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Effects of water management on peatland water table and peatland subsidence

Effekte des Wassermanagements auf den Moorwasserstand und die Höhensackung der Mooroberfläche

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Keywords: blocked ditch, ditch impounding, subsurface irrigation, grassland
Schlüsselwörter: Grabenanstau, Grabeneinstau, Unterflurbewässerung, Grünland

Abstract

Drained peatlands are hotspots for carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions. In Niedersachsen, 69 % of the peatland area is used for agriculture and is responsible for 11 % of the annual CO_2 and N_2O emissions. Raising peatland water tables to 0.30 m below surface could reduce emissions. In this study, three water regulation methods were tested to raise water table and to maintain grassland use on bog peatlands.

In the first method, weirs were installed to block ditches and retain surface runoff within the blocking ditches. For the second method, ditch impoundment, additional water was pumped into the ditches creating constant ditch water levels. The third method, subsurface irrigation, further increased the water table within the grassland by allowing water to flow from the ditch into the bog area via subsurface pipes.

Ditch impoundment and subsurface irrigation methods effectively raised the bog water tables. In the summer 2020, the mean water tables for ditch impoundment and subsurface irrigation reached 0.32 m and 0.23 m below surface, while the water table with blocking ditches was much lower with 0.61 m below surface.

Overall, the subsurface irrigation method successfully raised the bog water tables and reduced subsidence. Negative aspects of this method are the costs for pipes and weirs, the reduced trafficability and the increased water demand.

Zusammenfassung

Entwässerte Moore sind Hotspots für die Emission von Kohlendioxid (CO_2) und Lachgas (N_2O). In Niedersachsen werden 69 % der Moorflächen landwirtschaftlich genutzt und sind für 11 % der jährlichen CO_2- und N_2O-Emissionen verantwortlich. Eine Anhebung des Moorwasserstandes auf 0.30 m unter Geländeoberkante (GOK) könnte die Emissionen verringern. In dieser Studie wurden drei Methoden zur Wasserregulierung getestet, um Moorwasserstände anzuheben und die Grünlandnutzung in einem Hochmoor aufrechtzuerhalten.

Für den Grabenanstau wurden Wehre installiert, um Gräben zu blockieren und den Oberflächenabfluss zurückzuhalten. Beim Grabeneinstau wird ein konstanter Wasserspiegel in den Gräben durch zugepumptes Wasser generiert. Bei der Unterflurbewässerung wird der Moorwasserstand weiter erhöht, indem Wasser aus dem Graben über unterirdische Rohre in die Fläche geleitet wird.

Mit dem Grabeneinstau und der Unterflurbewässerung konnten die Moorwasserstände erhöht werden. Im Sommer 2020 erreichten die mittleren Moorwasserstände beim Grabeneinstau und der Unterflurbewässerung 0.32 m und 0.23 m unter GOK, während der Moorwasserstand beim Grabenanstau mit 0.61 m unter GOK deutlich niedriger lag.

Insgesamt konnten mit der Unterflurbewässerung Moorwasserstände erfolgreich angehoben und die Höhensackung der Mooroberfläche verringert werden. Negative Aspekte dieser Methode sind die Kosten für Rohre und Wehre sowie die Pumpe, die eingeschränkte Befahrbarkeit und ein erhöhter Wasserbedarf.

1. Introduction

In natural peatlands, plant-litter accumulates and deposits under wet conditions important carbon sinks. Over the last ten thousand years, natural peatlands removed a significant amount of CO_2 from the atmosphere, which lead to a carbon (C) accumulation equivalent to almost half the total atmospheric carbon content (Drösler et al. 2008). Drained peatlands are hotspots for greenhouse gas (GHG) emissions, especially when they are deeply drained and agriculturally used (Tiemeyer et al. 2020). Draining and fertilizing peatlands results in massive boosts in CO_2 and N_2O emissions, whereas there can be high methane (CH_4) emission from the drained ditches (Wilson et al. 2016).

Niedersachsen is the federal state with the largest raised bog area in Germany. Sixty-nine percent of the peatland area is currently used for agriculture, either as grassland or as cropland. Agricultural use degrades peat, which leads to estimated annual emissions of 10.6 million tons of CO_2 equivalents, accounting for 11 % of Niedersachsen's total emissions (Höper 2015 und MU 2016).

Thus, the reduction of peatland emissions is a key factor in mitigating climate change. Consequently, an agreement between the federal government and the states on climate protection through peatland conservation (BMU 2021) was reached. Partial or complete rewetting and a sustainable water- and land-management on all peatland sites should be the goal. By implementing peatland conservation measures, the lifetime of peatland sites should be prolonged and the degradation of peat properties should be slowed down.

Climate smart agriculture, which simultaneously reduces peat subsidence, must be developed to reduce GHG emissions. Studies have shown that sustainable water management conserves peat soils (Günther et al. 2020; Wilson et al. 2016). The water table position within the peat horizons generally determines the amount of CO_2 and CH_4 released to the atmosphere (Tiemeyer et al. 2020). Raising the water table to 0.30 m below surface may result in a considerable reduction in GHG emission (Wilson et al. 2016). Blocked ditches lead to the retention of water, which should help to raise the bog water tables during month with less or no precipitation. The water tables are controlled with an adjustable weir. Due to the low hydraulic conductivity (k_{sat}) of the degraded peat, high summer water tables may be difficult to achieve when only the ditches are blocked. By additionally pumping water into the blocked ditch, referred to hereafter as ditch impoundment, high water tables in the ditches could be maintained throughout the year. In order to raise the water table of the whole grassland and not just the area directly adjacent to the ditches, subsurface irrigation is an option. For this method, perforated pipes are installed perpendicular to the ditch at a depth of 0.50-0.70 m. These pipes irrigate subsoil in dry periods and drain the soils in periods of high rainfall. Subsurface irrigation has already been tested in the Netherlands mainly to avoid subsidence. In the Dutch trials, the water tables were relatively deep in the subsurface irrigation treatments (range of annual mean values 0.28 to 0.61 m below surface with a median of 0.41 m below surface) and only slightly higher than in the control (annual mean values 0.31 to 0.67 m with a median of 0.47 m below surface) (WEIDVELD et al. 2019).

This manuscript presents two research projects on climate- and peat-smart agriculture, which aim to raise the water tables on bog grasslands to 0.20–0.30 m below surface. Ideally, the water table should remain at this level and only be lowered during management phases (i.e. mowing, fertilizing) to support heavy machinery on the site. The goal of this study is to respond to the following questions:

1. What are effective methods to increase water tables on bog grasslands?

2. What is the effect of water table management on peatland subsidence and the trafficability by agricultural machinery?

3. How to test methods of water regulation and simultaneously sustainable agriculture?

Greenhouse gas measurements were collected by external partners within the project and will be published by them.

2. Material and Methods

2.1 Study Sites

We conducted field experiments on two bog areas in Northwest Germany to test different methods to raise bog water tables, while continuing conventional grassland use (Figure 1).

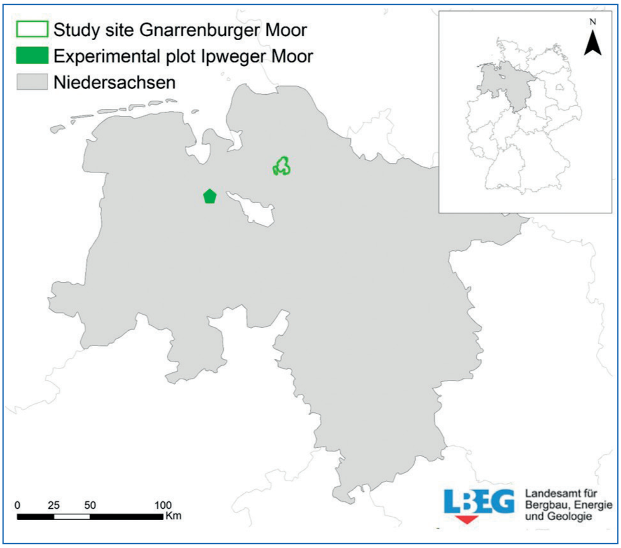

Fig 1: Overview of studied peatlands in Niedersachsen. Gnarrenburger Moor (53°21'00"N, 8°59'26"E) and Ipweger Moor (53°21'55.98" N, 8°18'31.464"E).
Übersicht der untersuchten Moorgebiete in Niedersachsen. Gnarrenburger Moor (53°.21`00`` N, 8°59'26"E) und Ipweger Moor (53°21'55.98" N, 8°18'31.464"E).

The peatland "Gnarrenburger Moor" (53°21'00"N, 8°59'26"E) is rather large, covering 6120 ha. The peatland depth is between 2 and 4 m with underlying fine sands. A highly degraded and compact black peat horizon (H 6-10 after the von Post scale for degree of peat humification; von Post 1924) is covered by a less degraded white peat (Sphagnum peat with low decomposition) horizon (H 1-5). In contrast to black peat, white peat has a higher hydraulic conductivity. The topsoil horizon consists of highly decomposed organic material (H10), which is due to agricultural activity. Isolated fens and Gleysols are present at the edges of the study area. The dominant land use in the Gnarrenburger Moor is agriculture, mainly grassland and, to a smaller extent, cropland with maize and potatoes.

The peatland "Ipweger Moor" (53°21'55.98"N, 8°18'31.464"E) with an area of 8980 ha consists mainly of bog peat over fen peat or over fine and medium sand, with a thickness of 3–4 m (Schneekloth and Tüxen 1975). The residual peat of the study area consists only of bog peat directly over fine and medium sands and is mainly used as grassland.

2.2 Experimental Plots

The capacity to raise water tables in a peatland depends on the intended land use and the properties of the residual peat. The following criteria were used to select the experimental plots: (i) at least 0.50 m of white peat, (ii) flat terrain, (iii) grassland use, and (iv) owner's consent. In the Gnarrenburger Moor, 13 plots were chosen for the monitoring of peatland water table and ditch water level, of which water management measures were tested at six plots (Figure 1). In the Ipweger Moor one experimental plot was installed, testing water management measures with subsurface irrigation and ditch impoundment (Figure 2).

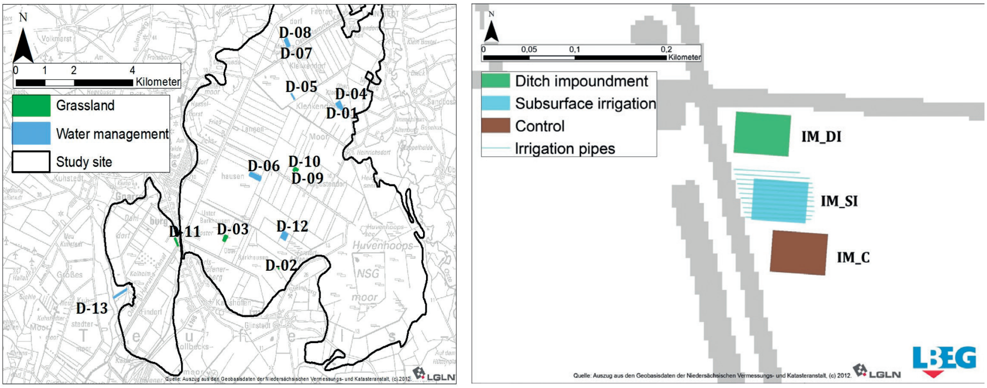

Fig. 2: Study plots in the Gnarrenburger Moor (left) and Ipweger Moor (right)
Untersuchungsflächen im Gnarrenburger Moor (links) und Ipweger Moor (rechts)

In this study, the results of two plots from the Gnarrenburger Moor (D-06 and D-07) and one plot from the Ipweger Moor (IM) are presented. In the Gnarrenburger Moor blocked ditch and subsurface irrigation were tested, while in the Ipweger Moor ditch impoundment and subsurface irrigation were determined. All study sites included controls. In the Gnarrenburger Moor the controls were drained by ditches. In the Ipweger Moor the control plot was drained with pipes placed every 4 m at a depth of about 0.7 m. The treatments and the control cover each an area of about 0.3 to 0.5 ha (Table 1).

2.3 Water regulation measures

During management phases, the water tables may be lowered temporarily in order to ensure trafficability of the peatland areas.

Blocking ditches allow the retention of surface- and rainwater. This will increase the water tables in spring and early summer compared to the control plots. With adjustable weirs in the ditches, winter precipitation is retained until a ditch water level of 0.30 m below surface is reached. The terrain slope should not exceed 0.30 m on each plot. Depending on the topography of the plot, several blocked ditch levels have been created.

Ditch impoundment is when in addition to blocking ditches water is pumped into the ditch to maintain high water tables throughout the year. A solar-powered pump was installed to maintain the desired ditch water level. The weirs have been lowered when drier site conditions were needed. Similarly, water tables were raised within a few days when water was pumped into the ditch.

Tab. 1: Treatments within the two bog areas and three study sites; measures to regulate the water table and water supply.
Maßnahmen zum Wassermanagement in beiden Moorgebieten und den drei Untersuchungsgebieten; Maßnahmen zur Regulierung des Moorwasserstandes und der Wasserversorgung.

Study site	Plot	Measures	Water supply
Gnarrenburger Moor			
D-06	Blocked ditch, level 1	Ditch blocked	no
D-06	Blocked ditch, level 2	Ditch blocked	no
D-06	Control	Ditch not blocked	no
D-07	Subsurface irrigation	Ditch blocked	Pumping of groundwater into ditch, subsurface pipes
D-07	Control	Ditch not blocked	no
Ipweger Moor			
IM-DI	Ditch impoundment	Ditch blocked	Pumping of surface water into ditch
IM-SI	Subsurface irrigation	Ditch blocked	Pumping of surface water into ditch, subsurface pipes
IM-C	Control	Drain pipes ditch not blocked	no

Subsurface irrigation should allow an intensive grassland use (3 to 5 harvests/a) with high summer bog water tables. Depending on the conductivity and the type of peat, pipes (6.5 to 8 cm in diameter) were installed at a depth of 0.50–0.70 m every 4–5 m with a small slope of 0.1 % towards the ditch. The pipes were circa 80 m long and led into a ditch, which was filled with water during the vegetation period.
The type of water supplied varied between the sites. In Gnarrenburger Moor due to insufficient surface water, groundwater was used. In Ipweger Moor surface water was pumped from a main ditch (Figure 3).

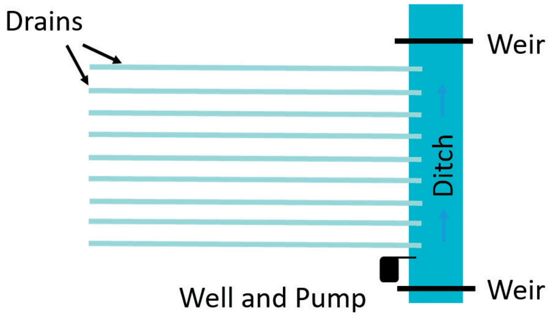

Fig. 3: Scheme of subsurface irrigation. The pipes of the subsurface irrigation are located at a depth of 0.5-0.7 m with a distance between the pipes of 4 m. The slope of the pipes is 0.1 % down to the peatland site.
Schema der Unterflurbewässerung. Die Rohre der Unterflurbewässerung befinden sich in 0.5-0.7 m Tiefe mit einem Abstand zwischen den Rohren von 4 m. Das Gefälle der Rohre beträgt 0.1 % abfallend zur Moorfläche.

2.4 Data assessment

Soil characteristics

A soil profile was dug at each plot and the soil horizons were described based on the "German Manual of Soil Mapping" (Ad-hoc-AG Boden 2005). At the D-06 and D-07-sites a mixed sample was taken from each bog soil horizon to a depth of about 1 m and analyzed for total organic carbon (DIN EN 15936:2012-11), total nitrogen (DIN EN 16168:2012-11) and $pH_{(CaCl2)}$ (DIN EN 15933: 2012-11 modified for field moist peat soils and a ratio of peat to $CaCl_2$-solution of 1:2,5 by volume). For all plots, 12 sampling rings of 250 and 100 cm^3 each were taken per horizon for further laboratory analyses of dry bulk density (DIN ISO 11272:2001-01) and saturated hydraulic conductivity (DIN 19683-9:2012-07). The 100 cm^3 sampling rings were used for horizons with low thickness to prevent mixing of the horizons.

Field measurements of the hydraulic conductivity

The hydraulic conductivity of peat below the water table was measured in the field using the auger-hole method (Van Beers 1962). These measurements were carried out in freshly drilled holes except for measurements in the Ipweger Moor in 2019, which were performed in the pipes of the groundwater monitoring wells. The existing monitoring wells are easy to access, have equilibrium water tables before measurement starts and thus, are easier to handle than freshly drilled holes.

Hydrological Monitoring

Water tables were monitored in the treatment plots, in the control plots and in the nearby ditches by absolute water level data loggers (Figure 4) (Rugged Troll 100, UGT, Müncheberg). In the Gnarrenburger Moor, four to eight water table monitoring wells were installed per treatment and in Ipweger Moor, five to eight water table monitoring wells. The pressure of the water column was recorded with hourly resolution. A recording barometer (Rugged BaroTROLL, UGT, Müncheberg) provided hourly air pressure data, used to compensate the water level data from the absolute pressure probes for barometric pressure changes. At plots with subsurface irrigation, the data of the water table measurements were sent daily to a server via a GSM module for the remote transfer of data. This procedure is necessary to react quickly to pumps failure with resulting of low water tables.

For Gnarrenburger Moor precipitation and potential evapotranspiration were obtained from the nearby meteorological station Bremervörde of the German Meteorological Service (DWD). On plots with subsurface irrigation, the amount of pumped groundwater was recorded daily. For Ipweger Moor weather data was used as averaged values of the meteorological stations Bremen, Bremerhaven and Friesoythe/Altenoythe (DWD), weighted by distance to the experimental plot.

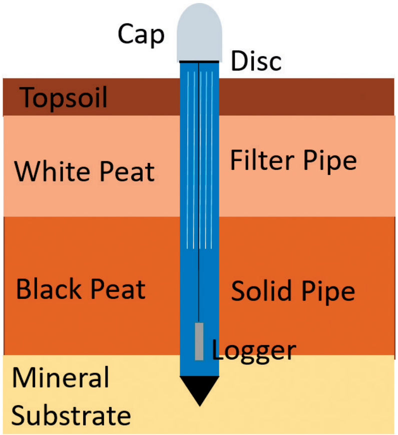

Fig. 4: Setup and function of a water table monitoring in peat soil. No black peat is present in Ipweger Moor. Groundwater tube (blue) fixed into the mineral subsoil, closed at the bottom with a cap (black), starting at the bottom with 1 m closed tube followed by 1 or 2 m (depending of peat depth) filter tube closed by a cap. Within the tube there is a data logger with a pressure sensor at its bottom hanging at a non-expandable rope (Dyneema rope PRO 2 mm, Kanirope, Dortmund) which is fixed on top of the pipe to a disc.
Aufbau und Funktion der Wasserstandssonden im Torfboden. Das Grundwasserbeobachtungsrohr ist im mineralischen Untergrund fixiert, am unteren Ende verschlossen, beginnt mit 1 m geschlossenem Filterrohr, darüber 1-2 m (ja nach Torfmächtigkeit) geschlitztes Filterrohr und verschlossen mit einer Kappe. Im Rohr hängt ein Datalogger mit Drucksensor am Boden and einem nicht-dehnbaren Seil (Dyneema PRO 2 mm, Kanirope, Dortmund) das an einem Ring an der Oberkante des Rohres befestigt ist. Im Ipweger Moor ist kein Schwarztorf vorhanden.

Elevation monitoring

Monitoring elevation can be used to document the oscillation of the peatland surface due to shrinking or swelling, and the amount of peat mineralization. Elevations were measured once to twice a year at each treatment and control plot. To determine inter- and intra-annual changes, elevations were recorded in February/March at highest water tables and in September/October at the lowest water tables. Elevations were recorded in five repetitions on a 10 x 10 m grid with a Trimble R8s GNSS (Sunnyvale, California) system.

Resistance to penetration

At the Ipweger Moor study site, the penetration resistance of the peat was recorded in ten parallel measurements on each experimental plot at a depth of 0 to 0.80 m with a penetrologger using a 5 cm^2 cone recording one pressure value per 1 cm depth increment (Eijkelkamp, Giesbeek, the Netherlands). The measurements were done three to five times during each vegetation period and four times during winter 2019/2020. To simplify the visualization, mean values of the penetration resistance were calculated for the top 0.05–0.20 m horizon and the adjacent 0.21–0.35 m horizon. The use of the penetrologger is a reproducible method to assess the ground load-bearing capacity and gives a rough estimate on mechanical characteristic of the ground as base for the trafficability and treading resistance of the plot after water regulation measures in comparison to the control plot. Additionally, other factors of the trafficability, e.g. tyre dimensions and weight of the tractors and the treading resistance, e.g. cattle breed or age, have to be taken into account. Measurements with the penetrologger were also done at the Gnarrenburger Moor study sites but did not allow additional findings and thus are not reported here.

2.5 Statistical Analysis

Seasonal and annual means were calculated for water table data. Medians and lower and upper percentiles were determined for hydraulic conductivity. Medians, lower percentile (10th) and upper percentile (90th) were provided for changes in elevation. Medians were used because these two parameters were not normally distributed. Data analyses and assessments were performed using Excel 2016 (Microsoft), R (RStudio), and changes in height were calculated with ArcGIS (Esri 2020) using the interpolation tool - nearest neighbour.

3. Results

3.1 Soil characteristics

The Gnarrenburger Moor profiles show a characteristic raised bog with peat thicknesses between 2 to 4 m. Below a completely degraded peat horizon, weakly to strongly degraded bog peat horizons follow (Table 2). Due to peat mineralization and the accumulation

Tab. 2: Soil profile description (after Ad-hoc-AG Boden 2005) for the blocked ditch experimental plot D-06 in the Gnarrenburger Moor. Soil type: Very deep Folic Histosol (HHv5).
Bodenprofilbeschreibung (nach Ad-hoc-AG Boden 2005) für die Grabenanstau Versuchsfläche D-06 im Gnarrenburger Moor. Bodentyp: Very deep Folic Histosol (HHv5).

Nr	Depth (cm)	Horizon	Peat type	Admixtures	Degree of decomposition (v. Post)	Volume of solid substances (classes)
1	20	hHvp	Hh		(H 10)	SV4
2	25	hHw1	Hhsa (Hhsu)	Bim, Bih	H 3-4	SV4
3	55	hHw2	Hhsa (Hhsu)	Bim, Bih, Be	H 5	SV3
4	90	hHw3	Hhs	Bim, Bih, Be	H 6	SV4
5	160	hHr1	Hhs	Be	H 6	SV4
6	210	hHr2	Hhs	Be	H 7-8	SV4

Elevation: 8.60 m a.s.l, admixtures of *Eriophorum vaginatum* (Be), *Calluna vulgaris* (Bih) and *Vaccinium oxycoccus* (Bim). Peat depth 2.1 m, fine and medium sand at peat basis. Volume of solid substances: classes SV3 = 5 - <7,5 % v/v, SV4 = 7,5- < 12 % v/v, SV 5 = ≥ 12 % v/v.

of mineral substances, the upper earthyfied (hHv) and ploughed horizons (hHvp) had a lower carbon content and a higher dry bulk density as the deeper horizons. Fertilization and liming additionally led to a higher pH and an accumulation of nitrogen in the earthyfied horizon (Table 3).
The white peat (H ≤ 5) thickness at the blocked ditch plot was about 0.55 m. The peat types mainly consist of *Sphagnum acutifolia* peat (Hhsa) with small proportions of *Sphagnum cuspidatum* peat (Hhsu) and unspecified *Sphagnum* moss peat (Hhs).

Tab. 3: Description of the soil chemical and physical parameters for the blocked ditch experimental plot D-06 in the Gnarrenburger Moor.
Beschreibung der bodenchemischen und -physikalischen Parameter für die Grabenanstau Versuchsfläche D-06 im Gnarrenburger Moor.

Nr	Depth (cm)	Horizon	Total organic carbon (TOC) (%)	Total nitrogen Nt (%)	pH $_{CaCl2}$	Dry bulk density (g/cm³)
1	20	hHvp	48.8	2.1	4.1	0.27 ± 0.03 (n=12)
2	25	hHw1	55.2	1.3	3.6	0.18 ± 0.02 (n=12)
3	55	hHw2	55.7	1.2	3.7	0.13 ± 0.012 (n=12)
4	90	hHw3	56.6	1.1	3.5	0.11 ± 0.005 (n=12)

At the subsurface irrigation plot D-07, the white peat (H ≤ 5) thickness was about 0.42 m, in the lower part mostly composed of *Sphagnum cymbifolia* peat (Hhsy) (Table 4). At 0.42-0.62 m depth, an uwnspecified *Sphagnum* moss black peat (Hhs) is found on top of a compacted *Cuspidatum* white peat horizon (Hhsu) at 0.62 to 0.80 m depth. Below 0.80 m black peat composed of unspecified Sphagnum moss peat starts (Table 5).

Tab. 4: Soil profile description (after Ad-hoc-AG Boden 2005) for the subsurface irrigation experimental plot D-07 in the Gnarrenburger Moor. Soil type: Very deep Folic Histosol (HHv5).
Bodenprofilbeschreibung (nach Ad-hoc-AG Boden 2005) für die Unterflurbewässerung Versuchsfläche D-07 im Gnarrenburger Moor. Bodentyp: Very deep Folic Histosol (HHv5).

Nr	Depth (cm)	Horizon	Peat type	Admixtures	Degree of decomposition (v. Post)	Volume of solid substance (classes)
1	16	hHv	Ha (fs, ms)		(H 10)	SV5
2	42	hHw1	Hhsy	Bih , Bim	H 2-3	SV4
3	62	hHw2	Hhs	Bim, Be	H 6	SV3
4	80	hHr1	Hhsu	Bw, Bim	H 5	SV3
5	100+	hHr2	Hhs	Bw, Bim	H 8	SV3

Elevation: 8,18 m a.s.l, admixtures of *Eriophorum vaginatum* (Be), *Calluna vulgaris* (Bih), *Vaccinium oxycoccus* (Bim) and *Polytrichum strictum* (Bw). Peat depth 2.2 m, fine and medium sand at peat basis. Volume of solid substances: classes SV3 = 5 - <7,5 % v/v, SV4 = 7,5- < 12 % v/v, SV 5 = ≥ 12 % v/v.

Tab. 5: Description of the soil chemical and physical parameters per horizon for the subsurface irrigation experimental plot D-07, Gnarrenburger Moor.
Beschreibung der bodenchemischen und -physikalischen Parameter pro Horizont für die Unterflurbewässerungs Versuchsfläche D-07, Gnarrenburger Moor.

Nr	Depth (cm)	Horizon	Total organic carbon (TOC) (%)	Total nitrogen Nt (%)	pH $_{CaCl2}$	Dry bulk density (g/cm³)
1	16	hHv	42.1	2.2	4.5	0.39 ± 0.05 (n=3)
2	42	hHw1	51.2	1.0	3.8	0.12 ± 0.003 (n=3)
3	62	hHw2	56.5	1.4	3.6	0.12 ± 0.005 (n=3)
4	80	hHr1	56.6	1.2	3.7	0.11 ± 0.004 (n=3)
5	100	hHr2	57.2	1.2	3.5	0.11 ± 0.004 (n=3)

The Ipweger Moor profile shows a raised bog with degraded topsoil over slightly decomposed *Sphagnum* peat (H3) over moderately and highly decomposed (H5/H6) raised bog peat over fine sand. The peat thickness exceeded 2 m on the raised bog. The original drainage pipes were at a depth of approximately 0.70 m in the control area (Table 6).

Tab. 6: Soil profile for the experimental field (blocked ditch and subsurface irrigation treatments), in Ipweger Moor, profile description, following Ad-hoc-AG Boden (2005). Soil type: Very deep Folic Histosol (HHv5).
Bodenprofil für die Versuche (Grabeneinstau und Unterflurbewässerung), im Ipweger Moor, Profilbeschreibung in Anlehnung an Ad-hoc-AG Boden (2005). Bodenart: Very deep Folic Histosol (HHv5).

Nr	Depth (cm)	Horizon	Peat type	Admixtures	Degree of decomposition (v. Post)
1	20	hHv	Hhs		(H 10)
2	50	hHw1	Hhs	Be, Bi	H 4
3	57	hHw2	Hhs	Be	H 6
4	120	hHr1	Hhs	Bi	H 3
5	125	hHr2	Hhs	Be	H 5
6	200	hHr3	Hhs	Be	H 6

Elevation: 0,02 m a.s.l., free water in bore hole at 0.9 m depth, admixtures of *Eriophorum vaginatum* (Be) and heather (Bi). Peat depth 2.2 m, fine and medium sand at peat basis

3.2 Hydraulic conductivity

The hydraulic conductivity (K_{sat}) varied between 3 and 5 cm/d at plot D-06 and between 2 and 3 cm/d at plot D-07 in the Gnarrenburger Moor. These values were determined in spring at bog water tables higher than 0.2 m below surface at soil temperatures of 5°C. This indicates that even the upper horizons, hHw1 and hHw2, mainly consisting of white (*Sphagnum*) peat, are rather compacted (Table 7).

Tab. 7: Saturated hydraulic conductivity determined by auger-hole method sites D-06 and D-07 at Gnarrenburger Moor, measured between the 19.03.19 and 01.04.19. Median, lower and upper quartile in parentheses.
Gesättigte hydraulische Leitfähigkeit, bestimmt mit der Bohrlochmethode an den Standorten D-06 und D-07 im Gnarrenburger Moor, gemessen zwischen dem 19.03.19 und 01.04.19. Median, unteres und oberes Quartil in Klammern.

Plot	**Auger hole depth (cm below surface)**	**Water table (cm below surface)**	**K_{sat} (cm/d)**
D-06	108	11 (7–13)	3.5 (2.8–5.1) (n=12)
D-07	106	14 (6–17)	2.2 (2.0–2.8) (n=12)

The hydraulic conductivity at the Ipweger Moor study site strongly varied (Table 8). Under dry conditions (deep water table), e.g. measurements before starting the experiment and in the control treatment in 2018, the K_{sat} was low. When the water table was close to the surface, (shallow water table), K_{sat} showed average (10– 40 cm/d) to high values (>40 cm/d). The hydraulic conductivity measured in the field are in accordance with standard values given in the current version of the German manual of soil mapping (Ad-hoc-AG Boden, 2005, Table 77). In the subsurface irrigation treatment, the pipes were installed at a depth of 0.65 m, where poorly and fairly decomposed *Sphagnum* peat is found at lower depths of down to 1.20 m.

3.3 Water tables

Blocked ditch

The retention of water during winter in the ditches at plot D-06 had little effect on the bog water tables. In 2019 and 2020, bog water tables differ only marginally from the control plots. The influence of little rainfall and, thus, the low climatic water balance in 2019 was especially evident in the low summer water tables (Table 9 and Figure 5). In winter, bog water tables were generally higher with values between 0.18-0.40 m below surface compared to summer with values between 0.63-0.78 m below surface.

Tab. 8: Saturated hydraulic conductivity K_{sat} determined by auger-hole method and corresponding water table at the Ipweger Moor experimental plots. Median, lower and upper quartile in parentheses. Number of replicates in italics.
Gesättigte hydraulische Leitfähigkeit K_{sat}, ermittelt mit der Bohrlochmethode, und entsprechendem Grundwasserspiegel auf den Versuchsflächen im Ipweger Moor. Median, unteres und oberes Quartil in Klammern. Anzahl der Wiederholungen in Kursivschrift.

Treatment	**Date**	**Water table (cm below surface)**	**Auger hole depth (cm below surface)**	**K_{sat} (cm/d)**
Before experiment	17.10.2016	85 (76–92)	200	1.7 (1.6–1.8) (n=6)
	06.04.2017	57 (54–60)	78	11 (9–15) (n=4)
Ditch impoundment	13.03.2018	4 (2–18)	196	11 (8–12) (n=5)
	14.03.2019	6 (5–8)	61	113 (80–161) (n=4)
Subsurface irrigation	13.03.2018	27 (23–34)	174	4.6 (3.2–7.2) (n=7)
	14.03.2019	6 (4–7)	62	38 (27–80) (n=4)
Control	13.03.2018	48 (39–59)	152	4.7 (2.2–5.5) (n=8)
	14.03.2019	18 (17–19)	76	8 (5–14) (n=4)

Tab. 9: Mean bog and ditch water levels on blocked ditch plots at two elevation levels (L1 and L2) and control sites in the Gnarrenburger Moor (Summer = May–October, Winter = November–April). Ditch: n=1; Bog: n=2.
Mittlere Moor- und Grabenwasserstände auf einem Standort mit Grabenanstau auf zwei Höhenstufen (L1 und L2) und Kontrollflächen im Gnarrenburger Moor (Sommer = Mai–Oktober, Winter = November–April). Graben: n=1; Moor: n=2.

Period	**Water table (m below surface)**					
	Blocked ditch level 1	**Blocked ditch level 2**	**Control**	**Blocked ditch level 1**	**Blocked ditch level 2**	**Control**
	bog	**bog**	**bog**	**ditch**	**ditch**	**ditch**
Winter 2018/2019	0.40	0.23	0.36	0.64	0.43	1.24
Summer 2019	0.78	0.62	0.75	1.02	0.84	1.36
Winter 2019/2020	0.36	0.18	0.31	0.63	0.40	1.11
Summer 2020	0.79	0.63	0.66	1.03	0.87	1.35
Year 2019	0.58	0.41	0.54	0.82	0.62	1.30
Year 2020	0.61	0.45	0.50	0.86	0.67	1.22

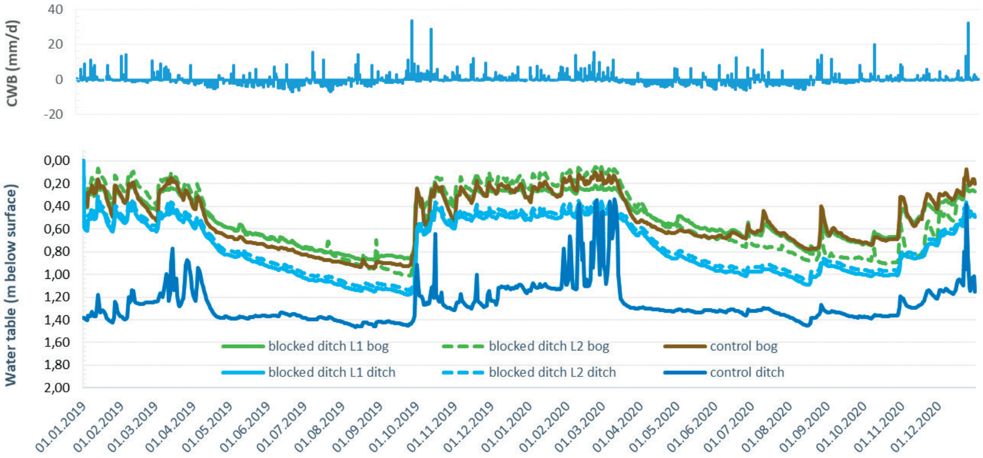

Fig. 5: Daily climatic water balance - CWB (Bremervörde weather station, DWD), ditch- and bog water tables at blocked ditch plot with two elevation levels (L1 and L2) and control plot, Gnarrenburger Moor. The two elevation levels L1 and L2 represent mean of north and south each. Naming scheme: plots (blocked ditch or control) – elevation level (L1 or L2, if applicable) – type of water table (ditch or bog).

Tägliche klimatische Wasserbilanz - KWB (Wetterstation Bremervörde, DWD), Graben- und Moorwasserstände auf einem Standort mit Grabenanstau mit zwei Höhenstufen (L1 und L2) und Kontrollparzelle im Gnarrenburger Moor. Die Höhenstufen L1 und L2 stellen jeweils den Mittelwert von Nord und Süd dar. Benennungsschema: Plots (gesperrter Graben oder Kontrolle) – Höhenstufe (L1 oder L2, falls zutreffend) – Art des Wasserstandes (Graben oder Moor).

Ditch impoundment

In Ipweger Moor, the control ditch had an average annual water table of 1 m below surface. The water table in winter was 0.2–0.8 m below surface, whereas the summer water tables dropped to over 1 m below surface in the control plot. At the ditch impoundment, ditches had an average annual water table of 0.2–0.3 m below surface. The water management led to water tables near surface of 0.0–0.1 m in winter and 0.4–0.6 m in summer (Table 10 and Figure 6). However, there is a strong water table gradient from the ditch to the center of the study area.

Subsurface irrigation

In the Gnarrenburger Moor, the subsurface irrigation on plot D-07 resulted in bog water tables above the control water tables in 2019 and 2020. With supplemental water provided by pumps, the ditch water levels remained high even during the summer months. The average bog water table in the subsurface irrigation plot was 0.22 m below surface, which is almost 0.3 m higher than the water table of the control plot (Table 11 and Figure 7) between the years 2019 and 2020. This required an annual groundwater supply of 310–335 mm.

Tab. 10: Mean ditch and bog water tables (m below surface) on control and ditch impoundment sites at Ipweger Moor (Summer = May–October, Winter = November–April). Ditch: n=1; Bog: n=5.
Mittlere Graben- und Moorwasserstand (m unter der Oberfläche) am Standort mit Grabeneinstau und Kontrolle im Ipweger Moor (Sommer = Mai–Oktober, Winter = November–April). Graben: n=1; Moor: n=5.

Period	**Bog water table (m below surface)**		**Ditch water level (m below surface)**	
	Ditch impoundment	**Control**	**Ditch impoundment**	**Control**
Winter 2018/2019	0.21	0.87	0.18	1.05
Summer 2019	0.45	0.95	0.17	1.08
Winter 2019/2020	0.06	0.65	0.23	1.02
Summer 2020	0.49	0.95	0.17	1.08
Year 2019	0.27	0.84	0.18	1.06
Year 2020	0.32	0.83	0.19	1.06

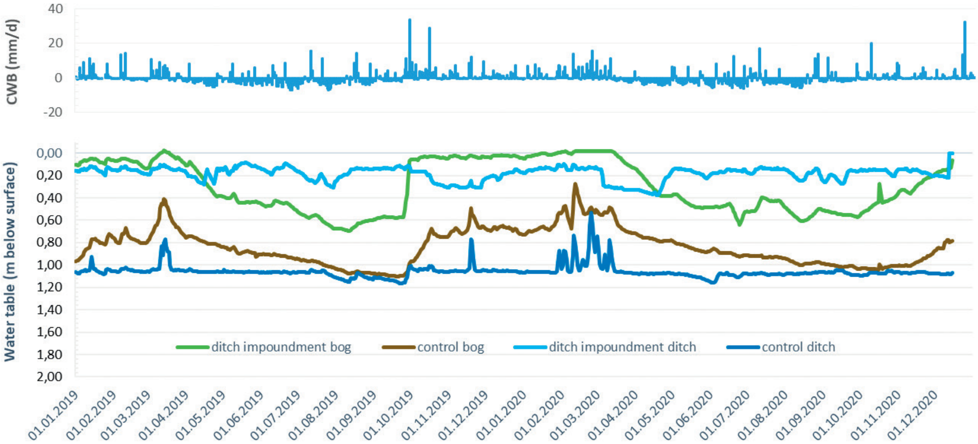

Fig. 6: Daily climatic water balance - CWB (triangulation of Ovelgönne, Bremerhaven and Friesoythe-Altenoythe weather stations, DWD), ditch and bog water tables at ditch impoundment and control plot IM (Ipweger Moor). Bog water table as mean value of bog water table monitoring wells (n=5).
Tägliche klimatische Wasserbilanz – KWB (Triangulation der Wetterstationen Ovelgönne, Bremerhaven und Friesoythe-Altenoythe, DWD), Graben- und Moorwasserstand am Standort mit Grabeneinstau sowie der Kontrollfläche im Ipweger Moor. Gemittelter Moorwasserspiegel (n=5).

Tab. 11: Mean ditch- and bog water tables on subsurface irrigation sites at Gnarrenburger Moor (Summer = May–October, Winter = November–April). Ditch: n=1; Bog: n=1.
Mittlere Graben- und Moorwasserstände auf dem Standort mit Unterflurbewässerung im Gnarrenburger Moor (Sommer = Mai–Oktober, Winter = November–April). Graben: n=1; Moor: n=1.

Period	**Water table (m below surface)**			
	Subsurface irrigation	**Control**	**Subsurface irrigation**	**Control**
	bog	**bog**	**ditch**	**ditch**
Winter 2018/2019	0.12	0.35	0.21	0.75
Summer 2019	0.34	0.63	0.18	0.72
Winter 2019/2020	0.05	0.24	0.35	0.84
Summer 2020	0.41	0.86	0.15	0.81
Year 2019	0.20	0.41	0.21	0.73
Year 2020	0.23	0.61	0.21	0.83

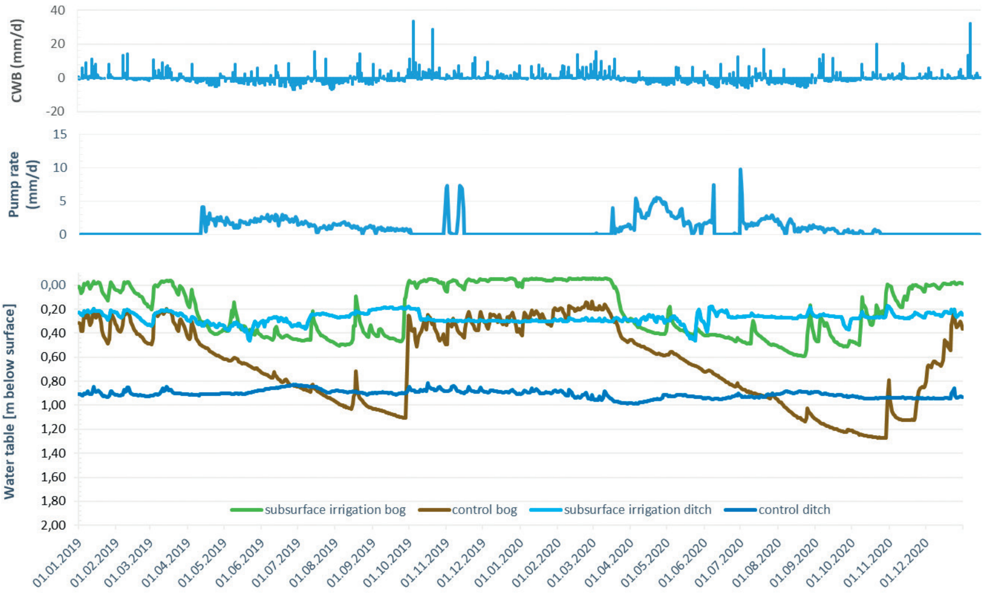

Fig. 7: Daily climatic water balance (Bremervörde weather station, DWD) and ditch and bog water tables at subsurface irrigation and control plot Gnarrenburger Moor.
Tägliche klimatische Wasserbilanz (Wetterstation Bremervörde, DWD) und Graben- und Moorwasserstände auf der Unterflurbewässerungs- und Kontrollfläche im Gnarrenburger Moor.

In Ipweger Moor, the subsurface irrigation showed, also in dry periods, mean bog water tables of 0.3 to 0.35 m below surface reached in the summer, while the ditch impoundment only reached water tables between 0.5 to 0.7 m below surface. In comparison to the control plot and the ditch impoundment, which showed a wide variety in fluctuations due to weather impact, the subsurface irrigation plot showed a higher and more constant water table. The water-regulating effect of this method became clear in winter months, where there was a drainage function in comparison to the ditch impoundment (Table 12 and Figure 7).

Although subsurface irrigation consists of closely installed pipes, bog water tables rise quickly after rainfall event in summer. Nevertheless, a few days after rainfall the bog water table falled back to the equilibrium value. This shows that the system is suitable to change the bog water within a couple of days, if lower or higher mean water tables are desired. For raising the water table, water supply is necessary if rain is scarce.

Tab. 12: Mean ditch and bog water tables (m below surface) on control and subsurface irrigation sites at Ipweger Moor (Summer = May–October, Winter = November–April).
Mittlerer Graben- und Moorwasserstand (m unter der Oberfläche) auf Kontroll- und Unterflurbewässerungsflächen im Ipweger Moor (Sommer = Mai–Oktober, Winter = November–April).

Period	Water table (m below surface)			
	Subsurface irrigation	**Control**	**Subsurface irrigation**	**Control**
	bog	**bog**	**ditch**	**ditch**
Winter 2018/2019	0.22	0.87	0.25	1.05
Summer 2019	0.32	0.95	0.19	1.08
Winter 2019/2020	0.17	0.65	0.30	1.02
Summer 2020	0.41	0.95	0.16	1.08
Year 2019	0.25	0.84	0.22	1.06
Year 2020	0.30	0.83	0.20	1.06

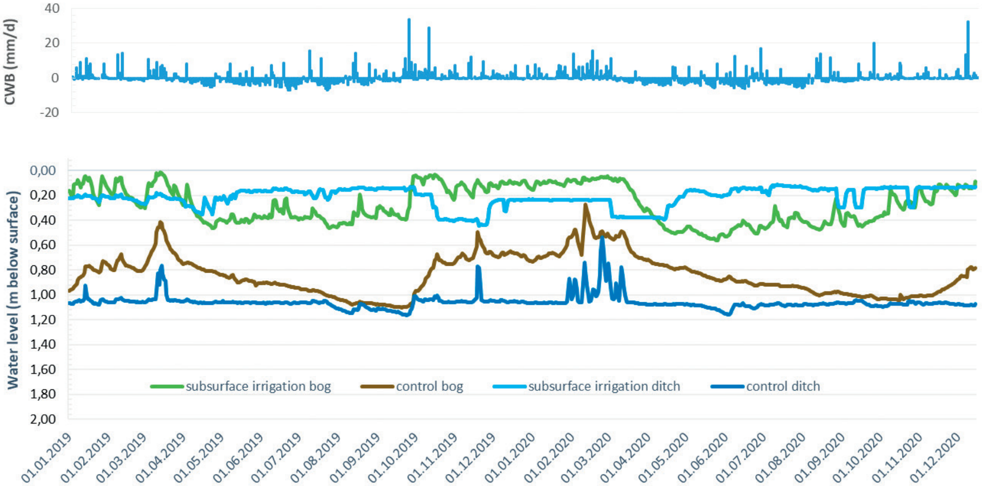

Fig. 8: Daily climatic water balance - CWB (triangulation of Ovelgönne, Bremerhaven and Friesoythe-Altenoythe weather stations, DWD), ditch and bog water tables at subsurface irrigation and control site IM Ipweger Moor. Bog water table as mean value of 5 groundwater table monitoring wells.
Tagesklimatische Wasserbilanz - KWB (Triangulation der Wetterstationen Ovelgönne, Bremerhaven und Friesoythe-Altenoythe, DWD), Graben- und Moorwasserstände auf der Unterflurbewässerungs- und Kontrollfläche im Ipweger Moor. Moorwasserstand als Mittelwert von 5 Pegelmessstellen.

3.4 Subsidence of peatland surface

From January 2017 to September 2020, the elevation at the blocked ditch plot decreased between 0.1 and 0.18 m. The peat at the control treatment subsided in the same range, between 0.19 and 0.10 m (Table 13). The elevation on plot D-07 with subsurface irrigation decreased on average from January 2017 to September 2020 as follows: D-07 subsurface irrigation site 0.08 m and control site 0.21 m. On the plot with subsurface irrigation, slight changes in elevation were recorded near the ditch, while on the control site the elevation decreases significantly during 2016–2020 (Table 13).
The ditch impoundment plot in the Ipweger Moor showed a mean height loss of 0.04 m. Eighty % of the values lay between an elevation gain of 0.01 m to a loss of 0.9 m.
The active water management of the subsurface irrigation with year-round high water tables across the entire area reduced the mean elevation loss to 0.02 m. More subsidence was observed in the eastern area at the end of the subsurface pipes, where losses of almost 0.10 m were measured. The greatest changes took place at the edge of the ditch, but central areas showed no elevation change. The control plot in the Ipweger Moor had a mean elevation loss of 0.12 m within the measurement period, with 80 % of the values lying between 0.09 and 0.16 m. Losses of elevation occurred evenly over the entire

control area. As 2018 was an extremely dry year, the terrain in the control plot subsided significantly and over the winter month, a “swelling” of the peat due to the rising water tables of the bog peat was measured. The ground elevation of the ditch impoundment and subsurface irrigation treatments remained almost stable.

Tab. 13: Height change, mean, 10- and 90-percentiles from September 2016 to September 2020 (in m). Positive values show height increase, negative height decrease. N: north, S: south.
Höhenänderung, Mittelwert, 10. und 90. Perzentil von September 2016 bis September 2020 (in m). Positive Werte zeigen eine Höhenzunahme, negative eine Höhenabnahme. N: Norden, S: Süden.

Plot	**Treatment**	**Change of height (m)**			
		Mean	**10th-Percentile**	**90th-Percentile**	**n**
D-06	Blocked ditch Level 1_N	-0.12	-0.09	-0.18	35
D-06	Blocked ditch Level 1_S	-0.17	-0.10	-0.27	35
D-06	Blocked ditch Level 2_N	-0.10	-0.06	-0.13	35
D-06	Blocked ditch Level 2_S	-0.18	-0.10	-0.26	35
D-06	Control_N	-0.19	-0.10	-0.30	30
D-06	Control_S	-0.10	-0.07	-0.13	30
D-07	Subsurface Irrigation	-0.08	-0.03	-0.12	28
D-07	Control	-0.21	-0.15	-0.27	28
IM	Ditch impoundment	-0.04	0.01	-0.09	46
IM	Subsurface Irrigation	-0.02	0.01	-0.06	41
IM	Control	-0.12	-0.09	-0.16	48

3.5 Resistance to penetration

Results show a correlation between dry conditions and a high penetration resistance at the Ipweger Moor sites. The curve runs parabolic with higher values in the dry summer months and lower values in spring and autumn, when water tables are closer to surface. In the drained control area, values of up to 1 MPa were measured in the upper horizon and 0.8 MPa at 0.21-0.35 m depth (Figure 9).

The resistance to penetration of 0.5 MPa is considered as the lower limit of trafficability (Schmidt 1995). Below this value, trafficability is limited, meaning that 0.10 m deep tracks will be expected.

As all water treatments in the Ipweger Moor showed low resistances to penetration with values below 0.5 Mpa when the bog water tables were high in spring, trafficability was not ensured during this period. Deep tracks remained after management events and far-

mers reported a feeling of “swimming” in the wet peat. Due to the high water saturation of the peat, the subsurface irrigation generally showed the lowest resistance values of below 0.5 MPa in the upper horizon. As the conditions in 2017 were extremely wet, all treatments showed low values in autumn. High values around 0.8 MPa were measured in August/September during the extremely dry conditions of 2018. In 2019 and 2020, the resistance to penetration remained below 0.5 MPa in the wet treatments. However, considering all treatments, the resistances to penetration fell rarely below 0.3 to 0.4 MPa, with the upper horison exhibiting lower resistances than the deeper peat (Figure 10).
The use of the penetrologger just gives a mechanical characteristic of the soil load-bearing capacity. The measured values of penetration resistance are affected, in addition to soil moisture, by the stability of the peat, the density of the roots, the peat structure and the proportion of fibers or mineral components in the peat. Nevertheless, other factors

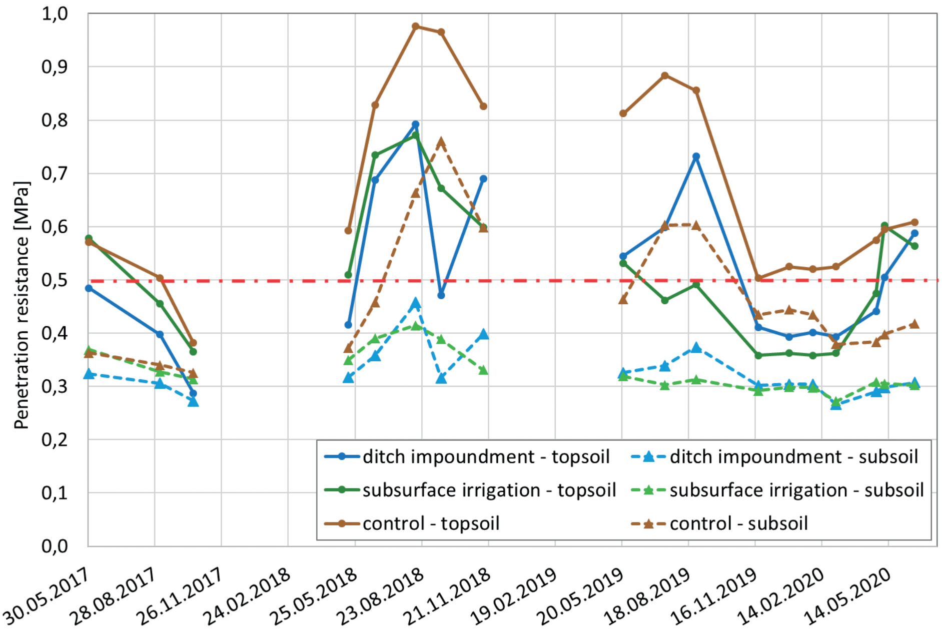

Fig. 9: Time course of the mean penetration resistance in topsoil (hHv, H 10, depth 0.05-0.20 m, continuous lines) and subsoil (hHw1, H 4, depth 0.21-0.35 m, dotted lines) on the control, ditch impoundment and subsurface irrigation treatments at the Ipweger Moor experimental field. Red line indicates the lower limit of trafficability. Bog water tables in figure 8.
Zeitlicher Verlauf des mittleren Eindringwiderstandes im Oberboden (hHv, H 10, Tiefe 0.05-0.20 m, durchgezogene Linien) und Unterboden (hHw1, H 4, Tiefe 0.21-0.35 m, gestrichelte Linien) auf den Versuchsflächen Grabeneinstau, Kontrolle Grabeneinstau, Unterflurbewässerung und Kontrolle Unterflurbewässerung im Ipweger Moor. Die rote Linie zeigt die untere Grenze der Befahrbarkeit an. Moorwasserstände in Abbildung 8.

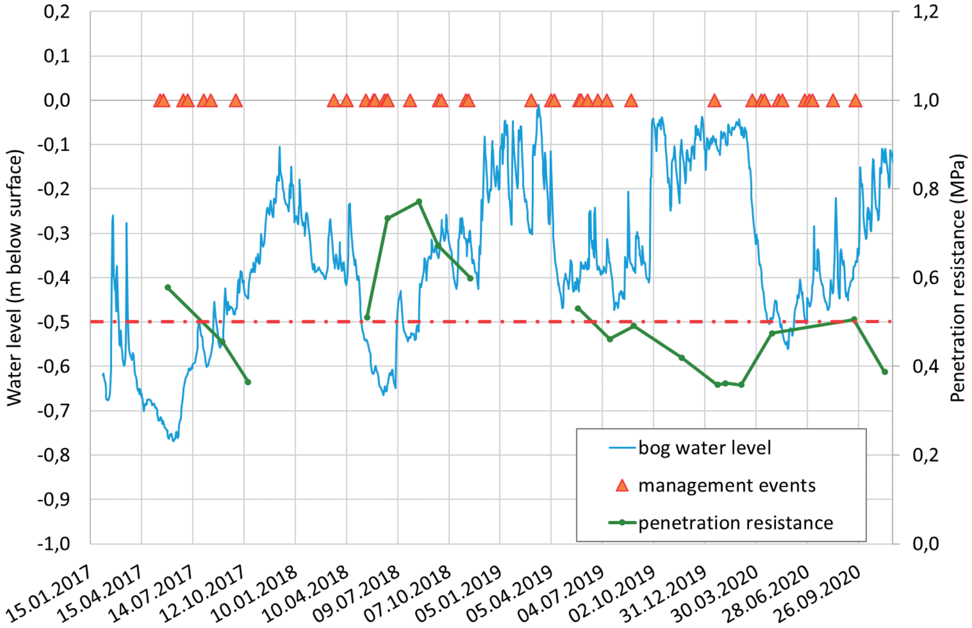

Fig. 10: Time course of the mean penetration resistance in topsoil (hHv, H 10, depth 0.5-0.20 m, right ordinate axis), bog water table below mean soil surface (left ordinate axis) and date of management events (e.g. fertilization, harvest) at the subsurface irrigation treatment (Ipweger Moor). Red line indicates the lower limit of trafficability.
Zeitlicher Verlauf des mittleren Eindringwiderstandes im Oberboden (Tiefe 0.05-0.20 m, rechte Koordinatenachse), des Moorwasserspiegels unter der mittleren Bodenoberfläche (linke Koordinatenachse) und Datum der Bewirtschaftungsereignisse (z.B. Düngung, Ernte) bei der Unterflurbewässerung im Ipweger Moor. Die rote Linie zeigt die untere Grenze der Befahrbarkeit an.

such as the weight of the machines or dimension and pressure of tyres are important for the trafficability as well. As can be seen in figure 9, management events, i.a. fertilization, mowing and harvesting, were possible and took place at dates, where the penetration resistance were below 0.5 MPa.

4. Discussion

Scientific studies on the effects of the water management measures blocked ditches and ditch impoundment in bogs are nonexistent. Only the effects of subsurface irrigation on bog water levels (e.g. Boonmann et al. 2021 & Weideveld et al. 2019), subsidence (e.g. Querner et al. 2012 & Querner et al. 2008), greenhouse gas emissions (e.g. van den Berg et al. 2021 & Deru et al. 2014), and trafficability (van den Akker et al. 2012) have been examined in some recent studies.

4.1 Blocked ditch

For this method, the ditches were blocked, but additional water was not pumped into the drain ditches. In the bog regions blocked ditch plots efficiently retained water during the winter months. Nevertheless, during the summer months the retained ditch water and the summer rainfall events were not sufficient to maintain high ditch water levels on the sites due to high evapotranspiration. It is not known if this phenomenon only occurs in dry years, when there is a negative water balance, i.e. precipitation is lower than potential evapotranspiration during the vegetation period. Nevertheless, even during the summer 2020 with an almost neutral climatic water balance of -18 mm the water table in the ditches was not maintained at the desired level.

For this treatment, ditch water levels as high as 0.20 m below ground surface were established during the winter. Maintaining ditch water level was limited because the ditches cannot be blocked above the upper edges of the embankments at the deepest section of the ditch. Thus, uneven terrain reduces the maximum water table that can be set.

Ditches may serve as a water reservoir and be used for water supply to peatlands during the vegetation period. Nevertheless, if the water demand for rewetting measures amounts to 1000 to 3000 m^3 per hectare, the ditch volume per hectare is not sufficient for this purpose. Assuming a ditch distance of 100 m, a ditch bottom width of 1 m, a slope area width of 3 m and a ditch depth of 1.5 m, he ditch volume is calculated to be 300 m^3 per hectare and thus much smaller than the required volume.

Moreover, blocked ditch plots were not effective in raising the bog water table compared to the control treatment. As was shown, the hydraulic conductivity of the bog peat was low and the water flow from the ditch into the peat was not sufficient to balance the evapotranspiration during the vegetation period. Consequently, peatland subsidence was not reduced by blocked ditch plots compared to the control, as shown by the ground elevation monitoring over a period of 3.5 years.

4.2 Ditch impoundment

Ditch impoundment further increases the water table within a plot by pumping water into the ditches. By ditch impoundment, the ditch water and bog water tables were considerably higher, especially during the vegetation period. The annual mean bog water table was raised by more than 0.50 m in the ditch impoundment compared to the control. This clearly shows that water availability is an important factor in rewetting bog grasslands. Water supply is necessary as long as excess rainwater cannot be stored temporarily on the plot in holding basins during the winter months.

From the farmer's point of view, ditch impoundment may be too wet for early maintenance and fertilization in spring, and even in summer, trafficability can be restricted during some days after rainfall. Moreover, bog water tables vary at a small scale within the sites, depending on the distance to the ditch. In winter and during periods of positive climatic water balance, bog water tables are the higher the farer away from the ditch. In the summer months, the opposite effect was observed. Both effects lead to heterogeneous water conditions, affecting trafficablity and bearing capacity at the small scale. In addition, rainfall may increase heterogeneity in the short term. With increasing vegetation density of a plant stand during the year, the trafficability should improve, as the quality of the root density is decisive for the trafficability (Blankenburg 2015).

Even with an active water management, i.e. temporary lowering of the weirs to improve trafficablity, a strong water table gradient was still detected in winter and in periods of positive climatic water balance. In these periods, the bog water tables were higher compared to the ditch water level, which makes it difficult to set the bog water tables via the ditches. In addition, the raising of the ditch water level affects the bog water tables after several days to several weeks. This depends mainly on the site-specific water conductivity of the peat. Therefore, in general, adjusting the weir depending on the needs of the farmers should be avoided.

The plots with the ditch impoundment showed a clear reduction in peat subsidence over the four years of the study. However, elevation losses were particularly evident in the center of the areas examined. This relatively high small-scale variation in elevation changes underlines the above-discussed aspect of heterogeneous hydrological conditions within this treatment.

4.3 Subsurface irrigation

Subsurface irrigation further increases the water table by allowing water to flow into the plot via subsurface pipes, distributing water from the ditch into the grassland. The annual average bog water tables remained at 0.2 to 0.3 m below ground surface over at least 2 years with subsurface irrigation. During the vegetation period, the bog water table was substantially raised compared to the control treatment at both study areas. Similar results were also obtained in the studies of Boonmann et al. (2021), Weideveld et al. (2019) and van Akker et al. (2012). During this period, subsurface irrigation was more efficient in increasing the bog water table than the ditch impoundment in the Ipweger Moor. Although the mean water table was only about 0.1 m higher in the subsurface irrigation than in the ditch impoundment plot during the summer months, this difference could be a crucial advantage, as within this range of water tables CO_2-emissions are linearly reduced with raising water tables (Tiemeyer et al. 2020, van den Berg et al. 2021).

As the bog water table reacts with little delay to changes in ditch water levels, subsurface irrigation can be used during early spring management phases, when water tables could be temporarily lowered in order to improve trafficability. After management events (i.e. fertilizing), ditch water levels can be raised again , which will lead to an increase in the bog water table. The efficiency of submerged drains depends on the saturated hydraulic conductivity of the peat (*kf* should be higher than 10 cm/day). Furthermore, the climatic water balance is an important driver of the hydraulic head. The subsurface irrigation treatments showed pronounced hydrological gradients between ditch and bog water table, although the distance of max. 4 m between the drain pipes is low. During dry summer periods, bog water table between the pipes was up to 0.30 m below ditch water level. After rainfall, bog water table raised quickly and fell after several days. This leads to two conclusions: First, plots with low hydraulic conductivity are little suited for subsurface irrigation, as a denser pipe network have to be established, which increases the installation costs. Secondly, the reaction time of the plot to changes in hydrological conditions is slow. Thus, short term changes in water management, e.g. in order to temporarily improve trafficability, are less effective than at plots with higher hydraulic conductivity.

In order to achieve high bog water tables for subsurface irrigation, additional water of 3000 m^3/ha had to be pumped into the ditch per year. An implementation of subsurface irrigation on a larger scale would require huge amounts of additional water. At the Gnarrenburger Moor, groundwater was used. This has the advantage of being not too deep (5–10 m) below surface and being available throughout the year. Nevertheless, the use of groundwater is restricted, especially from below bog peat bodies with slow groundwater formation. Moreover, groundwater may contain nutrients (e.g. nitrate) and especially reduced iron, which may lead to iron clogging. At the Ipweger Moor, surface water was used from the nearby Ipweger Moor canal. This water contains nutrients, especially phosphorous and ammonium from the surrounding bog grassland. Moreover, particles and especially peat fibres may block pumps and pipes.

The cultivation of bog grassland with subsurface irrigation and water tables around 0.30 m below ground level is possible (Querner et al. 2012), however, trafficability and grazing are limited at times, especially in spring, autumn or during wet periods in summer.

Elevation losses strongly depend on mean summer water levels and amount of nutrients in the peat (Nieuwenhuis & Schokking, 1997). Due to high mean water levels throughout the year, subsurface irrigation reduced subsidence during this experiment as also was shown by studies from van Akker et al. (2012) and Querner et al. (2012). However, it is still unclear how permanent this effect will be. Raising the water table leads to a floating of the peat, as there is less weight above the water table and the peat horizons below the water table may be relieved. This effect comes to an end when the water table does not continue to rise. Even if further shrinkage may be stopped by the wet peat conditions, peat mineralization may still continue as long as the peat is not totally submerged by water or due to high nutrient contents from fertilization. This may lead to further land subsidence as a consequence of the oxidative processes of decomposition.

4.4 General considerations on the water regulation methods

Especially ditch impoundment and subsurface irrigation were suitable methods to significantly increase the bog water table in the experimental plots.

On a large scale, the adjustment of high ditch water and bog water tables is limited by the fact that the ditches cannot be blocked higher than the embankment edge. In the summer months, a difference between ditch and bog water levels of about 0.30 m was observed, even in the subsurface irrigation treatment. It can be concluded, that a bog water table higher than 0.30 m below surface cannot confidently be achieved by ditch based water regulation during summer. Therefore, temporary flooding may be a method to further raise the bog water table. An adequately constructed ditch, e.g. with small dams on one side, is necessary.

The subsurface irrigation is suited to maintain high water levels all year round. The ditch impoundment, on the other hand, is only suited to maintain high summer water levels nearby the ditch. However, low water levels in the summer months lead to subsidence in the peat (Querner et al. 2012). Loss of elevation occurs particularly in the centre of the study site as a result of low summer water levels.

Uneven terrain, which is often observed for bog grassland, is another challenge. It may limit the maximum water table in the ditches, increase the number of necessary weirs per area and lead to inhomogeneous conditions for peat conservation and trafficability. Levelling may be considered, but may cause other problems, e.g. burying of fertile topsoil or uncovering of unfertile subsoil.

5. Outlook

Our results indicate that ditch impoundment and subsurface irrigation substantially raised the bog water tables on bog grassland. Further research should investigate trafficability, greenhouse gas emissions, and viable large-scale options for providing additional water. As bog water tables are more uneven within plots and are more affected by weather, plots with ditch impoundment are more difficult to manage than plots with subsurface irrigation.

On areas with ditch impoundment and subsurface irrigation, trafficability based on soil and site properties was severely limited at times. However, the actual trafficability depends on further factors, which were not investigated in our study. Trafficability could be improved by reducing surface pressure using special machines, increasing the density of the root layer by planting suitable grass species and varieties, or covering the soil with sand. Moreover, the studied water management measures may be especially problematic for grazing cattle that may sink into the ground under bad weather conditions. While meadows are frequently mown under good weather conditions and over a few days, grazing may last for weeks, when rain could temporarily reduce the bearing capacity, especially in those peat soils, which are already wet due to the increase in water table.

Literature data shows a significant non-linear relationship between the annual mean water table and the annual CO_2-emissions (Tiemeyer et al. 2020). Based on this study the average annual bog water tables for subsurface irrigation and ditch impoundment were raised in a way that should have led to a significant reduction in CO_2 emissions of up to 50 %. Long-term measurements are needed to determine the effect of water management measures on CO_2 emissions.

The increased demand of additional water for ditch impoundment and subsurface irrigation methods requires a catchment-based water management. This approach must consider opportunities for effective water retention, techniques for water distribution and the site-specific suitability of the methods. For a larger area, the water demand of the described methods cannot be met by groundwater extraction alone. The creation of water retention basins or other approaches need to be explored further.

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