, phosphate removal presented more pronounced differences ranging between 48% and 85% (Table 2). The culmination of these efforts occurred during the last monitored drain season, where peak removal efficiencies reached 91% for nitrate and 85% for phosphate. The heightened nitrate removal can be attributed to elevated water levels in the majority of the buffer area and a longer adaption time for anaerobic microbial community, fostering denitrification. However, it is crucial to acknowledge the potential contributions of other processes, including plant uptake and microbial assimilation (Lutz et al., 2020).

Contrary to initial expectations of a decline in phosphate removal over time, the sustained effectiveness of the SBZ can be attributed to its robust phosphorus sorption capacity (3.45 g P/kg dry mass), low current phosphorus saturation (7.7%), and a modest phosphorus load or retention of about 1kg P during the 4-years monitoring period, respectively (see Fig. 7). This longevity is further underscored by the anticipation that the P binding capacity will naturally recharge over time, potentially extending the duration of efficient phosphate removal of about a millennia. According to recent research by Lyngaa et al. (2021), reaching a critical phosphorus saturation of 25% would necessitate the retention of approximately 10000 kg P/ha within a water infiltration soil depth of at least 1m.

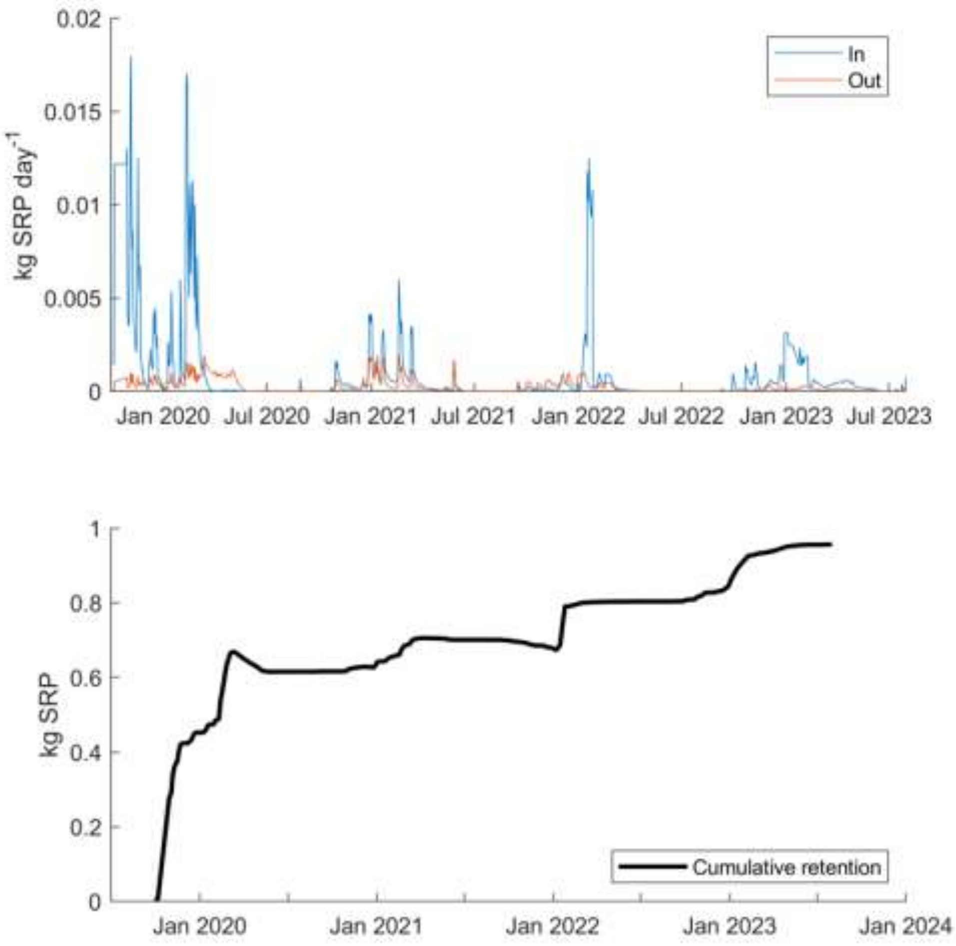

Fig. 7 Fluxes of phosphate at the drain water inlet (In) and at the end of the buffer zone (Out): cumulative import and export of nitrate and phosphate during the investigation period (see Figure 1 for sampling plots).

5. Bondesvad

The instrumentation of the SBZ Bondesvad started already in November 2021 however first sampling of the whole SBZ was first possible a year later due to several modifications of water inflow, extension of the distribution pipe from 50 m to 100 m (Fig. 8) at the end of the drain season 2021/2022 and the comparatively late start of the next drain season in November 2022 (see Table 3 for details).

Table 3. Instrumentation and modifications of the saturated buffer sones to increase the water inflow.

Datum	Activity	Remarks
11./12.10.21	Installation of piezometer transects	Big rocks in about 1 m depth disturbing the hand coring
26.11.21	Further installation of piezometers with “coring machine”	The piezometer at the edge of the field and of two in the buffer zone (all down to 1,5 m: distance between filter end and top of pipe)
8.11.21	Last piezometer installation	One remaining piezometer in the buffer zone (transect 3) which was not accessible by the Unimog
13.12.21	Connection of gauging stations, solar panel, data logger	Problems with a transformer
21.12.21	Re-positioning of solar panel, uplifting of bypass pipe, exchange of “transformer”	Still battery charge problems, ordering of new battery
05.01.22	Short test of increased bypass-outlet by 43 cm (diameter of bypass pipe is 20 cm	The water table was increasing to the soil surface in the well at the end of the distribution pipe and the lower part of the buffer zone became inundated the water was running direct in the stream (nearby the old drain outlet)
15.01.22	Moved two piezometers (the dry Bon 3-3 and the skew 4-3)	It was successful with 3-3 to go down to 120 cm and also to find a place for installing 4-39
17.01.22	The bypass outlet was increased by 30 cm	Now the maximum water table is reached, if water table rise due to strong increase of inflow (> 10 L/s) there will be water surface run off at the lowest point in the area (near transect 1)
21.01.22	Meeting with SEGES, land user and AU	Discussing the possibilities to increase the water infiltration: 1) Levelling of the soil surface to be able to increase the water bypass by another 5-10 cm, 2) extension of distribution pipe to the other side of the buffer zone
26.01.22	Levelling of soil surface in the SBZ to allow higher soil water tables/water flows	To avoid that water flows over the surface and “lost” unfiltered the soil surface was levelled
01.02.22	The bypass outlet was increased by another 7 cm	There is water standing now on the soil surface but seems to infiltrate before reaching the stream
April 22	Extension of distribution pipe	To increase the water inflow in the buffer zone the length of distribution pipe was doubled
04.05.22	Soil sampling and installation of two new piezometer transects	Soil samples were obtained for texture analysis and two additional piezometer transects were installed to cover the whole saturate buffer zone
09.11.22	Cleaning all piezometer incl. re-cleaning the first installed; start the Isco sampler	Water filled into the piezo 6-1a was immediately drained out
10.11.22	First sampling of all piezometers	The shallow Piezo in control-transect 6 was dry

Fig. 8 The saturated buffer zone Bondesvad fully instrumented in May 2022. Large rocks found in about 1 m soil depth and soil sampling for texture description.

Water flows

The drain water flow in Bondesvad is substantially higher than in Ulvskov due to ca. 6-times larger drained upland (ca. 30 ha). Daily averages higher than 30 L/s were recorded from January 2022 to October 2023 (Fig. 9). In the beginning of the monitoring the water infiltration was lower than 0.3 L/s and after the doubling of the distribution pipe to a length of 100 m the water infiltration could be increased to about 0.5 L/s. Accordingly, only a small proportion, i.e. ca. 10% of agricultural drain water was discharging the SBZ.

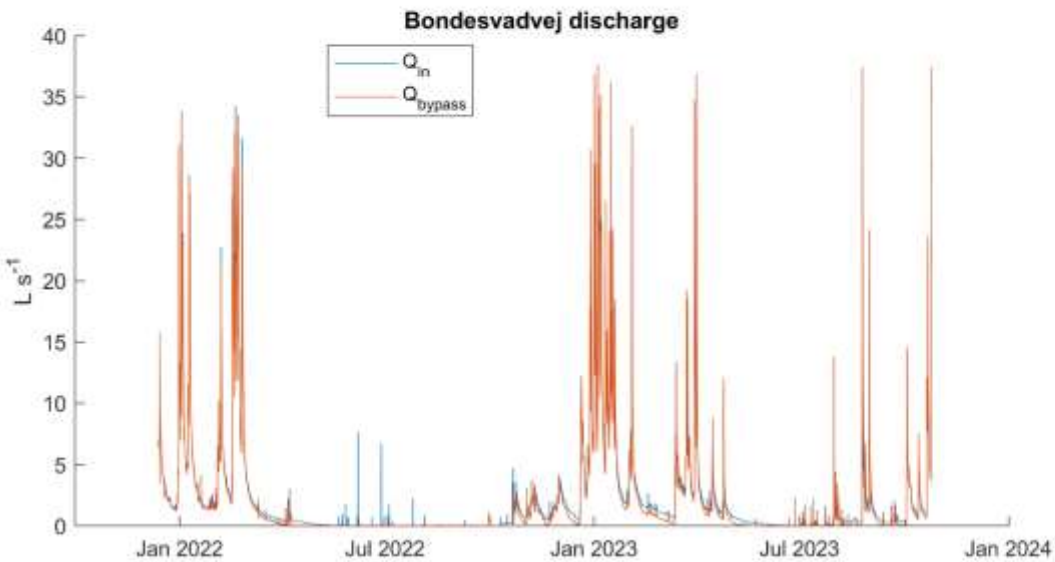

Fig. 9 The total water inflow from agricultural drain water in Bondesvad divided into the amount which was flowing into the SBZ (blue line) and the amount which was bypassed directly into the stream (red line).

Water quality changes and nutrient removal

The water sampling in the SBZ of Bondesvad shows that water quality becomes only slightly improved in case of nitrate, but a significant proportion of phosphate was likewise removed in this new SBZ. However, there are larger differences between the transects (Fig. 10). Thus, nitrate concentrations do not differ in the first transect but the inlet had slightly higher concentrations and in transect 5 and 6 there is a strong decline of nitrate which might be related to different water flows in the transect. It must be notified that transect 6 as control transect was only charged by groundwater from the field and water table at time of sampling was 1 m below soil surface compared to approximately 0.3 m in the other transects. Interestingly the phosphate concentration varied strongly in the groundwater before the distribution pipe (GW_{in}, see Figure 10) and in most cases the concentrations dropped down to the low level of the steam, i.e., ca. 0.030 mg/L. Apparently the soil in the buffer zone has a high P binding capacity as the SBZ site Ulvskov.

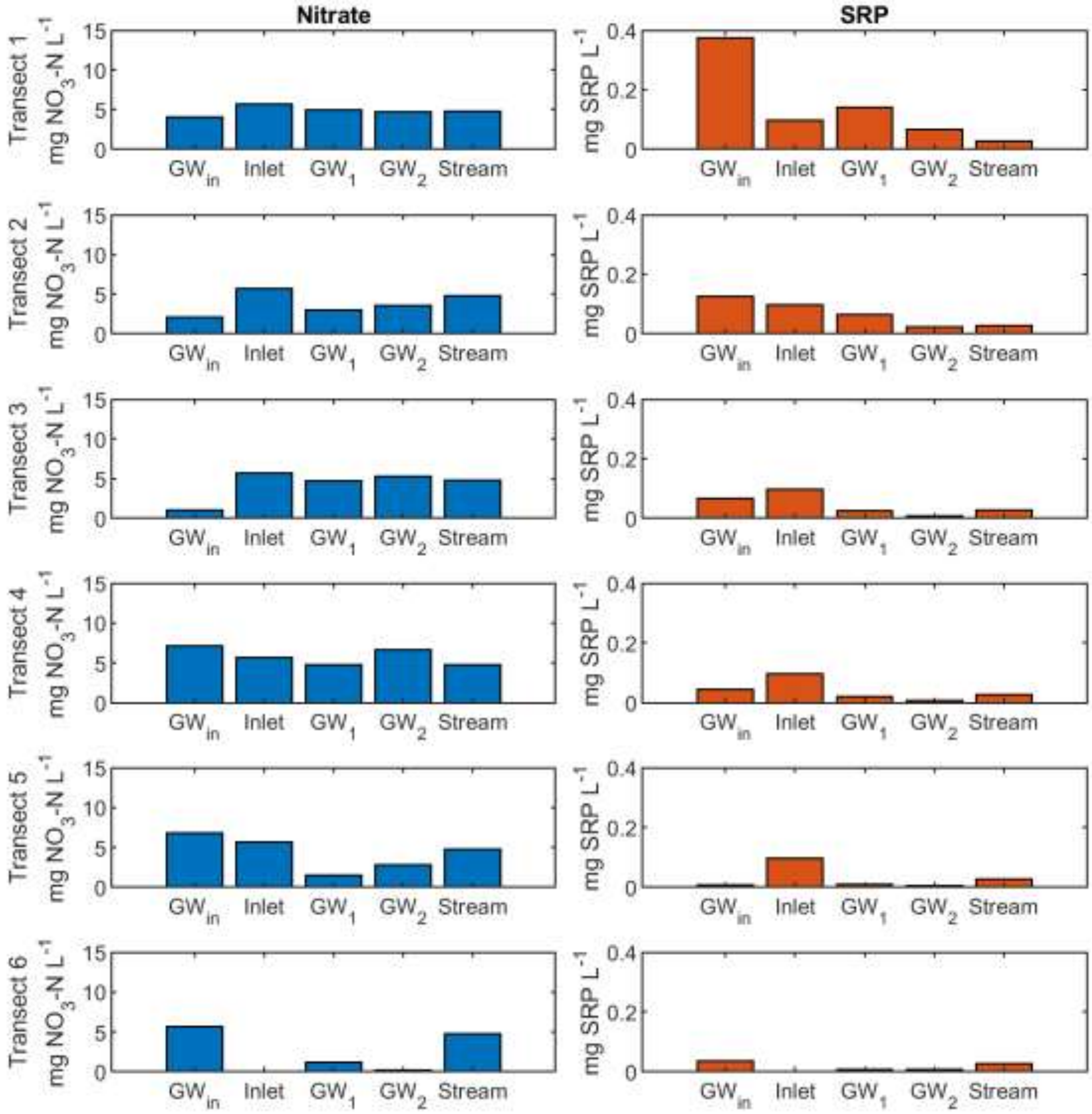

Fig. 10 Nitrate and phosphate concentration the groundwater from the field (GW_{in}), in the drain water (inlet), groundwater ($GW_{1,2}$) of the saturated buffer zone of the six transects and in the stream (mean of 2022-2023).

The nitrate removal efficiency in Bodensvad was approximately four times less effective than that in Ulvskov. However, the phosphate removal efficiency exhibited a comparable level in both locations (Table 4). The diminished nitrate removal is likely associated with lower water tables across a significant portion of the SBZ (Fig. 11). Additionally, slug tests indicate a shorter water residence time compared to Ulvskov (Fig. 12), and we also hypothesize a scarcity of available carbon in the sandy and rocky aquifer (Table 1, Fig. 8).

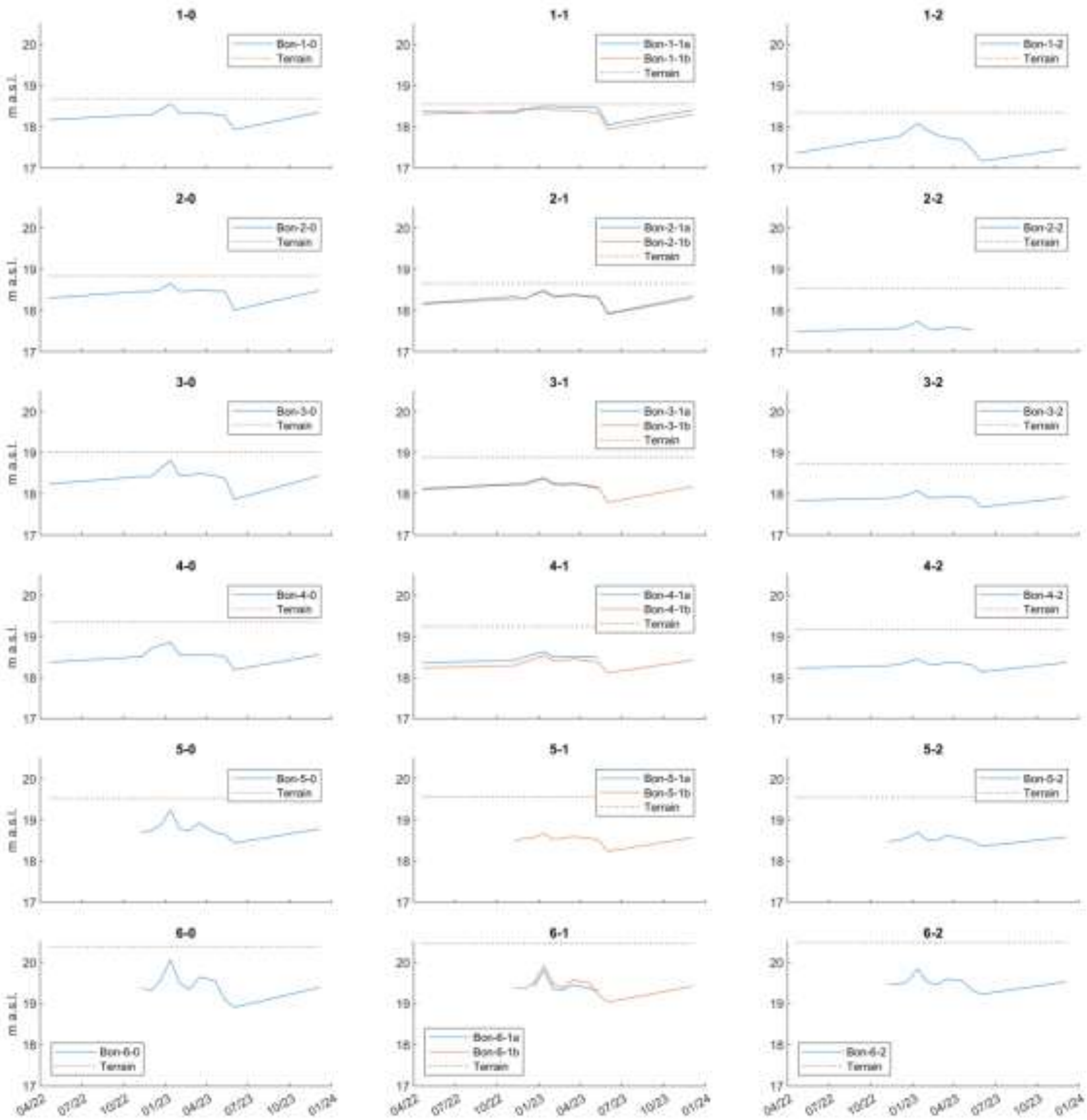

Fig. 11 The position and change of water tables in the saturated buffer zone Bondesvad (above sea level) in the six piezometer transects from the edge of the field down to stream (from left to the right) (the dashed brown line refers to the soil surface)

Table 4 Total removal and removal efficiencies for total dissolve nitrogen (TDN), nitrate-N (NO3-N), ammonium-N (NH_4-N), organic N (N_{org}), soluble reactive phosphorus (SRP) during three drainage seasons in the site Ulvskov.

		Sum in [kg]	Sum out [kg]	Removal [kg]	Removal [%]
TN	01/05-2022 – 30/06-2023	51.6	40.9	10.7	21
NO_3-N	01/05-2022 – 30/06-2023	47.5	37.3	10.2	21
NH_4-N	01/05-2022 – 30/06-2023	0.44	0.16	0.28	63
N_{org}	01/05-2022 – 30/06-2023	3.6	3.4	0.2	6
TP	01/05-2022 – 30/06-2023	0.95	0.24	0.72	75
SRP	01/05-2022 – 30/06-2023	0.83	0.18	0.65	79

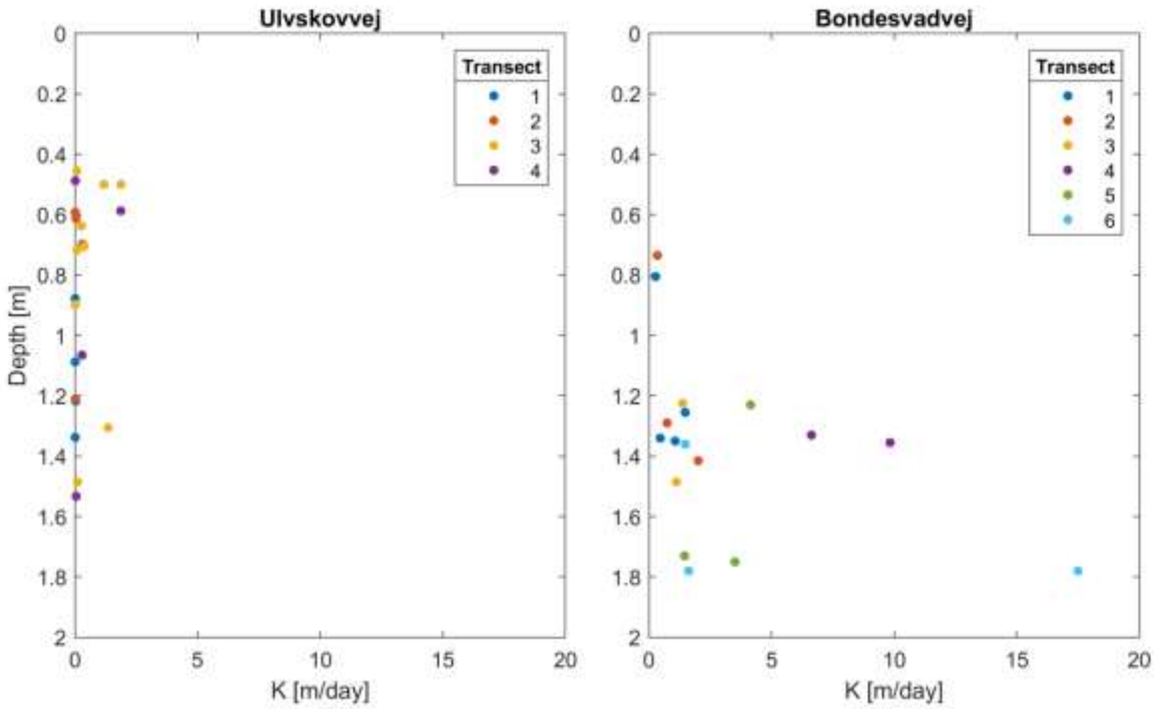

Fig. 12 Hydraulic conductivities of the two studied saturated buffer zones using slug tests (falling head) in all saturated piezometers according to the method described by (Bouwer & Rice, 1976).

6. Conclusions

In conclusion, the implementation of three pilot sites designated as saturated buffer zones (SBZ) in Denmark from 2019 to 2022 provided valuable insights into the effectiveness of this novel approach for removing nutrients, specifically nitrogen and phosphorus, from agricultural drainage water. The comprehensive monitoring program conducted across all sites included measurements of water inflow, water tables, water quality at the inlet, soil water transects within the SBZ, and soil characteristics.

The performance of the three pilot sites exhibited significant variability. Unfortunately, monitoring was discontinued at the "Gylling site" due to challenges in achieving a sufficient rise in groundwater table and water inflow, attributed to unfavorable site conditions. On the other hand, the "Ulvskov site" showed promising results in terms of water flow, water tables, and nutrient removal, with an impressive average nutrient removal efficiency of 77% for nitrate and 72% for phosphate. This surpassed the efficacy of other transport mitigation measures in Denmark.

However, the one-year monitoring of the recently established "Bondesvad site" revealed a limitation in capturing only a small proportion of drainage water (ca. 10% of total water flow from the fieldI. This limitation was attributed to unfavorable site characteristics, including excessively high clay content in the topsoil and a relatively low slope of the buffer area, coinciding with a low hydraulic gradient compared to the well-performing Ulvskov site.

In summary, while the SBZ approach demonstrated promising results in certain conditions, site-specific factors significantly influenced its effectiveness. The findings underscore the importance of considering local environmental conditions when implementing such mitigation measures in agricultural settings.

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8. Dissemination of results

The results of the project became presented during three international meetings (EGU Vienna, LUWQ Maastricht, WETPOL Bruges) and were introduced during a field workshop with different stakeholder in Germany in 2022 (see abstracts in the appendix). Currently, one scientific publication is drafted from the comprehensive data obtained in this project and another article should be published in 'Vand og Jord' in 2024. The preliminary titles are:

1) "A saturated buffer zone as cost-effective nature-based solution to mitigate the agricultural nutrient pollution" (to be submitted either to Water Research or to Environmental Science and Ecotechnology)
2) "Mættede bufferzoner i Danmark - Resultater fra tre kontrasterende randzone systemer i Midtjylland" (to be submitted to Vand og Jord)

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10. Appendix

EGU Meeting April 2022, Vienna

EGU General Assembly 2022

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EGU General Assembly 2022

Saturated buffer zones as novel drainage mitigation measure in Denmark

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Vegetated buffer strips have been introduced in some European countries since the 1980s to mitigate the deterioration of watercourses by surface runoff from intensively managed agricultural land. However, the effectiveness was proven to be less for the retention of dissolved nutrients than expected, as agricultural drainage water was directly charging streams via tile drainage pipes. Therefore, a new drainage mitigation measures was introduced in Denmark to lower the nutrient load of freshwater and eventually marine systems, called saturated buffer zone (SBZ). Drainage pipes are disconnected at the sloping field margin and to the riparian zone by diverting drainage water to a buried, lateral distribution pipe running parallel to the stream. Results of a 2-year monitoring study 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 was rather heterogenous varying by two orders of magnitude within the investigated transects. None the less, SBZs are a promising mitigation measure for removing nutrients from farmland.

LUWQ meeting September 2022, Maastricht

Saturated buffer zones treating agricultural drainage water: A new mitigation measure in Denmark

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Denmark reached a new political agricultural agreement in the fall of 2021, obligating Danish agriculture to reduce nitrogen (N) leaching to aquatic environments by 10.800 tons by 2027. Of the 10.800 tons N, 1500-tons must be reduced using collective methods, such as afforestation and natural and constructed wetlands.
New mitigation measures are currently being tested in Denmark as acknowledged mitigation measures like constructed wetlands are expensive to construct and only have an N-retention efficiency of around 25%. Saturated buffer zones (SBZs) are a recognized mitigation measure in the USA showing N removal rates of up to 84%. This promising result is obtained with a simple design of water saturating the riparian zone. The SBZ is now being evaluated under Danish conditions.
Two SBZ called ‘Gylling’ and ‘Ulvskov’ were constructed as pilot-scale testing facilities near Odder, Denmark funded by “Promilleafgiftsfonden” as part of the project “Videreudvikling og optimering af målrettede dræn- og lavbundsvirkemidler”. Monitoring began in September 2019 and includes investigations of hydrology, vegetation, soil, and water chemistry. Water samples were collected using automatic ISCO samplers and in piezometers installed in the SBZ. The phosphorus (P) retention and the N removal was evaluated using a mass balance approach. The investigation of the SBZ ‘Gylling’ ended in December 2020 due to low infiltration capacity of the soil matrix. Presumably due to a combination of a high groundwater table and a strongly degraded peat soil. The SBZ ‘Ulvskov’ showed greater promise with a water infiltration up to 8.6 L/s, before the adjoining bypass pipe was needed. The infiltration capacity, however, did decrease over time with bypass flow starting at 1 L/s, which might be explained by fine particles from the upland clay soil settling in the distribution pipe. Inlet flow to the SBZ increased to 2.1 L/s with no bypass flow, after rinsing the distribution pipe in December 2021. The SBZ ‘Ulvskov’ showed an overall N removal and P retention of 87% and 76%, respectively. Additionally, biomass analysis from ‘Ulvskov´ shows that the plant uptake could explain 30% of the N removal and all of the P removal. This underlines SBZs as promising mitigation measure for agricultural drainage water. In conclusions, SBZ has great potential to be implemented as a mitigation measure. The Gylling case, however, shows that SBZ are not suitable at all locations. Consequently, more data are necessary before SBZ can be an approved mitigation measure in Denmark.

Workshop on buffer zones 2022, Bad Schwartau

Am Ende ist das Dränrohr ein Weg zur Senkung der Stoffbelastung von Gewässern

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Seit den 1980er Jahren wurden in einigen Ländern Europas Gewässerrandstreifen etabliert, um die Nährstoffeinträge aus landwirtschaftlichen Nutzflächen zu verringern. Seit dieser Zeit gibt es eine kontroverse Diskussion über den Sinn bzw. die Wirksamkeit dieser Maßnahme. In der Folge wurden in Dänemark die Breite der Gewässerrandstreifen von Anfangs 2 m auf 10 m erhöht und dann später wieder auf 2 m herabgesetzt. Heute wissen wir aus umfangreichen Untersuchungen der letzten Jahrzehnte, dass die Retentionsleistung sowohl von der Form und Art der Nährstoffe aber auch insbesondere von der Beschaffenheit der Gewässerrandstreifen bezüglich des Reliefs, der Bodeneigenschaften und der vorherrschenden Vegetation abhängt. Ganz unabhängig von diesen Faktoren gelangt jedoch ein großer Anteil insbesondere von gelösten Nährstoffen ungehindert über Dränrohre in die Vorflut. Die Universität Aarhus hat in enger Zusammenarbeit mit anderen Forschungseinrichtungen des In- und Auslandes unterschiedliche „Drainage-basierte Maßnahmen“ untersucht, die die Retentionsleistung der Gewässerrandstreifen erhöhen und dabei geleichzeitig weitere vorteilhafte aber auch potenziell nachteilige Effekte für Mensch und Umwelt beleuchtet. Zu diesen Maßnahmen zählen die sogenannten noch nicht implementierten „Integrated bufferzones“ und „Saturated bufferzones“ aber auch schon seit einigen Jahren etablierte „Miniwetlands“ die aus dänischer Perspektive eingehender betrachtet und breiter diskutiert werden sollen.

A saturated buffer zone as cost-effective nature-based solution to mitigate the agricultural nutrient pollution of streams in Denmark

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Abstract

According to the EU Water Framework Directive 2000/60/EC (WFD), all waters including surface and ground waters must achieve at least good ecological status by 2027. However, it can be challenging as the compliance with the WFD can result in costly investments and set limits for agricultural and industrial production. Agriculture is reported by the European Environmental Agency as one of the key drivers for failure in realizing good ecological status in EU water bodies. Thus, intensively farmed agricultural land can have significant losses of nutrients through drainage, soil leaching, ditches, and surface runoff. According to the Danish political agreement "Agreement on green conversion of Danish agriculture" published 4th of October 2021, it is planned to achieve around 1,500 t of total nitrogen reduction using collective methods, such as afforestation as well as use of restored natural and constructed wetlands. The saturated buffer zone (SBZ) is a new drainage mitigation measure and was not tested in a Northern European context yet. The simple principle is that drain water from the field becomes reconnected to the non-cropped riparian zone. Specifically, drainage water and riparian buffer soil are reconnected by a buried, lateral perforated distribution pipe running parallel to the stream (0.5-1 m below soil surface), which redirect the drainage water into the riparian zone. In this paper, we present the performance of the first pilot-scale SBZ established in Denmark in 2018. Based on comprehensive field-testing the efficiency of the newly established SBZ for removing nutrients from agricultural tile-drain water was proven during three subsequent drain seasons from 2019 to 2022. Specifically, we investigated: 1) the site hydrology, i.e., water inflow and spatial differences of soil water fluxes, hydraulic conductivity, and ground water table changes, 2) effects on water quality and nutrient removal such as total dissolved nitrogen, nitrate, ammonium, and phosphate and 3) assessment of long-term performance regarding P sorption and cost efficiency. The SBZ investigated showed an overall N removal and P retention of 77% and 72%, respectively. Additionally, biomass analysis from the pilot site shows that the plant uptake could explain 30% of the N removal and all the P removal. This underlines SBZs as promising mitigation measure for agricultural drainage water, however specific site factors need to be considered before of successful implementation.