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A hydrological comparison of drained, pristine, and recently rewetted bogs. Early signs of improvement?

Eirik Walle
Natural Resource Management

Preface

This thesis completes the degree of Master of Science in nature management at the Norwegian University of Life Sciences (NMBU) at Ås. It is part of a collaboration with three other students: Ola Eian, Aase Johansen, and Hannah Utseth. I am very happy to have been part of this group, and I thank my companions for the interesting discussions and long but fun days of field work. I learned a lot from their work, which helped me place my own study in a larger context.

I owe my supervisors at NMBU, Jan Vermaat and Jonathan Colman, a great deal of gratitude. Their guidance, constructive comments and sound editorial suggestions helped me in producing a thesis of which I am proud. Their humor and curiosity lifted the spirit and made working on this project great fun. I am also indebted to Marte Fandrem at NTNU, whose expertise in this field and role as counsel was enlightening and guided me away from making bad mistakes in the writing process. I also wish to thank Pia Frostad at the Soil and Water Lab of MINA at NMBU for running chemical analyses in the lab for me. The data from those analyses form a crucial part of this thesis.

The financial support we received from the Norwegian Environment Agency (Miljødirektoratet) for the field work is gratefully acknowledged, and I wish to thank Pål Martin Eid at the Norwegian Nature Surveillance Service (Statens Naturoppsyn) for showing us mire restoration in action, and for his advice on site selection.

Lastly, I am ever grateful to my fiancé Heidi for her love and support. Writing this thesis cost a lot of our free time together, but she always cheered me on and even proofread several drafts of the paper. That called for some unparalleled patience, and I admire her for it.

Eirik Walle

Eirik Walle
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Abstract

Excavation of drainage ditches over centuries has caused widespread drying and degradation of mires in Norway. The Norwegian government therefore presented an action plan in 2016 for restoring mires by blocking these drainage ditches. The aim is to restore hydrological functioning by increasing water levels, effectively rewetting the mires and thereby halt further decomposition of the peat. This study compared seven triplets of pristine, drained, and recently rewetted (between 2015 and 2019) ombrotrophic bogs, to investigate whether changes in water table depths (WTD) and water chemistry could already be detected. I measured WTD in several hand-dug wells along linear transects. pH, concentration of dissolved organic carbon (DOC) and electrical conductivity (EC) were used as hydrochemical indicators of mire state and decomposition level. I analyzed the data using linear mixed effect models which control for similarities within transects and triplets. The results show that water tables were higher on rewetted bogs than on bogs that have remained drained. Water was also more evenly distributed in rewetted sites. pH was lower in degraded mires than in pristine ones, but I found no difference between the drained and rewetted bogs. DOC was lowest in pristine sites, and although drained and rewetted sites had similar levels overall, it did show a declining trend with time since rewetting. In addition, EC levels on rewetted sites were between those of pristine and drained bogs. Based on these findings, I conclude that the Norwegian restoration program appears to be successful in increasing water levels in rewetted bogs, with a possible early response in water chemistry, suggesting lowered rates of peat degradation.

Sammendrag

Utgraving av dreneringsgrøfter gjennom århundrer har ført til utstrakt uttørking og nedbryting av myrer i Norge. Norske myndigheter presenterte derfor en handlingsplan i 2016 for restaurering av myrområder gjennom oppdemming av disse dreneringsgrøftene. Målet er å gjenskape hydrologisk funksjon ved å øke vannivået i myrene og dermed bremse nedbrytingen av torva. Denne studien sammenlignet sju tripletter som hver bestod av en urørt, en drenert, og en nylig restaurert (mellom 2015 og 2019) nedbørsmyr, for å undersøke om det allerede er mulig å se endringer i vannspeilnivå og vannkjemi. Jeg målte avstand fra myroverflate til vannspeil i flere håndgravde brønner langs linjetransekter. pH, oppløst organisk karbon (DOC) og elektrisk ledningsevne (EC) ble brukt som vannkjemiske indikatorer på myrtilstand og nivå av nedbryting. Jeg analyserte dataene med lineære miksmodeller som tar høyde for likheter mellom målinger gjort langs samme transekt eller innenfor samme triplett. Resultatene viser at vannspeilet lå høyere i restaurerte myrer enn i de drenerte. Vannet var også jevnere fordelt på restaurerte myrer. pH var lavere i forstyrrede myrer enn i de urørte, men jeg fant ingen forskjell mellom drenerte og restaurerte myrer. DOC var lavest i urørte myrer, og selv om de restaurerte samlet sett hadde likt nivå som drenerte så fant jeg tegn til at DOC var lavere på myrene som var restaurert først enn på de nyere. I tillegg var EC-nivået på restaurerte myrer mellom urørte og drenerte. Basert på disse funnene konkluderer jeg med at det norske restaureringsprogrammet virker å ha lykkes i å øke vannivået i myrer som tidligere er blitt drenert. Dette har igjen ført til tidlige, men små endringer i vannkjemi, noe som kan bety redusert nedbryting av torv.

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1. INTRODUCTION

1.1 What are peatlands, and how are they formed?

In some places, the soil near the surface is perpetually saturated with water because of a balance of water loss and gain throughout the year. We call these areas wetlands. A mire is a form of wetland that we find in boreal regions (Wheeler & Proctor, 2000) – the northern parts of the world. Mires often provide favorable conditions for the development of peat mosses (*Sphagnum* spp.), which thrive in wet habitats (Andrus, 1986). Moss does not possess roots, and *Sphagnum* mosses rely on contact with the water table – the upper boundary of the water-saturated zone – to get enough moisture. *Sphagnum* species*,* in particular, can store large amounts of water, even in dead cells. When these plants grow, they release hydrogen ions into their environment, lowering the pH (Clymo, 1964). Each plant exists as a continuum of life and death, growing from its top and steadily dying from below (Clymo, 1970). In this way, they produce the very substrate on which they grow. The dead remains decompose very slowly. Over time, as more and more vegetation grows and dies, the decaying organic matter from the mosses and other plants gets compacted by the weight of the accumulating layers above it. The physical environment below in the dense waterlogged soil is not conducive to high rates of decomposition; pH is low due to the acidification by the mosses, and the oxygen content is low due to water saturation. This combination of low pH and low oxygen levels is tolerable only to a few microbes (Andersen et al., 2013). Because of this, the organic matter only partially decomposes, in a very slow process. The resulting matter is what we call peat: Accumulations of dead, very slowly decaying plant matter. Peat is not formed exclusively by *Sphagnum*, and not exclusively in mires. Other kinds of wetlands can also produce it, and collectively we refer to these peat producing areas as peatlands (Finlayson et al., 2018).

Mires come in different kinds based on their topographies, and the water in them has varying chemical properties depending on where it comes from (Moen, 1998). *Fens* are mires in which the water table is in contact with groundwater. This water source is usually high in minerals and nutrients, and thus can support diverse communities of plants. Such mires are also called minerotrophic, or rich mires (Lindsay, 2016). Poor mires, or *bogs*, get most or all their water and nutrient input from precipitation because the water table lies higher than the groundwater. Bogs depend on precipitation to remain waterlogged. Rain and snow are poorer in nutrients than groundwater, often supporting a less diverse, but more specialized plant community. Bogs are also called ombrotrophic mires, from the Greek "ombros", meaning rain.

In both fens and bogs, most of the water exchange with the world outside them happens in the upper layers – the acrotelm (Ingram, 1978). The acrotelm is a zone of active vegetation growth and decay, and it is less dense than deeper peat. Because of this, water moves through it more easily; it has higher hydrological conductivity. Here, water levels readily fluctuate – increasing with added precipitation on rainy days and decreasing on drier days. Water escapes this zone largely by evapotranspiration – the combination of evaporation and transpiration through plants – and by 'spilling over' into outlet streams. Below this zone, in what is called the catotelm, the soil is chronically saturated, forming a barrier through which no more water can enter.

1.2 Why do we care about peatlands?

Because peat accumulates slowly, peatlands grow slowly. About 1 mm of peat is added each year (Ohlson & Dahlberg, 1991; Aaby & Tauber, 1975). This means digging just 1 meter down in a mire can take you back 1000 years. With so much organic matter packed so tightly, peatlands are very rich in carbon. A square meter of peat in forested peatland contain up to 40 times more carbon than the trees growing above it (Magnan et al., 2020). Considering peatlands cover 24 % of all the forest area in the boreal zone (Wieder et al., 2006), their important role as carbon stores is apparent. While covering only 3 % of the land surface, boreal peatlands contain an estimated 30 % of the world's terrestrially bound carbon (Gorham, 1991).

Mires have been identified to play an important part in regulating waterflow in drainage basins (Bullock & Acreman, 2003; Holden, 2005). Peat can consist of up to 90 % water, retaining it in its pores (Boelter, 1964), and mires reach their water uptake limit quickly in periods of wet weather (Holden, 2005). Depending on topography, vegetation and the height of the water table, large amounts of rain and snowmelt can collect on a mire's surface. As water accumulates, it flows towards outlets, directed by gravity and topography (Holden et al., 2008). Its velocity depends on the amount of water and types of vegetation in its path. Surface flow can range from a millimeter per second to several centimeters (Holden et al., 2008). By the time water collected from a rainstorm reaches larger river systems, the flood peak may already have passed. Evapotranspiration also removes some of the water on its way across a mire, reducing the volume of the discharge. All of this, in turn, may affect the size and timing of flood events during spring and after heavy rainfall (Holden, 2005).

Peatlands are widespread in Fennoscandia and are considered to deliver several important ecosystem services (Finlayson & Milton, 2018; Magnussen et al., 2018). They also host specific and specialized communities of plants, animals, and other organisms (Littlewood et al., 2010). Their value, however, has only recently been appreciated, and changes in land-use have already driven the decline of peatland areas worldwide for centuries (van Asselen et al., 2013). Peatlands have been destroyed to make room for infrastructure and urban development (Grzybowski & Glińska-Lewczuk, 2020); excavated to extract peat (Gerding et al., 2015), which is used for combustion fuel and horticulture; and, most commonly, drained. The goal of draining peatlands is to change the properties of the soil, creating conditions more favorable to pasture, food- and forest crops (Laine et al., 2006).

1.3 What happens when you drain a mire?

When you dig a ditch in a mire, and connect this ditch to existing waterways, runoff increases (Boelter, 1972). This changes the balance of input and output, and the water table starts to drop. If it drops below the level of waterlogged peat in the catotelm, atmospheric oxygen can seep into the tiny pores and cavities. Exposure to oxygen changes the metabolic activity of microbes (Freeman et al., 1996) and increases the decomposition rate (MacDonald et al., 2018). When organic compounds are metabolized, they are split into progressively smaller molecules, largely ending up as H_2O and CO_2 (Bridgham & Lamberti, 2009). This is termed mineralization. Differently sized molecules of organic particles rich in carbon can dissolve in the mire water (Laine et al., 2014). This dissolved organic carbon (DOC) may then be "flushed out" as water is discharged into larger aquatic systems, reducing the carbon content of the mire. Production of DOC is part of the natural process of decay in healthy mires. However, increased decomposition means increased production of DOC. The loss of carbon through DOC is thus greater after draining, owing to the combination of increased production and export. Further decomposition produces and releases acidifying compounds as well, including CO_2, which lower the pH when they dissolve in the mire water, by increasing the amount of available hydrogen ions (De Vries & Breeuwsma, 1987; Laiho, 2006). But the processes governing pH in degraded peat are complex, and site specific conditions like nutrient availability and vegetation can yield varying outcomes (Holden et al., 2004). The effects of increased decomposition can also be detected as an increase in electrical conductivity (EC), due to higher ion loads from mineralization of organic materials (Asadi & Huat, 2009; Howson et al., 2021; Walter et al., 2019).

Over time, as peat dries and decomposes, its structure weakens and the small pores that no longer have the same water tension to support them collapse (Laine et al., 2006). After a mire has been ditched and drained, it can sink by up to 8 mm per year for the subsequent 50 years (Hoogland et al., 2012), a phenomenon termed subsidence. The denser, drier and more decomposed peat has lower hydraulic conductivity, meaning water does not flow through it as easily as in "healthy" peat (Price et al., 2003). Because of this, more precipitation collects on or close to the surface and diffuses very slowly into dry compact peat (Baird, 1997). This reduced capacity to absorb and retain water leads to increased downstream runoff.

The sum of all the changes to the water balance and water chemistry has consequences for the ecosystem of the mire: As the soil dries, the peat forming mosses are outcompeted by more drought-tolerant plants, usually shrubs and herbaceous plants, changing the botanical profile (Laine et al., 1995). Over time, surrounding forest may encroach on the mire, decreasing its surface area. Trees are favored by the more aerated soils that drained mires provide. They also take up large amounts of water through their root systems, thereby exacerbating the drying effect of draining (Laine et al., 2006). Alteration of the landscape affects the species composition of insects, and birds. Indeed, these changes impact the entire ecosystem.

A drained mire has a lower water retention capacity and releases more carbon than an undrained, "pristine" mire. Whereas pristine peatlands are weak carbon sinks – slowly taking up more carbon from the atmosphere than they release – degraded peatlands are sources of it (Joosten et al., 2016). When many drained mires add up to large areas of degraded peatland, the consequences reach farther than the boundaries of any single mire. Globally, degraded peatlands add 2 gigatons of CO_2 to the atmosphere each year (Joosten et al., 2016), twice the amount released from all commercial air travel in 2019 (Graver et al., 2020).

1.4 The plan to restore drained mires in Norway

In Norway, almost 9 % of total land area has been estimated to be peatland (Bryn et al., 2018). That is over 28,000 km^2, or an area roughly the size of Albania. This estimate has considerable uncertainty, though, but a full discussion of this is beyond the scope of this thesis. Draining mires for forestry and agriculture has been practiced in Norway for centuries (Moen et al., 2017), with many mires drained by the excavation of ditch networks in the 1950's and 60's. One important goal of this was to increase economically productive forest area. Recently, peatland restoration has gained attention as a low-cost means of mitigating current and reducing future greenhouse gas (GHG) emissions (Leifeld & Menichetti, 2018). In 2016, the Norwegian government, through its environmental and agricultural agencies, presented an action plan to restore disturbed mires (The Norwegian Environment Agency, 2016). The main restoration strategy is blocking ditches and cutting trees on degraded mires, following methods developed elsewhere in Northern Europe (Craft, 2016). These methods are outlined in Quinty and Rochefort (2003).

The Norwegian government stated three general goals for its restoration program (The Norwegian Environment Agency, 2016, p. 7):

- A reduction in GHG emissions
- Adaptation to increased flooding and fires due to climate change
- An improved ecological condition

The aim is to achieve these goals by halting and reversing the processes that followed draining of mires. They updated the action plan in 2021 (The Norwegian Environment Agency, 2021), but the goals remained the same. The overarching goal of restoring a mire is therefore to recreate the hydrological conditions from before it was disturbed. Reversing peatland drainage, logically, involves filling the areas up with water again, meaning raising the water table. Because of this, the process is also called *rewetting*. This entails slowing down the runoff and reducing evapotranspiration (Kløve et al., 2015) – the two main modes by which water escapes a mire (Finlayson & Milton, 2018). In order to slow down runoff, plugs are installed in the ditches, trapping incoming water and allowing for it to be absorbed into the surrounding peat soil (Quinty & Rochefort, 2003). The plugs are usually made out of peat from the immediate surroundings (Rova & Paulsson, 2015). Evapotranspiration is reduced by cutting and clearing the forest that has encroached on the mire, using old aerial photographs to determine the historical extent of the mire surface.

Several studies and reports have evaluated the effect of peatland restoration in different countries (e.g. González & Rochefort, 2019; Hedberg et al., 2012; Menberu et al., 2018; Ronkanen et al., 2015). However, little knowledge exists on whether rewetting so far has been successful in changing hydrological conditions on drained peatlands in Norway. The aim of this study is to investigate whether changes in hydrological and biophysical parameters can already be detected, a couple of years after rewetting, and to use this to evaluate the preliminary outcome of the governmental peatland restoration program.

1.5 Study design and hypotheses

A common way of studying the effects of rewetting is to collect data on a site before and after the ditches have been blocked. This data can then be compared with non-rewetted mires in the same area. This is termed a before-after control-impact study design (BACI; Smith, 2002). However, except for a pilot study (Kyrkjeeide et al., 2018), data on the conditions of drained mires in Norway *before* rewetting are lacking. My study therefore investigated effects of rewetting by surveying rewetted and non-rewetted mires in parallel, using the non-rewetted mires as proxies for the condition before rewetting.

Pristine mires – mires that have not been drained, were similarly added to the study as proxies for the conditions before draining. As the goal of the restoration program is to revert mires to prior conditions, the pristine mires represent the desired condition. Each survey location in this study hence consisted of a triplet of a pristine, a drained, and a rewetted mire. Several locations were surveyed, to improve the study's statistical strength. In the surveys, I collected data on four parameters: Water table depth (WTD), acidity (pH), water carbon content (dissolved organic carbon; DOC), and electrical conductivity (EC).

Haapalehto et al. (2011) investigated what happens to the water table after plugging ditches in Finnish mires and found that the water level had increased quickly over the first five years, and then more slowly before stabilizing. In a larger study of 46 mires across Finland, Ronkanen et al. (2015) also found plugging ditches to be effective in raising the water table. As the same techniques have been applied in the Norwegian mire restoration project, the same pattern should emerge. In comparing rewetted, drained, and pristine mires, I therefore expected rewetted and pristine mires to have similar WTD, which should be higher than those in drained ones (hypothesis 1; H1). If rewetting has worked according to plan, ditch blocking leads water into the peat flanking the ditch (The Norwegian Environment Agency, 2016). As a consequence, the water table should not only be higher overall after rewetting, but it should be more evenly distributed. My second hypothesis was therefore that pristine and rewetted mires have similar WTD profiles, which are more evenly distributed than in drained mires (H2).

Mitigating GHG emissions is also an important goal, which involves reducing CO_2 efflux from respiration, e.g. by slowing down decomposition rates. Ronkanen et al. (2015) found levels of dissolved organic carbon (DOC) to decrease after rewetting, indicating a change in microbial metabolism, and that the chemistry is affected when water is arrested on the mire. The relationship between DOC and water level has also been demonstrated by Strack et al. (2015), showing that DOC were lower in restored sites when the measurement site was waterlogged. I expected to find the same in this study – that DOC levels on rewetted mires would be lower than the drained ones, and similar to concentrations on pristine mires (H3).

Draining mires reduces the abundance of *Sphagnum* (Punttila et al., 2016). Less *Sphagnum* means less acidification, which leads to the possibility that the pH increases over time. However, aerobic decomposition following water table draw-down increases acidity in the soil to a larger degree (Laiho, 2006). Just as reduced decomposition following rewetting can lower DOC, I hypothesize that it increases pH to levels of pristine mires (H4). The release of ions from decomposition will also lead to an increase in electrical conductivity (EC; Walter et al., 2019), so if rewetting is successful in reducing the rates of decomposition, then this should be detectable as reductions in EC. Comparing drained, rewetted, and pristine mires, EC should then be similar on the rewetted and pristine mires, with both having lower levels than the drained mires (H5). The hypotheses are summarized in table 1.

Table 1. Summary of hypotheses about the relationship between drained, pristine, and recently rewetted mires.

Hypothesis #	Parameter	Hypothesis
1	Water table depth (WTD)	Rewetted and pristine mires have similar WTD, and shallower than drained mires.
2	Water table profile	Rewetted and pristine bogs have similar water table profiles, and more evenly distributed than drained mires.
3	Water carbon content (DOC)	DOC levels on rewetted bogs are lower than on the drained, and similar to concentrations on pristine mires
4	pH	pH on rewetted bogs is similar to pristine mires, and higher than on drained ones.
5	Electrical conductivity (EC)	EC is similar on the rewetted and pristine mires, with both having lower levels than the drained.

2. Materials and methods

This study was carried out in parallel with three other master thesis studies, on vegetation (Ola Eian and Aase Johansen) and insects (Hanna Utseth). Together, we selected only ombrotrophic bogs as the focus of study. An evaluation of mire richness for restored sites was supplied by Pål Martin Eid in the Norwegian Nature Surveillance Service (Norw.: Statens Naturoppsyn, SNO) which coordinates the restoration efforts. We also carried out a preliminary evaluation of mire richness based on topographic maps. Because ombrotrophic bogs get most or all their input from precipitation, they are not likely to be found in deep depressions in the terrain where water will flow in from the surrounding area. Nor will they have large or many streams flowing into them. These evaluations were supplied with an assessment of the vegetation in the field, as poor and rich mires differ in their vegetation structures (Moen, 1998).

2.1 Survey location selection

From a list of completed restoration projects (SNO, unpubl. data), only bogs within a reasonable travelling time from the campus of the Norwegian University of Life Sciences (NMBU) were selected. Every survey location was a triplet of a drained, a rewetted, and a pristine site. Sites in each triplet were chosen to be as close to each other as possible, to minimize differences in small-scale climatic and hydrological parameters between them, and to increase the probability of managing to survey all sites within one location in the same day. Some bogs were drained on only part of their areas, so that different parts of one bog could represent different conditions. Such bogs were preferred in site selection. For bogs with both pristine and disturbed or rewetted states, a distance of at least 50 meters was kept between the sites. This fits with Boelter (1972) who found that the water draw-down effect of one drainage ditch did not reach farther than 50 meters.

Digital terrain models from LIDAR scans accessed through the map portal hoydedata.no (The Norwegian Mapping Authority) were used to identify pristine and drained sites. Ditches are often readily visible as straight lines in the terrain. They typically show on drained mires, and not on pristine ones (figure 1).

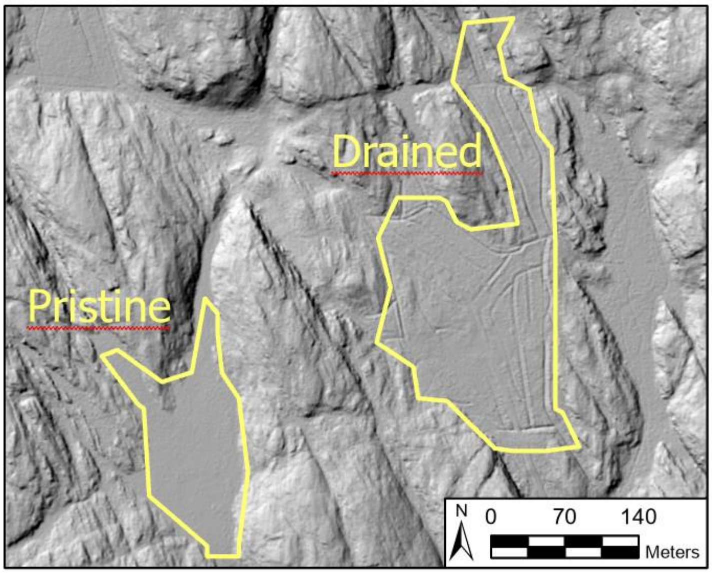

Figure 1. Digital terrain models (DTM) showing a pristine (Stormyr, to the left) and drained (Starrmåsan, to the right) bog (outlined in yellow) A flat and smooth surface indicates a pristine site, while ditches are visible as a network of straight furrows. Central point coordinates: 59.820779N 10.930625E. DTM map from the Norwegian Mapping Authority (Norw.: Kartverket). Mire (bog) areas extracted from the map service AR50 (NIBIO). Map made with QGIS version 3.14.

2.2 Site description

Due to time constraints, only 7 locations were surveyed for this study (listed in table A1 in the appendix). All 7 locations are in southeastern Norway, in the counties Viken, and Vestfold and Telemark (figure 2), in the boreonemoral and southern boreal vegetation zones. They have a continental climate, with annual rainfall ranging from 750 mm to 2000 mm (The Norwegian Water Resources and Energy Directorate). Four of the bogs covered two different conditions – three had both rewetted and pristine areas, while one had a drained and a pristine area. There was no information on when ditches in the disturbed sites were excavated, but historical aerial photographs indicate that all were older than 50 years. The rewetted mires were restored between 2015 and 2019. All bogs had undergone similar restoration efforts, with one plug placed per estimated 20 cm drop in height along selected ditches (Pål Martin Eid, pers. comm., meeting 15.04.2020).

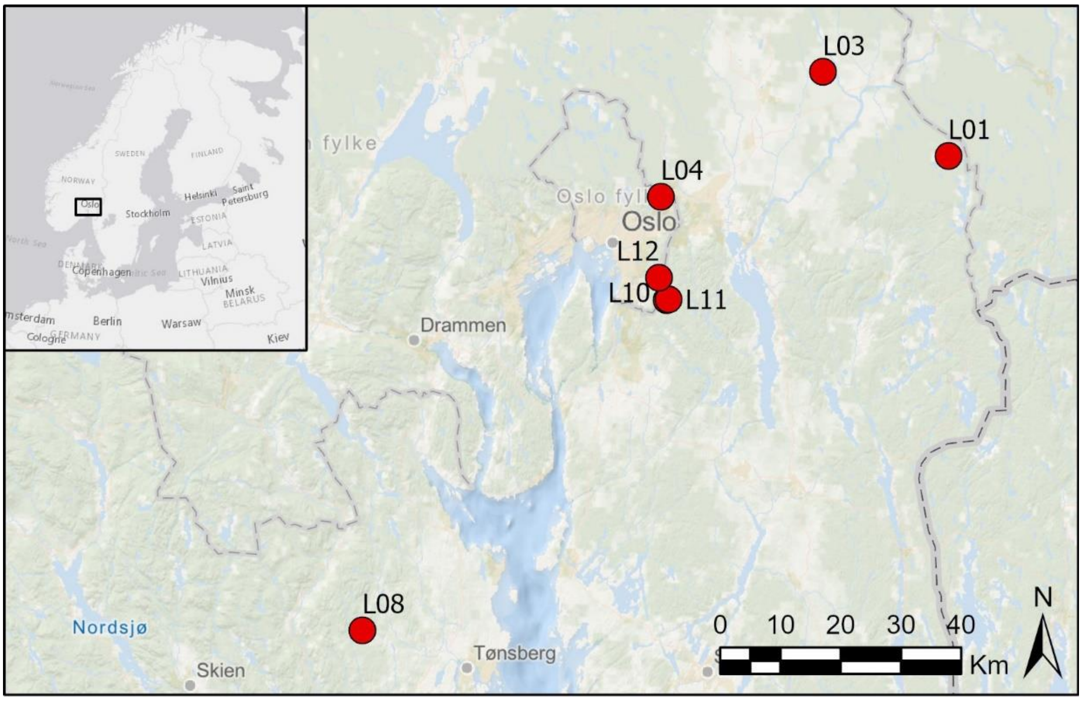

Figure 2. Map of the 7 survey locations (dots). Only six dots are visible, as L10 and L11 were very close together. All sites are in southeastern Norway. Location tags refer to location IDs used in the survey (see table A1 in the appendix). Background map: Esri ocean. Map created in QGIS 3.14.

Field work was carried out during daylight hours between the 2nd of June 2020 and the 3rd of September 2020. I visited all the sites twice to capture some of the temporal variations that could occur.

2.3 Water table depth

I measured water table depths (WTD) at several points along linear transects, ranging from 30 to 50 m in length (figure 3). One to three transects were placed at representative places on each bog. On drained and rewetted sites, transects were placed perpendicular to ditches. The measuring points were spaced 6-10 m apart, but I included more measuring points when necessary, to capture any intersecting ditches. At each measuring point, I dug a small well using sticks and my hands. Porewater was then allowed to flow into the well from the surrounding peat (figure 3). When the water level had stabilized, the distance from the ground surface to the water surface was measured using a folding ruler, providing a sample for what I defined as "specific WTD". If I did not hit water by a depth of 50 cm down in the soil, I stopped digging and set the WTD for that well to 50 cm, although it may have been deeper than this. I did this to save time, and to mitigate disturbance from excavating too deeply into the mire. I logged the GPS coordinates of start and end points of transects and marked these points in the field with sticks and strings, which made it easier to locate them during the second visit. The same transects were measured on both visits.

I then estimated water table levels relative to other points along the same transect. To achieve this, a rope was tied above the ground for the entire length of each transect. The rope was tied to trees, or sticks pushed into the mire at both ends of the transects and tightened (figure 3). By using a spirit level (length 80 cm), the rope was adjusted to become as horizontally level as possible. I then recorded the distance from the rope to the ground and the rope to the water surface. The water table depth relative to a fixed, horizontal plane above, was defined as the "relative WTD". The position of a ditch along each transect was registered so that I could calculate the distance to the nearest ditch for each well. I obtained and used the estimated position of ditches on each transect from my fellow students (Eian & Johansen, unpubl. data).

To evaluate how the water was distributed along the transects, I made an estimation of how varied the water table was along each of them with a sinuosity index. The index is normally applied in river research where it is used to estimate how much a river meander. A river's sinuosity is defined as the distance it flows between two points divided by the distance of a straight line between these points (Mueller, 1968). A perfectly straight river will have a horizontal sinuosity of 1. Similarly, a perfectly level water table, or indeed a still water surface, has a vertical sinuosity of 1. In statistics, a common measure of variation is variance – the sum of squared differences from the mean, divided by the number of measurements. However, variance does not consider the order of the measurements, as all the values are lumped together in the equation. Sinuosity is a crude estimation of variation, but it accounts for the directional order of the measurements. If the water table goes up and down a lot while expanding laterally out over an area, it has a high sinuosity. For the purposes of this study, I used the geometric (Euclidian) distance between the WTD for each well along each transect.

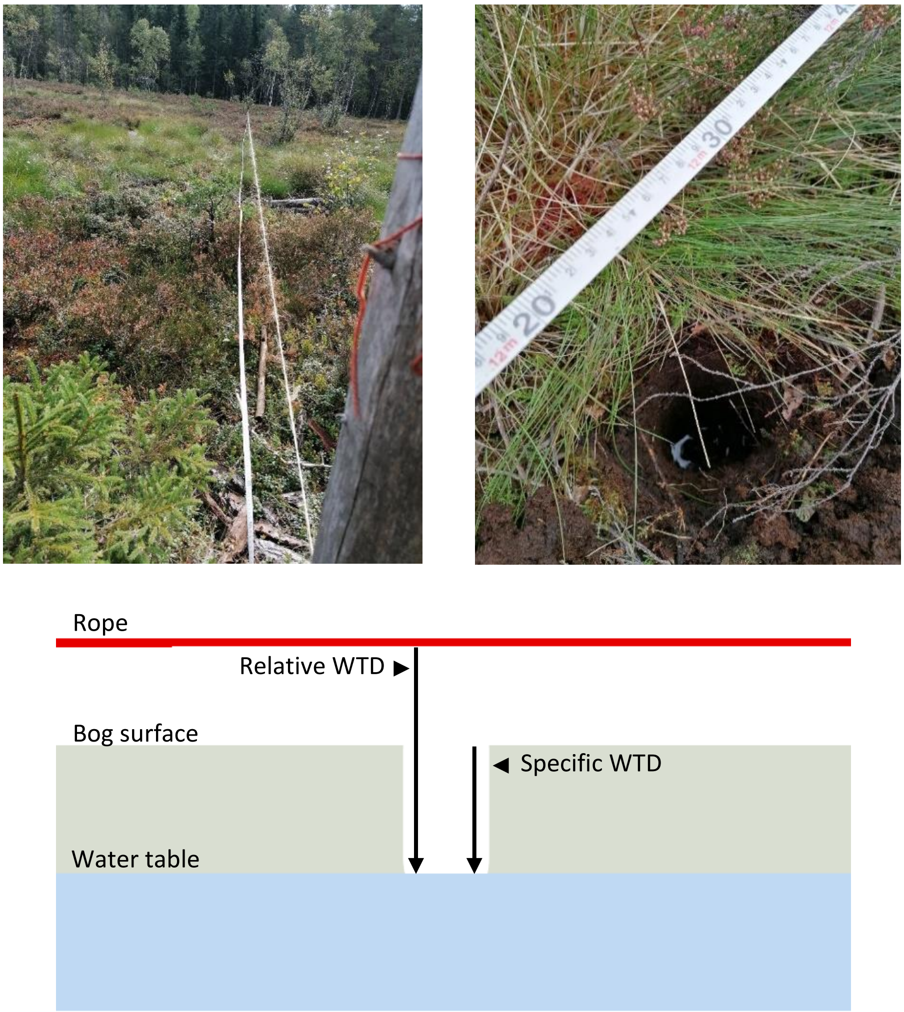

Figure 3. Above**:** Transect setup for the measurement of water table depths (WTD). Wells were dug by hand (right), and variation in the terrain was estimated using a level rope fixed over the length of the transect (left). Below: Schematic representation of WTD measurement.

2.4 Water chemistry

On each bog, I measured water chemistry at several different points to account for spatial variation. pH was measured *in situ* by collecting water in a small plastic container (approximately 1 L), and then submersing the measuring cell of a Metrohm 704 pH meter (Metrohm AG, 1997) in the collected water (figure 4). Electrical conductivity was measured similarly using a WTW LF 340 conductivity meter (WTW GmbH & Co., 2002) with a Tetracom 325 probe (WTW GmbH & co., 2002). I submersed the probe directly into the bog water and measured the conductivity in microsiemens per cm (µS/cm).

Unfortunately, due to faulty equipment, I was able to measure conductivity only on five of the seven locations, and only during the first visit.

I drew water samples for DOC content measurements from the same container of water in which pH was measured. The water was filtered through 5 mm syringe filters w/ 0.45 µm polyethersulfone membrane (VWR International) attached to 15 mL and 50 mL syringes. Samples were then deposited into 50 mL sample tubes (115x28mm; PP. Sarstedt AG & co, KG). A minimum of 10 mL was collected per sample. While in the field, water samples were kept out of the sun in order to minimize photodegradation of the organic compounds. Samples were refrigerated at the end of the field day and stored until analysis, which occurred within 1-3 weeks. GPS coordinates of measuring points were logged so that samples could be collected from approximately the same position on both visits.

Figure 4. Left: pH was measured by first collecting water in a container, and then submersing the measuring cell of a pH meter into the container. Right: Electrical conductivity (EC) was measured by submersing the measuring cell of conductivity meter directly in the bog water.

Carbon contents in the water samples were measured by a lab technician at NMBU on a TOC-V CPN (Shimadzu Corporation) with an ASI-V autosampler (Shimadzu Corporation). The process of measuring organic carbon content in water samples first involves removing dissolved *in*organic carbon. This is achieved by adding a strong acid which leads to the oxidization and release of inorganic carbon as CO_2 (Sugimura & Suzuki, 1988). The remaining sample is then transmitted to a furnace, exposing it to temperatures above 600 °C (Shimadzu Corporation, 2003). This ignites the organic carbon, which oxidizes and releases it as CO_2. The amount of CO_2 released is measured and gives an estimation of the organic carbon content of the sample. The machine's output is DOC concentrations in milligrams per liter (mg/L).

2.5 Statistical analyses

The data were managed with Microsoft Excel (Microsoft Corporation, 2021) and exported to R (R Core Team, 2021) for statistical analyses. I sorted the data by sites and locations (3 sites/treatments per location). WTD data were further grouped into transects. I performed linear regression analyses, although in order to account for grouping effects of data clustered on transects and mires, nested within locations, linear mixed effects models were used. Mixed effects models estimate the variance of the response variable for each grouping factor. Assuming that the data within each group are samples from a normal distribution, the algorithm adds an error term to each value of the response variable. To create such models in R, I used the R package "lme4" (Bates et al., 2015) with "lmerTest" (Kuznetsova et al., 2017). "lmerTest" calculates test statistics and p-values for model predictors, using Satterthwaite's method (Satterthwaite, 1946) to estimate the model's degrees of freedom. The threshold for declaring statistical significance was set to 0.05 %.

For water table measurements, the grouping factors were the locations, and the transects nested within locations. This nesting is necessary, as each transect belong to only one location, meaning the lower grouping level is not independent from the higher grouping level. Bogs were omitted as a grouping factors even though they represent a grouping level between location and transect. Since every location consists of only three bogs, and these represent the three different treatments, the grouping factor is not independent from the treatment effect the model is evaluating. For water chemistry, only location was used as a grouping factor, omitting bogs as grouping factors for the same reason as above.

3. Results

3.1 Water table depths (WTD)

There was a small but pronounced variation in specific WTD between treatments (figure 5). Rewetted bogs had significantly higher water tables than drained bogs ($p = 0.003$; table 2). The rewetted bogs also appeared to have slightly higher water tables than the pristine ones, but the difference was not statistically significant ($p = 0.136$). There was a small increase in WTD overall between visits.

There was large variation in measurements among the different survey locations. The spread in the data, as measured by the samples' standard deviations (SD), was largest among locations (SD = 6.69), and smallest among transects (SD = 1.96). This means the different locations themselves are an important factor influencing WTD, probably due to differences in precipitation and hydrological characteristics of their catchments. The residual variance was also high (SD = 14.47), meaning there was a lot of variation in WTD measurements not explained by the model.

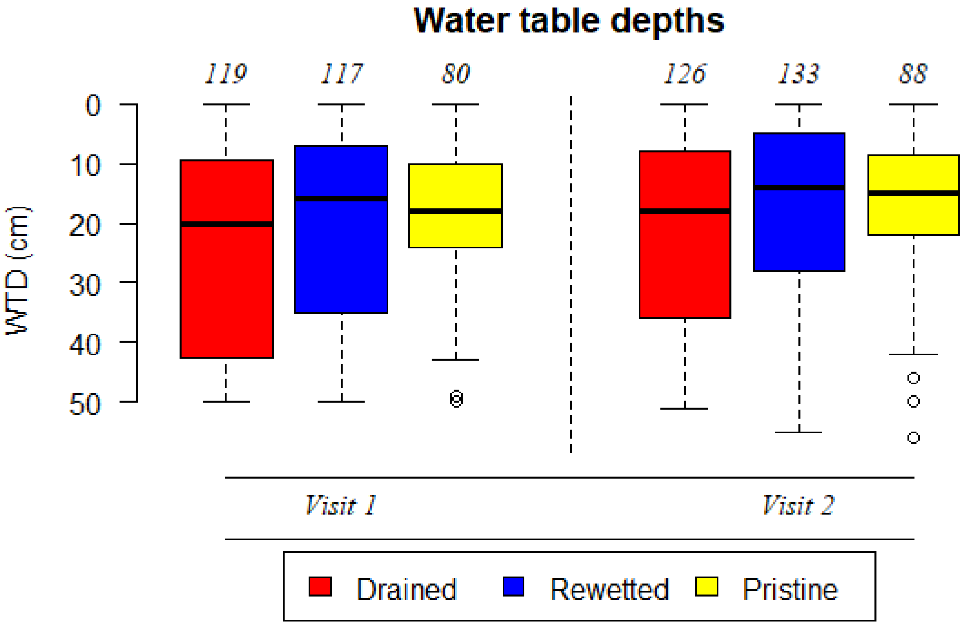

Figure 5. Box-whisker plot of specific water table depth (WTD) measurements on drained (red), rewetted (blue), and pristine bogs (yellow). The boxes cover 66% of measurements (±1 standard deviation (SD) from the mean); whiskers indicate 95 % confidence interval (± 2 SD); medians are indicated by thick solid horizontal line. Dots indicate single outliers. Numbers above the boxes indicate sample sizes.

Table 2. Output of linear mixed effect model of specific water table depth (WTD; measured in cm) by bog treatment and visit number (1 and 2). Differences in estimates between the treatments are listed, along with standard errors for the estimates, and a t-test result represented by a p-value. Statistically significant p-values (at the 95 % confidence level) are indicated in bold. Standard deviations (SD) for random effects are listed. These indicate the spread in the data at the different grouping levels. The random effects are nested; transects within locations.

FIXED EFFECT PREDICTORS	Difference	SE	p-value
Rewetted – Drained	4.04	1.34	**0.003**
Rewetted – Pristine	- 2.20	1.48	0.136
Drained – Pristine	- 6.24	1.47	**< 0.001**
Visit 1 – Visit 2	2.21	1.13	**0.050**
RANDOM EFFECTS	SD		
Transect	1.96		
Location	6.69		
Residual	14.47		

There was a larger spread in the water table measurements on drained (SD = 17.41; table A2 in the appendix) and rewetted (SD = 16.38) bogs than on the pristine ones (SD = 11.36), resulting in the red and blue boxes in figure 5 being taller than the yellow ones. Most of the measurements on pristine sites were at 10 – 30 cm below ground (figure 6). Rewetted and drained sites had more instances of water both on the bog surface and very deep below, i.e., reflecting deeply drained, dry conditions. There were more instances of hitting no water at 50 cm depth on the drained bogs than on either of the other two treatments. Conversely, I recorded the most instances of open water on rewetted sites, but the water was still mostly below the surface.

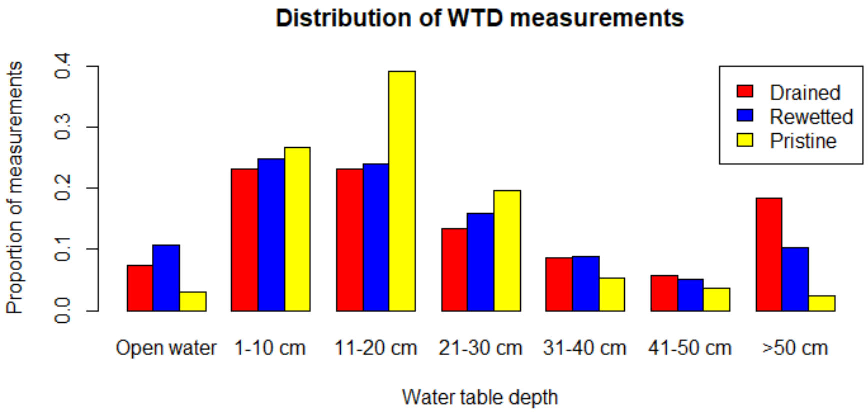

Figure 6. Distribution of measurements of water table depths, sorted by mire treatment. There were more instances of hitting no water at 50 cm depth on the drained mires than on either of the other two treatments. Pristine mires had less open water, but more water close to the surface than the other treatments. There was also greater variation in measurements on rewetted and drained sites.

3.2 Water table profiles

There was a significant difference between rewetted and drained mires in relative water table levels ($p < 0.001$; table 3). Furthermore, the relationship between relative water table depth and the distance to nearest ditch differed. The correlation between relative WTD and ditch distance on rewetted bogs was not different from zero ($p = 0.613$), while it was positive on drained bogs ($p = 0.005$). This suggests that the water table is dropping towards the ditches on drained bogs, while it is more level on rewetted bogs (figure 7). The two lines intersect at around 20 m, suggesting that overall, the drawdown effect on the water table reaches at least that far into the bogs.

Table 3: Linear regression model of the relative water table level and the distances to nearest ditch (Ditch$_0$). SE = Standard error. Statistically significant p-values (at the 95 % confidence level) are indicated in bold. The model is graphically represented in figure 7.

PREDICTORS	Estimates	SE	P-value
Intercept [Rewetted, Ditch$_0$]	-35.86	-2.19	**< 0.001**
Condition [Drained]	-14.99	2.98	**< 0.001**
Ditch, slope on rewetted	0.09	0.18	0.613
Ditch, slope on drained	0.85	0.30	**0.005**

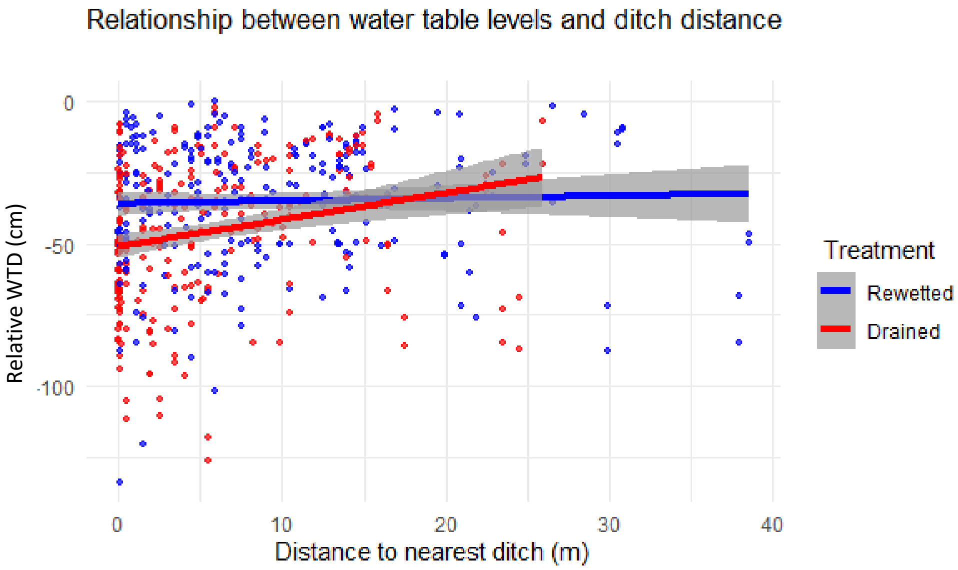

Figure 7. Water table (WT) levels, relative to fixed height above the terrain, against distance to the nearest ditch. Linear regression fits for rewetted (blue) and drained mires (red) are drawn, with shaded area indicating 95% confidence interval of the regression line. All sites were visited twice, and all values are plotted. Plot created using the R package ggplot2 (Wickham, 2016).

Calculations of sinuosities based on WTD and position of wells along transects, shows drained mires to have much higher values than the rewetted and the pristine (figure 8), implying drained bogs have more uneven water table profiles. Rewetted bogs were not statistically different in sinuosity from pristine bogs without ditches (p = 0.264; table 4). There was not much variation in the sinuosity index among locations (SD = 1.22).

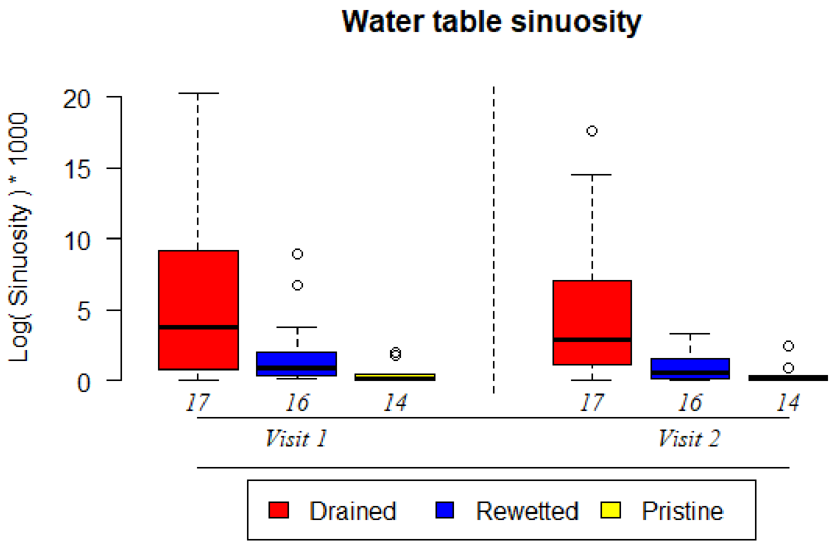

Figure 8. Water sinuosity across different mire treatments. The y-axis is log transformed and divided by 1000 to produce smaller integers. A lower score indicates less fluctuation and a more level water table. Numbers below the boxes indicate sample sizes, i.e., the number of transects.

Table 4. Water table sinuosity by bog treatment. Results from linear mixed effect model, with survey locations as random effect factor. Sinuosity index values were log-transformed, and then divided by 1000. SE = Standard error. SD = Standard deviation. Statistically significant p-values (at the 95 % confidence level) are indicated in bold.

FIXED EFFECT PREDICTORS	Difference	SE	p-value
Rewetted – Drained	- 4.52	0.91	< 0.001
Rewetted – Pristine	1.09	0.97	0.264
Drained – Pristine	5.60	0.99	< 0.001
Visit 1 – Visit 2	-0.83	0.77	0.283
RANDOM EFFECTS	SD		
Location	1.22		
Residual	3.75		

3.3 Dissolved organic carbon on rewetted, drained, and pristine bogs

Rewetted and drained bogs were not significantly different in how much organic carbon was dissolved in the water (p = 0.827; table 5; figure 9A). Pristine bogs, on the other hand, had lower concentrations of DOC than the rewetted ones (p = 0 0.005). The model shows that DOC levels increased slightly between visits (p = 0.013), which is backed up by results of paired Student's t-test showing an increase in DOC between visits ($p < 0.001$). There was considerable variation among locations, and the model had a lot of residual variation.

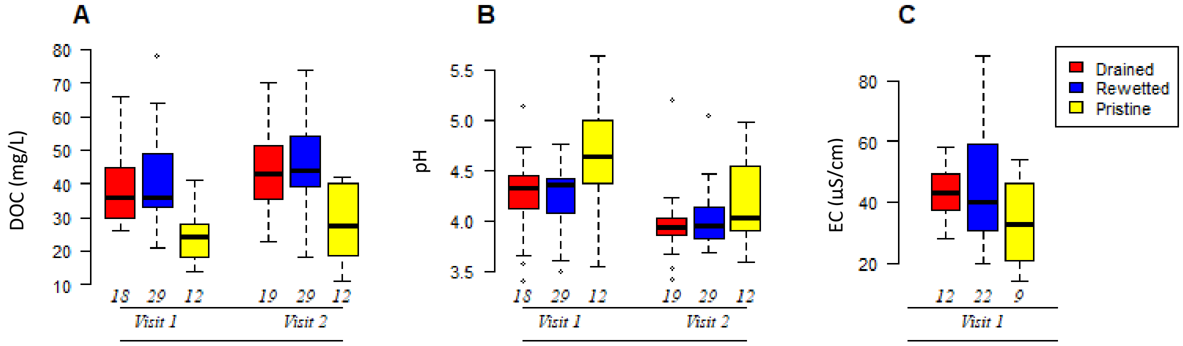

Figure 9. Box-whisker plots of water chemistry variables; dissolved organic carbon (DOC; plot A), pH (plot B), electrical conductivity (EC; plot C). Numbers below the boxes indicate sample sizes.

Table 5. Statistical outputs of linear mixed effect models with dissolved organic carbon (DOC), pH and electrical conductivity (EC) as independent variables, respectively, and mire condition and visit number (1 and 2) as fixed effects. The table shows the differences (diff.) in estimates between the treatments along with the standard errors (SE) of those estimates, and a p-value from a t-test indicating the probability of the difference being equal to zero. P—values significant at the 95 % confidence level are indicated in bold. EC was measured at only one visit. Individual mires and groups of mires (locations) were added as random effects to control for grouping effects.

VARIABLE →	DOC (mg/L)			pH			EC (µS/cm)		
PREDICTORS ↓	Diff.	SE	p-value	Diff.	SE	p-value	Diff.	SE	p-value
Rewetted – Drained	- 0.73	2.33	0.75	- 0.13	0.08	0.862	3.12	2.90	0.288
Rewetted – Pristine	- 16.52	2.68	**< 0.001**	0.26	0.09	**0.005**	- 6.09	3.38	0.078
Drained – Pristine	- 15.78	2.90	**< 0.001**	0.27	0.10	**0.006**	- 9.20	3.70	**0.017**
Visit 1 – Visit 2	4.11	1.99	**0.041**	0.28	0.07	**< 0.001**	-	-	-
RANDOM EFFECTS	*SD*			*SD*			*SD*		
Location	5.65			0.12			12.26		
Residual	10.72			0.36			8.92		

Looking at only rewetted bogs, linear regression of DOC concentrations by the year of ditch plugging showed a trend towards higher levels on the more recently rewetted bogs (figure 10). This suggests a yearly decrease in DOC (slope coefficient = - 4.60, $p < 0.001$; table 6). Due to the smaller sample size in this subset of measurements (58 samples total, from two visits to seven bogs), only a linear model was used to investigate this relationship. One of the bogs, Sakkhusmåsan, was rewetted in 2015, the earliest in the survey. At this bog, the mean DOC level in collected water samples was not significantly different at the 95% level from the mean of pristine mires (Welch two sample t-test, p = 0.12).

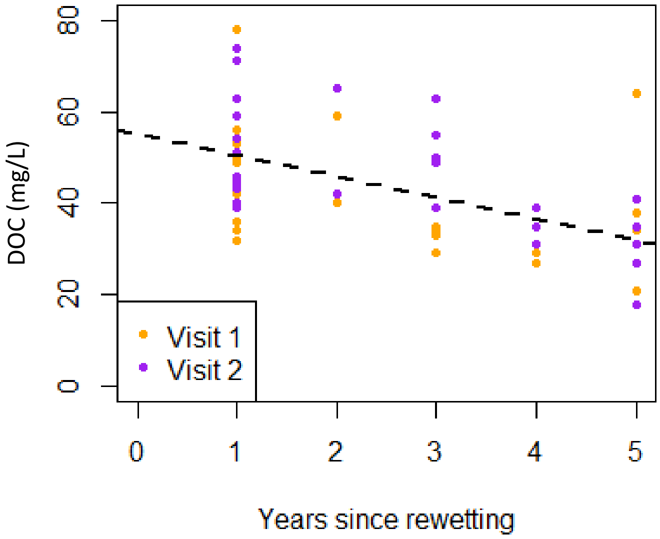

Figure 10. DOC concentrations on rewetted bogs by the years since rewetting. Year 0 = 2020. Samples are differentiated by visit number. Number of samples: 58. Number of bogs = 7. Slope coefficient: 4.60 ($p < 0.001$); intercept: 48.21 ($p < 0.001$).

Table 6. Results from linear regression of concentrations of dissolved organic carbon on rewetted bogs by year of rewetting and the visit on which the samples were collected.

PREDICTORS	Estimates	SE	p-value
Intercept [Rewetted year 0]	48.21	5.19	**< 0.001**
Year of rewetting	-4.60	0.93	**< 0.001**
Visit	4.59	2.93	0.123

3.4 pH levels

The pH on rewetted bogs was not significantly different from drained bogs (p = 0.862; fig. 9B). Pristine bogs had significantly higher pH than both rewetted (p = 0.005) and drained ones (p = 0.006), and a somewhat larger spread in the measurements (SD = 0.54) than in either rewetted (SD = 0.33) or drained sites (SD = 0.41). The mixed model showed there was not much variation between locations. Although there was a significant drop in pH between visits, this change did not affect the difference between treatments, which sustained the same pattern between visits (fig. 9B). An estimated linear relationship between pH and year of restoration on the rewetted bogs was not different from zero (p = 0.78), indicating no correlation.

3.5 Electrical conductivity (EC)

The data showed a difference in EC between rewetted and pristine bogs which was approaching statistical significance ($p = 0.078$; fig. 9C). Between rewetted and drained bogs, however, the similarity was clearer ($p = 0.288$). The difference between pristine and drained bogs was statistically significant ($p = 0.017$). EC on rewetted bogs were estimated to be between drained, which had highest conductivity, and pristine which had the lowest. At this time, though, the data indicate that rewetted bogs are more similar to drained ones than pristine ones. There was no correlation between time since rewetting and EC level. It is important to note that the lower number of EC measurements and locations increase the uncertainty of these estimates, so with more measurements the differences or similarities may become clearer.

4. Discussion

A central question in this study was whether we already see characteristics in rewetted bogs in Norway that make them hydrologically more similar to pristine bogs compared to drained ones, even though rewetting occurred only 1-5 years ago. For all the variables I measured, the drained and the pristine bogs differed significantly: drained bogs had lower water tables, higher amounts of DOC, lower pH, and higher electrical conductivity. The stage was set, then, to see if rewetted bog was more like one than the other, or if they were somewhere in between.

4.1 The water table has risen

Several studies on peatland water tables show increased water table shortly after the blocking of drainage ditches (e.g. Haapalehto et al., 2011; Worrall et al., 2007). Because of this, I anticipated that bogs that had plugs installed in their ditches would have higher water tables than still drained bogs, despite having no prior knowledge of the water tables before rewetting. This was my first hypothesis (H1; table 1) and I found limited support for it: The rewetted bogs generally had lower specific WTD than the ones that had remained drained. The difference was not large, and I did not find the clear and sharp increase in water table levels that was reported in Haapalehto et al. (2011). There was a larger spread in WTD measurements on the rewetted and drained bogs than on the pristine ones. This is probably due to the more frequent occurrences of both very wet and very dry conditions along their transects.

There was also a small increase in water tables between visits, but the change was similar across treatments. Water tables fluctuate naturally throughout the year in response to rain and drought (Holden et al., 2011). The rise was probably due, then, to precipitation between visits, and the similar rise across treatments may reflect the fact that all sites within a location was usually surveyed in the same day. Earlier studies have found intact and degraded peat soils to differ in water uptake potential, leading to differing patterns of water table responses to rainfall (Holden et al., 2011; Price et al., 2003). Rewetted and drained mires also differ in their response to weather (Ahmad et al., 2021). Although my results showed no such difference, more detailed and frequent measurements of both water tables and meteorological variables are necessary to evaluate this properly.

The next question I wanted to investigate was whether it was possible to see the water table levelling out in the rewetted bogs. My hypothesis was that water tables in rewetted bogs already were more level than those in drained ones (H2). This would indicate water had slowed its moving towards the ditches, and the surrounding peat had started to "fill up" with water. My findings support this hypothesis – both by showing the water tables of rewetted and pristine bogs had a less variable topographic quality, as measured by its sinuosity, and most convincingly, by the results showing the water table did not tend to slope down toward ditches on rewetted bogs (fig. 7). In fact, the greatest difference in WTD between drained and rewetted bogs were observed near the ditches. A rapid rise in water level adjacent to ditches after plugging has also been demonstrated by Worrall et al. (2007). They found water tables just one meter from ditches to increase by an average of 7 cm over the course of half a year.

Boelter (1972) demonstrated a clear pattern in water table drawdown shortly after ditching, with a larger drop close to the ditch than farther away. Extending the logic following this, water tables may increase more rapidly near the ditches as they are filled up with water. Water is added to ditches when rain is falling directly on them. However, they will also be supplied with water flowing on and near the surface from adjacent bog areas. Whether the rising water table near ditches is due to infiltration from rising ditch water or a damming effect exerted by pools forming in ditches is uncertain. There is currently a scarcity of studies on the relationship between distance to ditches and the rate of water table increase. It may depend on several factors, like the size of the bog, the placement of the ditch on the bog, and topography. The factors determining the distribution of water in peatlands are complex, even before we consider draining and rewetting. The data collected for this study are not useful in investigating this topic, which would require more continuous measurements at several fixed point along the transects.

A highlighted goal of the Norwegian restoration program (The Norwegian Environment Agency, 2016), even stated on its title page, is to reduce GHG emissions. A recent study by Evans et al. (2021) claims water table management to be very important in mitigation global GHG emissions from drained peatlands. According to their study, raising the water table in deeply drained peat soils by 10 cm can reduce CO_2 emissions by 3 tons per hectare per year. Although the same study found that raising the water table increases methane emissions, the net reduction in GHG is positive. In my survey, the estimated difference in WTD levels was 4 ± 1.3 cm between the seven drained and seven rewetted bogs (table 3). The data also show that although there were more instances of open water along the transects on rewetted bogs compared to the other treatments, the water was still mostly under the surface (fig. 6). This is important, as methane escapes more readily into the atmosphere through open water surfaces (Cooper et al., 2014). When the water table stays below ground, methane is more likely to oxidize and become trapped (Joosten et al., 2016). Rewetting these bogs should therefore already have positive effects on GHG emissions. Detailed CO_2 and methane efflux measurements would be needed for a clear, quantitative estimation. One such study is already underway, at the Regnåsen-Hisåsen nature reserve in eastern Norway. That study employs at traditional BACI approach, but data collection is still in the "before" phase, with rewetting scheduled for the fall of 2021 (The Norwegian Environment Agency, 2021).

Increased water table height may also be a sign of decreased runoff. This study aimed initially to measure runoff, but rudimentary measurements of surface water flow in discharge streams were unsuccessful. There was rarely any movement detectable at the short timeframes allowed by the study setup. Runoff and carbon release are linked through the export of organic carbon dissolved in the discharge water (Holden, 2005). This means the successful damming of peatlands, as indicated by increased water levels, may 'lock' some of those organic compounds in the peat soils where their further decomposition and ultimate release as CO_2 may be slowed. The GHG reduction would then be further improved by reverting water chemistry characteristics back to "natural" levels.

4.2 But water chemistry was largely unchanged

I had three hypotheses regarding differences in water chemistry between the treatments (H3-H5). The data in this study did not show a significant difference in water chemistry characteristics between drained and rewetted bogs, although DOC showed a trend towards higher concentrations in the more recently rewetted ones. The one bog that was rewetted five years ago, had levels of DOC as the pristine controls, suggesting similar rates of mineralization. A similar timeline was demonstrated by Menberu et al. (2017) who found mires in Finland had returned to natural DOC levels after 5-6 years. This can be interpreted as a cautious estimate of the time needed for elevated DOC concentrations to drop after rewetting. This pattern of DOC decrease is not a given outcome, as a study by Strack et al. (2015) found DOC concentrations on a bog in Canada to increase 10 years after rewetting. They speculated that it may have been due to rising water tables “washing out” mineralized carbon produced and stored in the upper layers of the soil. A similar explanation was offered by Worrall et al. (2007) after finding the same effect, although on a shorter timescale. The natural processes in peatlands are slow, so there are probably long-term dynamics not captured by this study.

pH was lower in both rewetted and drained bogs compared to the pristine ones, which suggests that the bogs became more acidic after draining. This could mean that the output of acidifying compounds is greater from rapidly decomposing peat than from the natural growth and decay of *Sphagnum* moss. Howson et al. (2021) reported a similar difference in acidity between intact bogs and bogs drained for forestry. In a study of one poor and one rich mire excavated for peat extraction, Lundin et al. (2017) found pH to increase after rewetting on the rich mire, while it decreased in the poor one. If the mires are reverting towards natural states, one may infer that pH increased in the poor mire after draining, which is contrary to my results. However, the degraded bog in their study had a pH of almost 5.4 and dipped to just below 5 four years later. I measured both pristine and degraded bogs to have a pH levels closer to 4. The bog in their study was also a heavily harvested site in which peat extraction had been going on for over 100 years before rewetting. In some areas, peat was excavated to depletion, exposing the morainic landscape beneath. This means that their study sites probably did not have as much peat to be degraded in the first place, and so the physical environment may have affected acidity differently than in more moderately degraded peatlands. The dynamics of pH are, as it turns out, a complicated matter. A full discussion is beyond the scope of this study and could comprise a whole thesis on its own.

The EC in rewetted bogs was found to be between that of pristine and drained bogs. A large spread in measurements caused this estimate to be similar to both of the other treatments (i.e. not significantly different), which were significantly different from each other. This may indicate that EC in some of the rewetted sites have started to change towards natural levels. The lack of statistical significance is likely due to the combination of large variation and small sample size. There were no signs of a negative correlation with time since rewetting, but the sampled bogs represented only three different years of rewetting (2016, 2017 and 2019). The low sample size for this parameter makes it difficult to make clear inferences about the effect of rewetting. However, the same pattern of decreasing EC in rewetted bogs has previously been detected in a large-scale study in Finland (Menberu et al., 2017). Elevated EC is due in part to increased rates of decomposition and mineralization causing the dissociation of constituent ions from organic compounds (Menberu et al., 2017; Smith & Doran, 1997) which then dissolve in the mire water. Conversely, a decrease in EC suggests a reduced rate of decomposition and mineralization. However, not all ion concentrations respond in the same way to draining and rewetting (Haapalehto et al., 2011). More detailed chemical analyses are necessary to untangle the dynamics of mineralization and nutrient cycling in these rewetted bogs.

4.3 Limitations of the study design

There are many ways in which this study can be improved upon for further investigations. The modified BACI approach employed here exposes it to an array of possible sources of error. They mostly pertain to variation in conditions between the different sites of each location, i.e., each triplet, and between the different dates the sites were surveyed. Large residual variance in several of the models, specifically for WTD and DOC show that there is a lot of variation not explained by the different treatments and the simple grouping of measurements by survey locations. Furthermore, a note of caution should preface the use of different areas of the same bog as different treatments. This study placed a minimum distance of 50 meters between differing treatments based on the reach of ditches' drawdown effects found by Boelter (1972). Although my results support Boelter by showing that the ditches on the surveyed bogs had an average impact zone of at least 20 meters (the distance at which rewetted and drained bogs had equal relative WTD), his study considered only the short-term effects (< 1 year) of excavating ditches. Decades-old ditches may have had the time to produce effects at larger distances, as suggested by a more recent study by Paal et al. (2016). 50 meters between survey sites of different conditions should be a strict minimum, but larger distances would be preferable in the future.

A traditional BACI approach, in which the hydrological and chemical conditions are investigated before and at several times after restoration of a bog, could reduce a lot of uncertainty. Prior knowledge of the conditions of a subject before a treatment is applied is important to produce answers about any effects it may have. Kløve et al. (2015) suggested this method for monitoring hydrological effects of peatland restoration. I did not have this prior knowledge, and the project's time frame did not allow for a multi-year investigation. Many studies of peatland dynamics have time frames of several years, like Strack et al. (2015) and Lundin et al. (2017), although some studies covering a single survey campaign season have yielded fruitful results (e.g. Wang et al., 2020; Worrall et al., 2007). The important thing to note about these studies, however, is that they produce timeseries with several datapoints, often starting before restoration efforts are applied to a site. For the sinuosity index, such timeseries would be useful to investigate changes along the same transects over several months and years.

Researchers of peatland hydrology measure the state of peatlands in many ways. Budgets of water inflow and outflow give insights into a mire's water balance and the peat's retention capacity (Menberu et al., 2018). Remote sensing is used increasingly, so that several peatlands can be monitored simultaneously (FAO, 2020). Even satellite data can be used to monitor water table dynamics on peatlands (Burdun et al., 2020). The common way of studying and monitoring water table depth is, however, by installing a pipe in the soil, shielded from precipitation (Faulkner et al., 1989), and either reading the water level manually, or instrumentally using a piezometer (Kløve et al., 2015). In this study, I used a crude method of measuring water table depth. Roots and dense soil made digging an arduous task in very degraded bogs, sometimes resulting in narrow wells that were difficult to measure. The rope tied above transects was also often difficult to make completely level. Sticks and thin trees were not ideal posts to tie the rope between. To make the rope level at distances of 30 m and more, it had to be pulled very tightly, often bending the trees and pulling down the sticks. The rope could therefore have been drooping towards the middle in some cases, even if it appeared level through the eyes of a tired student. Holding a spirit level to the rope may also not have been a sensitive enough method to ensure true level. The result may have been the appearance of shallower relative WTD near the middle of the transects. In addition to these uncertainties, limiting digging to 50 cm of soil depth leaves out a lot of potential variation within transects and between treatments. These issues could be ameliorated in future surveys by using pipe wells for WTD measurements (Faulkner et al., 1989), and high resolution topographic survey of transects using DGPS and terrestrial laser scanning (Anderson et al., 2010). However, these are costly and time-consuming techniques compared to the methods employed in this study.

4.4 Implications for management

Important to bear in mind is the very short time since most of the bogs were rewetted. Indeed, the median year of rewetting for the seven locations was 2018 – two years before the field work of this study. The similarities in DOC and pH between drained and rewetted bogs should therefore not discount the value of these parameters as indicators of restoration effect and status. Pristine bogs were still significantly different from the two other treatments, meaning there may be potential to see a shift towards their characteristics on a longer timescale. Rewetting is only the start of the restoration process, and for bogs that have used millennia to form, damage caused by draining will likely take decades to repair.

In the updated governmental action plan (The Norwegian Environment Agency, 2021), a monitoring regime is proposed for rewetted mires using fixed transects for vegetation surveys. Such surveys use vegetation structure as proxies for water saturation, chemistry, and GHG emissions. Although some vegetation can respond quickly to rewetting (Punttila et al., 2016), the overall change is very gradual and there are many potentially confounding factors. Vegetation was surveyed along the same transects in one of this study's parallel investigations (Johansen, 2021), but apart from a decrease in drought tolerant heather (*Calluna vulgaris*) there was not yet a detectable change in botanical profiles after rewetting. Direct measurements may yield a more precise picture of hydrological development and could be an important supplement to vegetation surveys.

This study's design allowed for comparisons of multiple bogs over a brief period, with low costs and manpower required. In Norway, the number of completed restoration projects is large and growing. Peatland restoration has become a relatively fast-paced and hands-on enterprise, with over 25 sites restored in 2020 alone. It could be useful to couple the quick and simple methods of this study with the planning stage when mires are surveyed before rewetting (The Norwegian Environment Agency, 2021), but with a more accurate levelling system and DGPS for surface measurements. This would produce valuable information for re-surveys at later times, and potentially increase the sample size drastically. It is important, in that case, that subsequent surveys happen at the same time of year, as this study shows that pH and DOC levels change throughout the year. Seasonal variation in DOC has also been demonstrated by Rosset et al. (2020). In addition, the selection of proxies and controls requires careful planning. Other factors, like nitrogen and phosphorus content could be included, as their levels too vary between pristine and degraded peatlands (Holden et al., 2004).

5. Concluding remarks

The Norwegian restoration program aims to restore the hydrological conditions on mires, most importantly by increasing the water table and reducing runoff. The three goals – mitigating GHG emission, adaptation to climate change, and improved ecological conditions – rely on slow, natural processes to follow ditch blocking. But these goals are vaguely defined, which makes defining success difficult, much less declaring it.

This study shows that comparing recently rewetted bogs with both drained and pristine sites can produce valuable insight into the hydrological effects of blocking drainage ditches. It shows that the Norwegian restoration program has been largely successful in raising water tables in degraded bogs, while keeping the water mostly under the surface still. This suggests that the peat soils still have an appreciable capacity to absorb and retain water, which are important factors in flood regulation. Wetter soil is also more conducive to the growth of peat forming mosses.

Despite the short time since rewetting, electrical conductivity had changed in the direction of natural levels, represented by pristine bogs. pH and DOC concentrations had not changed overall, but DOC levels tended to be lower at older sites, and at natural levels five years after rewetting. These changes are probably attributable to the increased water levels, which slows decomposition and mineralization, and reduces GHG emissions. My findings show that the treatments applied to drained bogs in Norway are likely appropriate in achieving the goals of the restoration program, and that positive changes are already detectable.

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Appendix

Table A1. Location (loc) and site information. For sites with several treatments on the same bog, the area is specified with the direction (North (N), South (S), East (E), West (W)). Bog surface area is approximated from aerial photgraphs. *Area size cover several treatments.

Loc ID	Treatment	Name	Area (1000 m2)	Elevation (m above sea level)	Latitude	Longitude	Visit 1	Visit 2	Total water samples	Transects
L01	Rewetted 2015	Sakkhusmåsan E	175*	329	60.07047	11.72985	11.08.2020	20.08.2020	10	2
L01	Drained	Villpostmyra	71	318	60.0679	11.73766	11.08.2020	20.08.2020	4	2
L01	Pristine	Sakkhusmåsan W	175*	329	60.07047	11.72985	11.08.2020	20.08.2020	4	2
L03	Rewetted 2016	Aurstadmåsan S	846*	180	60.18635	11.34348	12.06.2020	27.06.2020	8	2
L03	Drained	Flakstadmåsan	1815	178	60.17377	11.32768	13.06.2020	27.06.2020	4	2
L03	Pristine	Aurstadmåsan W	846*	180	60.18635	11.34348	12.06.2020	27.06.2020	2	3
L04	Rewetted 2017	Romsmåsan	49	265	59.98592	10.88315	08.06.2020	03.09.2020	10	3
L04	Drained	Lomtjern	6	324	59.9958	10.87898	11.06.2020	29.08.2020	8	3
L04	Pristine	Rudsputten	17	352	60.00242	10.86585	11.06.2020	29.08.2020	8	2
L08	Rewetted 2018	Veggermyra S	45*	80	59.31096	10.09532	13.08.2020	25.08.2020	4	2
L08	Drained	Strandemyra	184	105	59.31262	10.07666	13.08.2020	25.08.2020	6	2
L08	Pristine	Veggermyra N	45*	80	59.31096	10.09532	13.08.2020	25.08.2020	2	2
L10	Rewetted 2019	Fjøsmåsan	5	219	59.83215	10.92171	02.06.2020	30.06.2020	8	2
L10	Drained	Blåsynmåsan	35	226	59.84601	10.93242	04.06.2020	30.06.2020	8	3
L10	Pristine	Torsmåsan	4	222	59.84436	10.91317	04.06.2020	30.06.2020	2	1
L11	Rewetted 2019	Eiriksvannsmåsan	16	237	59.83271	10.92794	03.06.2020	01.07.2020	8	3
L11	Drained	Starrmåsan	15	284	59.82147	10.93242	09.06.2020	01.07.2020	4	2
L11	Pristine	Stormyr	17	249	59.82033	10.928	02.06.2020	01.07.2020	4	2
L12	Rewetted 2019	Øgårdsmåsan	66	247	59.8652	10.89593	14.06.2020	26.06.2020	10	3
L12	Drained	Skullerudmåsan N	35*	243	59.86145	10.8604	13.06.2020	26.06.2020	4	2
L12	Pristine	Skullerudmåsan S	35*	243	59.86145	10.8604	13.06.2020	26.06.2020	2	2

Table A2. Mean ± 1 standard deviation of water table depth (WTD; cm) and water chemistry measurements at different locations (loc). DOC = Dissolved organic carbon (mg/L); EC = electrical conductivity (µS/cm). EC was measured at only five locations, and in only one visit. *Standard deviation not calculable because the sample size is 1.

		WTD		DOC		pH		EC
Loc ID	Treatment	*Visit 1*	*Visit 2*	*Visit 1*	*Visit 2*	*Visit 1*	*Visit 2*	*Visit 1*
L01	Rewetted 2015	33.7 ± 16.6	38.4 ± 15.2	36.8 ± 16.5	30.4 ± 8.7	3.8 ± 0.2	4.1 ± 0.3	*no data*
L01	Drained	28.7 ± 11.0	34.6 ± 10.5	63.5 ± 3.5	65.5 ± 6.4	3.5 ± 0.1	3.6 ± 0.2	*no data*
L01	Pristine	27.8 ± 15.9	31.3 ± 14.1	33.5 ± 10.6	32.5 ± 10.6	4.4 ± 0.9	4.3 ± 1.0	*no data*
L03	Rewetted 2016	9.2 ± 12.0	9.8 ± 11.5	30.0 ± 3.5	35.0 ± 3.3	4.5 ± 0.1	4.2 ± 0.5	35 ± 7.3
L03	Drained	19.1 ± 14.9	22.7 ± 16.0	38.0 ± 2.8	44.0 ± 1.4	4.6 ± 0.3	4.0 ± 0.3	43 ± 0.0
L03	Pristine	14.6 ± 7.2	19.1 ± 9.2	25.0	29.0*	4.3*	3.9*	46*
L04	Rewetted 2017	15.6 ± 20.0	19.8 ± 16.5	33.0 ± 2.4	51.2 ± 8.8	4.4 ± 0.1	4.0 ± 0.3	30 ± 3.3
L04	Drained	26.8 ± 19.0	30.0 ± 16.8	35.8 ± 4.5	41.0 ± 13.3	4.3 ± 0.1	3.8 ± 0.2	43 ± 3.7
L04	Pristine	7.9 ± 7.8	11.5 ± 9.7	18.8 ± 3.9	27.3 ± 15.5	4.8 ± 0.2	4.2 ± 0.4	24 ± 7.6
L08	Rewetted 2018	35.0 ± 15.2	21.1 ± 9.8	49.5 ± 13.4	53.5 ± 16.3	3.6 ± 0.1	3.8 ± 0.0	*no data*
L08	Drained	24.6 ± 15.5	13.1 ± 8.3	35.7 ± 9.0	38.3 ±11.4	4.3 ± 0.8	4.4 ± 0.7	*no data*
L08	Pristine	21.8 ± 4.6	14.8 ± 6.2	28.0	27.0*	3.5*	3.8*	*no data*
L10	Rewetted 2019	21.1 ± 15.5	5.6 ± 3.9	43.8 ± 7.9	44.5 ± 4.7	4.49 ± 0.1	4.1 ± 0.1	35 ± 8.3
L10	Drained	9.6 ± 7.4	7.8 ± 6.3	59.0*	57.0 ± 4.2	4.1*	3.8 ± 0.1	41*
L10	Pristine	21.2 ± 15.8	15.0 ± 15.5	17.0 ± 4.2	17.0 ± 4.2	5.3 ± 0.5	4.5 ± 0.2	26 ± 11.3
L11	Drained	34.0 ± 22.2	18.8 ± 19.4	27.8 ± 1.7	32.5 ± 4.1	4.4 ± 0.0	4.0 ± 0.0	31 ± 3.4
L11	Rewetted 2019	21.7 ± 16.3	8.8 ± 6.9	39.0 ± 6.1	43.5 ± 3.1	4.3 ± 0.3	3.9 ± 0.2	31 ± 8.6
L11	Pristine	20.8 ± 9.7	7.3 ± 6.0	28.0*	28.0*	4.5*	4.0*	35*
L12	Drained	27.1 ± 20.6	28.6 ± 19.2	45.0 ± 0.0	43.0 ± 2.8	4.4 ± 0.1	4.0 ± 0.0	50*
L12	Rewetted 2019	22.4 ± 11.7	22.8 ± 12.7	59.2 ± 11.9	64.2 ± 8.3	4.3 ± 0.1	3.9 ± 0.1	62 ± 12.1
L12	Pristine	19.3 ± 4.8	21.2 ± 4.2	37.0*	42.0*	4.4*	4.0	53*
All loc	Drained	24.0 ± 17.8	22.5 ± 17.1	39.6 ± 12.1	43.6 ± 12.5	4.3 ± 0.4	4.0 ± 0.4	39.3 ± 6.9
All loc	Rewetted	21.5 ± 17.4	17.8 ± 15.3	41.2 ± 13.3	45.8 ± 13.2	4.2 ± 0.3	4.0 ± 0.3	39.1 ± 15.0
All loc	Pristine	18.6 ± 10.9	17.0 ± 11.7	24.5 ± 8.3	27.8 ± 11.0	4.6 ± 0.6	4.2 ± 0.4	31.1 ± 12.8

Norges miljø- og biovitenskapelige universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway