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# Quantification of peat volume change in Northern peatlands

## A study of mires capacity to swell and shrink and its relation to mire age and land management

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# Abstract

## Quantification of peat volume change in Northern Peatlands: A study of mires capacity to swell and shrink and its relation to mire age and land management

*Anna Engman*

Peatlands are important ecosystems that provide ecohydrological functions related to carbon storage and cycling, water quality, flood attenuation, and groundwater recharge. One key characteristic that gives peatlands these functions is the capacity to swell and shrink upon wetting and drying, commonly referred to as peat volume change. This property of peat volume change is closely related to the fluctuations of the water table and has a buffering effect on the water table depth relative to the peat surface, which acts as an important control on many ecohydrological functions such as carbon cycling, vegetation composition, and biogeochemical processes.

In an attempt to fill a gap of knowledge, this thesis investigated peat volume change for multiple Northern peatlands close to Umeå, Sweden, using groundwater level and mire surface level data obtained during the summer of 2021. The objectives were to investigate the temporal trends and characteristics of changes in the water table and peat volume at the studied site and to determine how peat volume change capacity differs for mires of different ages, as well as different land management such as natural, drained and restored peatlands.

It was found that old (older than 2000 years) mires have a significantly smaller peat volume change capacity compared to young mires (younger than 1000 years), as well as smaller specific storage, indicating that factors that change as the peatland evolves are important for the ability to expand and contract. It was also found that the relationship between the mire surface and water level was linear for some mires but not for others, including drained and old mires. For the drained mires this could be explained by very deep water tables compared to the natural mires, however, they did not stand out among the natural mires concerning peat volume change capacity. The comparison between a restored mire and a drained gave ambiguous results. It was also found that the specific storage, which is directly related to the compressibility of the peat, was greater during drying conditions compared to rewetting conditions, highlighting peatlands ability to maintain wet conditions. The study provides a deeper understanding of peat volume change in Northern peatlands and the factors related to this phenomenon, which is crucial for further studying of peatland ecohydrology.

**Keywords**: peatland, peat volume change, ecohydrology, specific storage, peatland age

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# Referat

### Kvantifiering av volymförändring i torvmyrar: En studie av myrars förmåga att svälla och krympa och dess relation till ålder och markskötsel

*Anna Engman*

Torvmarker är viktiga ekosystem som bidrar med ekohydrologiska funktioner relaterade till kollagring och kolcykling, vattenkvalitet, minskad översvämningsrisk och grundvattenbildning. En egenskap hos torv som är viktig för dessa funktioner är förmågan att svälla under våta perioder och krympa under torrperioder. Denna torvvolymförändring är relaterad till fluktuationer i grundvattennivå och kan även ha en buffrande effekt på grundvattendjupet (avståndet från markytan till grundvattenytan), vilket påverkar flertalet ekohydrologiska funktioner såsom kolcykling, vegetationssammansättning, och biogeokemiska processer.

I ett försök att fylla en lucka i kunskapen kring detta fenomen undersökte detta examensarbete torvvolymförändringar för flera torvmarker, eller myrar, i närheten av Umeå baserat data för grundvattennivåer och nivån på myrars markyta som erhållits under sommaren 2021. Syftet var identifiera trender och egenskaper hos de olika myrarnas förändring i grundvattennivån och myrnivå, samt att ta reda om det finns någon skillnad i torvens kapacitet för att svälla och krypa hos myrar med olika ålder, samt olika markskötsel såsom naturliga, dränerade och restaurerade myrar.

Resultatet visade att äldre (äldre än 2000 år) myrar har en betydligt mindre kapacitet att svälla och krympa jämfört med yngre myrar (yngre än 1000 år), samt mindre specifik magasinkoefficient, vilket indikerar att faktorer som förändras när myren blir äldre är viktiga för förmågan att svälla och krympa. Resultatet visade också att förhållandet mellan myrens marknivå och grundvattennivå var linjärt för vissa myrar men inte för andra, inklusive dränerade och gamla myrar. För de dränerade myrarna kunde detta förklaras av mycket djupa grundvattennivåer jämfört med de naturliga myrarna, men de stack inte ut bland de naturliga myrarna vad gäller förmåga att svälla och krympa. Jämförelsen mellan en restaurerad myr och en dränerad gav tvetydiga resultat. Man fann också att den specifika magasinkoefficienten, som är direkt relaterad till torvens kompressabilitet, var större under torra perioder jämfört med våta perioder, vilket visar på myrens förmåga att upprätthålla våta förhållanden. Studien gav en djupare förståelse för myrars förmåga att svälla och krympa och faktorerna relaterade till detta fenomen, vilket är av betydelse för vidare forskning om torvmarkers ekohydrologi.

**Nyckelord**: torvmark, myr, torvvolymförändring, ekohydrologi, specifik magasinkoefficient, ålder

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# Preface

This master thesis of 30 credits concludes five years of studies within the Master's Programme in Environmental and Water Engineering at Uppsala University and the Swedish University of Agricultural Science.

I would like to thank my supervisor Kevin Bishop, Department of Aquatic Sciences and Assessment at the Swedish University of Agricultural Science, first of all for allowing me to contribute to the ongoing research on peatlands during the summer of 2021, which led me to do my thesis on these important ecosystems. Secondly, for his guidance, engagement, and support during the thesis work and for providing a lot of insight into the world of peatlands.

I also want to thank my subject reader Thomas Grabs, Department of Earth Sciences: Program for Air, Water and Landscape Sciences at Uppsala university, for valuable feedback and encouragement throughout the project.

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Lastly, these five years of studying would not have been as fun as it has been without the support of family, friends, and classmates. Thank you!

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# Populärvetenskaplig sammanfattning

Bevaring och restaurering av våtmarker får allt större uppmärksamhet som ett sätt att anpassa samhället och naturen till ett förändrat klimat. Myrar är en typ av torvbildande våtmarker som är vanligt förekommande på norra halvklotet, inte minst i Sverige. Växter som dör bryts med tiden ner, men på grund av våta förhållanden och en syrefri miljö blir nedbrytningen ofullständig och växtmaterialet ackumuleras med tiden som torv vilket gör att myrar bildas och bibehålls. Myrar som ekosystem är otroligt viktiga då de, samt torvmarker generellt, bidrar med ekosystemtjänster som skydd av biologisk mångfald, vattenrening, grundvattenbildning, minskad översvämningsrisk och kollagring. Globalt sett lagrar torvmarker ca 30% av världens landbundna kol, vilket gör dem till en otroligt viktig kolsänka. Torv är ett speciellt material, det fungerar i likhet med en svamp genom att svälla och krympa som svar på förändringar i myrens hydrologiska förhållanden. Under torra perioder sjunker grundvattennivåerna i myren och då torvens porer inte längre är fyllda med vatten kollapsar de och torven krymper i volym. När det sedan kommer ett regn som återigen höjer grundvattennivån återfuktas torven och sväller. Förutom grundvattennivån och markytans position är även grundvattendjupet, det vill säga avståndet från markytan ner till grundvattenytan, en viktig parameter. Myrens förmåga att svälla och krympa har nämligen en buffrande effekt på grundvattendjupet, vilket i sin tur har stor betydelse för de växter som trivs i våta förhållanden, men även för koldioxid och metanutsläpp.

Sommaren 2021 placerades mätutrustning ut på flertalet myrar utanför Umeå i Västerbotten för att mäta just torvens volymförändring. Det bedrivs redan omfattande forskning på flera av dessa myrar och volymförändringen är även den en viktig pusselbit. När torven sväller och krymper märks detta främst på att myrens markyta höjs och sänks. För att mäta torvens svällning och krympning användes mätutrustning fixerad med hjälp av järnstänger i det mer fasta och statiska mineraljord-lagret under torven för att mäta grundvattennivån relativt en fast punkt, samt även mätutrustning som var förankrad i det rörliga översta lagret och för att mäta avståndet ner till grundvattenytan. Med dessa data gick det att beräkna markytans position på myren. Resultatet av sommarens mätkampanj var ett stort dataset som visar hur myrens markyta, grundvattennivå och grundvattendjup varierar över tid. Detta examensarbete använde den insamlade datan från sommarens mätkampanj för att undersöka volymförändringen hos torv med syftet att ta reda om det finns någon skillnad i torvens kapacitet för att svälla och krypa hos myrar med olika ålder. Då det också fanns data för dränerade myrar och en restaurerad myr undersöktes även om detta kunde påverka kapaciteten för att svälla och krympa. Några av de studerade myrarna är särskilt intressanta då de är en del av en ”kronosekvens”, en grupp geografiskt närliggande myrar med liknande egenskaper men med olika ålder, som bildats till följd av landhöjningen som pågått sen dess att inlandsisarna smälte bort. På grund av att de ligger i så nära anslutning till varandra delar de många egenskaper som påverkas av klimatförhållanden, geologi och vegetationssammansättning, men de har en tydlig skillnad i ålder. De övriga studerade myrarna var något äldre en de äldsta på kronosekvensen.

Resultatet från studien visade att de yngre myrarna (yngre än 1000 år) svällde och krympte mycket mer under mätperioden än vad de äldre (äldre än 2000 år) gjorde, och hade större magasinkoefficient. Detta tyder alltså på att torven i yngre myrar har större kapacitet till att svälla och krympa. Åldern hos myrar är en intressant aspekt då många faktorer som har betydelse för torvens förmåga att svälla och krympa förändras med stigande ålder. Med tiden så ökar myrens tjocklek genom ackumulationen av döda växter, och vegetationssammansättningen ändras då näringsförhållandena förändras. Genom att undersöka skillnader för myrar med olika ålder kan man därför få en inblick i hur olika faktorer påverkar torvens volymändring, och en förståelse för hur detta hänger ihop är viktigt för fortsatta studier av myrar och deras funktioner. De två dränerade myrarna som undersöktes hade avsevärt djupare grundvattennivåer än resterade myrar, något som är en förväntad effekt av dränering. Volymförändring hos de dränerade myrarna stack dock inte ut något i jämförelse med de naturliga, och slutsatsen var att ett annat tillvägagångsätt behövs för att reda ut skillnaden mellan naturliga och dränerade myrar. För den restaurerade myren, en tidigare dränerad myr som blivit återvätt, jämfördes mätningar från två olika delar av myren. Volymförändringarna mättes både där grundvattennivåerna borde påverkas av att det tidigare dränerande diket har blockerats, samt nedströms blockeringen där myren således fortfarande dräneras. Resultatet visade en väldigt stor skillnad i torvvolymförändring för de två olika platserna, där torven i den dränerade delen svällde och krympte kraftigt under mätperiod medan den återvätta delen förblev relativt konstant. Det är dock svårt att säga om detta är en effekt av restaureringen eller om de specifika plasterna där mätningarna gjordes verkligen är representativa. Men det är oavsett ett intressant resultat för fortsatta studier av just denna myr.

Sammantaget har denna studie berört flera aspekter av volymförändringar i torvmyrar och kan förhoppningsvis bidra till nya uppslag för fortsatt forskning inom ämnet som gör att vi bättre förutspår hur myrar kan vara ett hjälpmedel i framtida klimat och miljöarbete.

# Contents

# 1 Introduction

Peatlands, or mires, are characterized by deep accumulations of partially decomposed organic material, also referred to as peat. They cover about 3-4% of the Earth's surface and although they are spread across all climate zones, Northern peatlands, those found across the boreal and subarctic zones in the Northern Hemisphere, are dominating (Vitt 2008). Peatlands are very important ecosystems that provide services such as biodiversity, carbon storage, freshwater storage, and flood control (Waddington et al. 2015). As peat is mainly made up of carbon, peatlands store almost a third of the world's total amount and thus play an important role in the global carbon cycle (Yu 2011). Preservation and restoration of peatlands are advocated as a nature-based solution that will be good for water quality, but also as a means of regulating flow extremes – reducing flood peaks, delaying the timing of flood peaks, maintaining low flows during drought, and promoting the formation of groundwater.

Peatlands are often covered in a carpet of the moss species *Sphagnum* (Vitt 2008) which ecophysiological traits are essential for the function and persistence of these wetland ecosystems (Waddington et al. 2015). The structure of Sphagnum moss, both alive and decomposed, gives peat the ability to expand and contract upon wetting and drying, a phenomenon often referred to as peat volume change, or sometimes more illustrative as "mire-breathing". Many studies have observed that the peat surface follows seasonal changes in the water table (Howie and Hebda 2018; Kennedy and Price 2005; Nijp et al. 2019; Price 2003; Price and Schlotzhauer 1999); rising as the water level increases during precipitation events and falling as the water level declines during dry periods. Values of peat volume change that have been reported in these studies include 0.7-10 cm during the spring and summer season (Kennedy and Price 2005; Price 2003; Price and Schlotzhauer 1999) and 2-34 cm yearly (Howie and Hebda 2018), as well as 1.2-6.2 cm of spatial variation within the same mire (Nijp et al. 2019). This phenomenon is an important self-regulating mechanism for peatlands, as it has a stabilizing effect on the water table depth relative to the peat surface, which acts as an important control on many ecohydrological functions such as carbon cycling, vegetation composition, biogeochemical processes (Blodau et al. 2004; Kettridge et al. 2015; Limpens et al. 2008) and stream runoff from peatlands. During dry periods a lowering of the peat surface maintains the water table closer to the surface, making water more accessible for surface vegetation and decreasing the frequency of drought for peat mosses (Nijp et al. 2017; Waddington et al. 2015). The distance to the water table is also important for the mires' ability to bind and store carbon (Serk et al. 2021). The expansion and contraction of peat also have implications on water storage properties and flow processes. A study on a Swedish bog found that 40 % of water storage changes were caused by swelling and shrinking of the peat, rather than changes in water content (Kellner and Halldin 2002).

Although some degree of peat volume change is likely to occur for most peatlands, the magnitude of peat volume change can vary greatly between different peatlands and is affected by the physical properties of the peat. Peat surface adjustments can for example be closely related to the change in water table for loose, uncompressed peat, whereas for compressed peat containing roots of shrubs and trees the peat surface does not follow the water table change (Waddington et al. 2015). Permanent compression of the peat material can be caused by drainage, and drained peatlands have been observed to lose their elastic property and thus the hydrological self-regulating mechanisms (Howie and Hebda 2018).

The age of peatlands is also an aspect that affects several factors that are related to peat volume change. As peatlands age, vegetation composition and the microbial community are altered due to changes in the concentration of important nutrients and other biogeochemical compounds (Wang et al. 2021). There also tends to be an increase in peat depth and peatland area, as well as changes in bulk density and peat structure with increasing age. All these factors affect the physical properties of the peat that determines its compressibility and elastic properties, and they could be better understood by studying peatlands of different ages.

An issue today is that many of the world's peatlands are drained to be used for agriculture and forestry (Joosten and Clarke 2002). Another concern is that climate change projections for the Northern hemisphere predict increased temperatures and evapotranspiration, as well as more extreme precipitation events and longer dry periods (IPCC 2007). This is likely to cause lowered water tables and drier surface conditions in Northern peatlands (Kettridge et al. 2015), affecting many of the important self-regulating mechanisms. Preservation and restoration of peatlands are advocated as a nature-based solution to protect and restore the ecohydrological functions and make them more resilient to future changing conditions and restore the services provided. Rewetting through the blocking of ditches is a common measure to restore hydrological conditions that benefit peatland flora and fauna as well as carbon capture (Howie et al. 2009; Wallage et al. 2006).

Due to the importance of peat volume change to ecohydrology, biochemistry, and water storage, this self-regulating mechanism needs to be better understood in order to protect peatland ecosystems and improve their resilience to future changes. There is currently a lack of available data about this phenomenon, and current modeling of peatland processes often fails to include peat volume change and its related feedback mechanisms in the models (Waddington et al. 2015). There is a need for peat volume change to be included in future modeling of peatland processes to achieve the correct representation of peat moss drought occurrence or mire-water dynamics, as well as the runoff regime from mires (Nijp et al. 2017; Kellner and Halldin 2002).

To contribute with additional knowledge about peat volume change, 27 pairs of groundwater level sensors were installed on 24 mires in the northern part of Sweden at the beginning of summer 2021. The reason a pair of sensors were used was to obtain measurements of water table changes both relative to a fixed point and relative to the moving peat surface. With this information, the absolute water level, the water table depth relative to the mire surface, the mire surface level, and their changes over time could be calculated, from which the expansion and contraction of the peat, i.e. the peat volume change, could be quantified. This data was collected from mires with varying characteristics, including natural, drained, and restored mires, as well as mires of different ages. 15 of the studied mires are part of a research effort studying changes in biogeochemical properties and vegetation composition etc. along a chronosequence of 'young' to 'older' mires, ranging from decades to thousands of years since the start of the peat formation. The resulting dataset is unique with regards to the large number of mires that are included as well as the variation in age. It provides a great opportunity to study the elastic property of peat and needs to be examined in order to gain insights into peatland ecohydrology and answer questions that could help further the understanding of this phenomenon of volume change in peatlands.

**Figure 1:** A typical Northern peatland and one of the peatlands studied within this thesis project, located outside of Vindeln, Sweden (site S2, Hålmyran)

## 1.1 Objectives

The purpose of this thesis was to examine a dataset of continuous groundwater level and mire level measurements, collected from 24 peatlands in Northern Sweden during the summer of 2021, to acquire a deeper understanding of the process of peat volume change at the studied sites. To do this, the following research questions were answered:

- What temporal trends and characteristics of water table change and peat volume change can be observed at the studied sites?
- How does peat volume change capacity differ for mires of different ages, as well as land management (natural, drained, restored)?
- Can the difference in peat volume change capacity be explained by mire properties and hydrometeorological conditions such as mire depth and water table dynamics?

# 2 Theory

## 2.1 Peat volume change

Peat volume change mainly occurs due to changes in the absolute water table and is affected by the physical properties of the peat. A lowering of the water table causes an increase in effective stress, resulting in compression of the peat and closing of pore spaces. A consequence of this compression is decreased saturated hydraulic conductivity and increased moisture retention capability, which mitigates further water losses such as lateral drainage. Similarly, a rising water table leads to the expansion of the peat and pore spaces, resulting in a reduction of the moisture retention capability and greater potential for water loss through drainage and evapotranspiration (Waddington et al. 2015).

The compressibility of peat is controlled by physical properties that are mainly the result of the degree of decomposition (Price 2003). The degree of decomposition generally increases with depth in the peat profile leading to a similar reduction of compressibility in deeper layers (Rezanezhad et al. 2016). Although the term peat *volume* change is commonly used to refer to this behavior of compression and expansion, the change in volume is mainly manifested by shrinkage and compression of peat in the vertical direction (Kennedy and Price 2005), displaying itself through a rise and fall of the surface position of the mire. This change in mire surface level can be the result of changes in soil volume both above and below the water table. A decrease in the mire surface position in a drained mire was shown by Price and Schlotzhauer (1999) to be caused both by shrinkage above the water table and by compression in the saturated peat below the water table. In this particular study, compression below the water table contributed more to the total volume change. The explanation could be that lowering the water table increases the weight of the overlying soil so that the soil below is compressed. This is likely to occur for drained mires with a large unsaturated zone. In natural mires, however, the unsaturated zone is very shallow and therefore its contribution to peat volume change is expected to be small in such systems. Changes in mire surface position can also be affected by atmospheric pressure and methane gas dynamics. Falling atmospheric pressures have been related to the expansion of entrapped gas volume, causing a rise in the mire surface (Strack et al. 2006).

## 2.2 Water storage properties and compressibility

The expansion and compression of peat influence water storage in peatlands. In fact, changes in water storage are more affected by changes in soil volume rather than water table fluctuations (Price 2003). This is in contrast to mineral soils which do not have this ability to expand and contract. Changes in water storage in an aquifer are governed by its storativity $S$, defined as the volume of water released from storage per unit area and per unit change in head. For incompressible soils or unconfined aquifers, storativity is typically equal to the specific yield $S_{\mathrm{y}}$, the volume of water released from storage through drainage of the pores due to gravity as the water table declines. For confined aquifers, changes in water storage mainly occur due to compression of the matrix and the aquifer thickness ($b$). For this case, storativity is typically equal to the elastic storativity $S_{\mathrm{y}} \times b$, where $S_{\mathrm{s}}$ is a parameter called specific storage related to the compressibility of the matrix. For highly compressible peat in peatlands, both these processes may operate and affect water storage and storativity through equation 1. Specific yield is generally greater than the specific storage, however, in peatlands with relatively high compressibility, low bulk density, thick and poorly decomposed peat layer, and large water table fluctuations, the specific storage component may be more significant (Price and Schlotzhauer 1999). For shallow systems where pressure is relatively low and water is not significantly compressible, $S_{\mathrm{y}}$ is mainly governed by the compressibility of the aquifer according to Equation 2 (where $\rho_{\mathrm{w}}$ is the density of water, $g$ is the gravitational acceleration and $\alpha$ is the compressibility of the matrix). Specific storage can thus be used as a measure of the profile-averaged compressibility, which relates both to the elastic properties of the peat material and to water storage.

$$S = S_{\mathrm{s}} \times b + S_{\mathrm{y}} \tag{1}$$

$$S_{\mathrm{s}} = \rho_{\mathrm{w}} g \alpha \tag{2}$$

Volume change (compression and expansion) in a thick layer mainly manifests itself through changes in the vertical peat thickness. Thus, the elastic storativity $S_{\mathrm{y}} \times b$ can be estimated from the surface elevation change ($dz$) per unit change in head ($dh$) (Price and Schlotzhauer 1999):

$$S_{\mathrm{s}} \times b = \frac{dz}{dh} \tag{3}$$

The hydraulic head $h$, or total head, is the sum of the pressure head (the energy due to pore fluid pressure) and the elevation head (the gravitational energy arising from elevation) (Ge 2003). For peatlands, vertical gradients in hydraulic head can be assumed to be small and negligible, meaning that the elevation and pressure head cancel out. Thus $dh$ can be represented by either the pressure head or the total head. If the total head is constant for the whole aquifer depth, it can thus be represented by the absolute water table position $GWL_{\mathrm{A}}$ measured in this project.

This is based on the assumption that most peat volume changes occur in the saturated zone, or that the unsaturated zone is very small. When the unsaturated zone becomes dominant, this will have implications on the definition of elastic storativity as it is explained above. As the water table declines, the thickness of the unsaturated zone increases. As a result, the peat soil matrix in this zone loses the support provided by surrounding water, leading to an increased mass that exerts pressure on the peat below. The result is a collapse of the peat in the unsaturated zone as well as compression of the peat below. When the changes in pore water pressure in the unsaturated zone are what cause changes in the mire surface position, this will not be related to any changes in absolute water level. If elastic storativity is estimated as equal to $dz/dh$, with $dh$ represented by the change in water table position, this definition will not capture the actual change in head that occurs in the unsaturated zone which could cause $S_{\mathrm{y}} \times b$ to be overestimated.

# 3 Method

## 3.1 Site description

The 24 peatlands studied within this project are located in the county of Västerbotten in Northern Sweden. Geographically they are distributed into two groups, with 15 of the peatlands located northeast of Umeå, along the coast of the Gulf of Bothnia, and 9 located approximately 60 km further inland, in the municipality of Vindeln (see the map in Figure 2). Included are peatlands with different status (natural, drained and restored), and they were also divided into four different ages classes based on their age (*young*, *intermediate*, *old* and *very old*). The studied peatlands, their status, and age class, are listed in Table 1 and are further described in the following paragraphs.

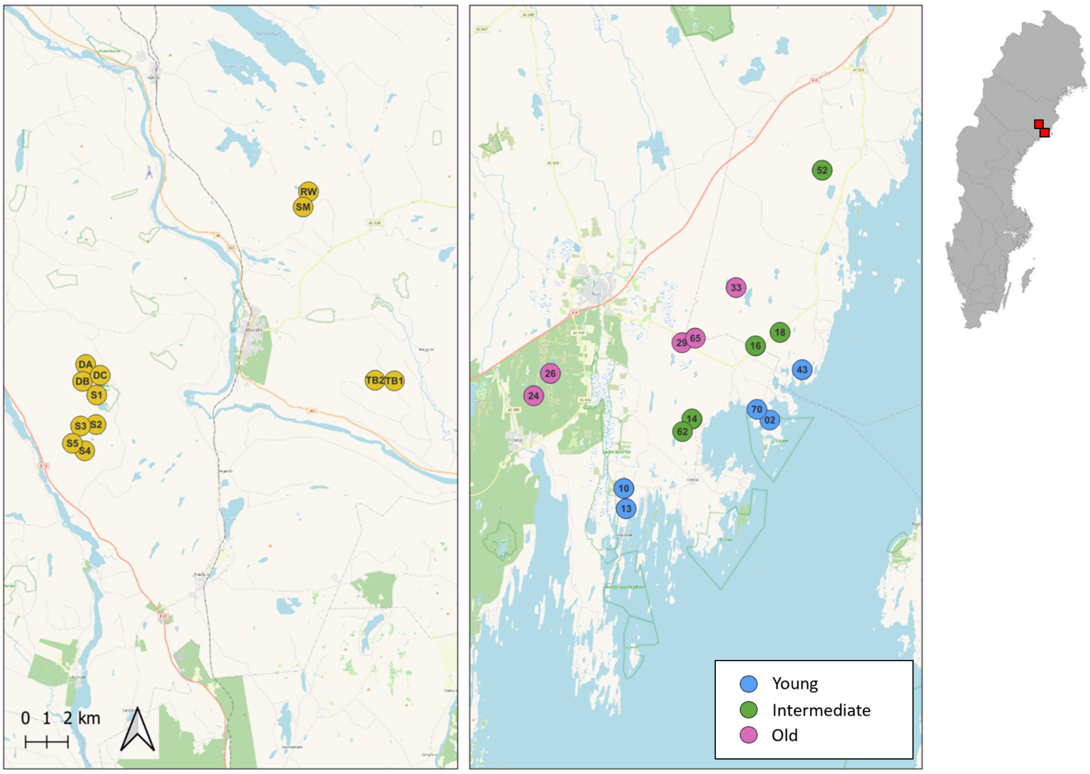


**Figure 2:** Map showing the location of the studied peatland sites located close to Vindeln (left) and the sites on the coast close to Umeå that are a part of a peatland-chronosequence (right). The coloring represents the age group each site was assigned to.

**Table 1:** List of the peatland sites studied within this project. Each mire is equipped with one logger pair (one *site*), with the exception of the mire Degerö which has 3 logger pairs, and the mire Trollberget which has two logger pairs. The sites are grouped into 4 age classes: *young* (younger than 1000 years), *intermediate* (1000–2000 years), *old* (2000-4000 years), and *very old* (4000-8000 years). Two of the mires are not included in any age class because their age is unknown.

| Site | Mire/Group | Age class | Status |
|---|---|---|---|
| 2 | Chronosequence | young | |
| 70 | Chronosequence | young | |
| 43 | Chronosequence | young | |
| 13 | Chronosequence | young | |
| 10 | Chronosequence | young | |
| 52 | Chronosequence | intermediate | |
| 14 | Chronosequence | intermediate | |
| 18 | Chronosequence | intermediate | |
| 16 | Chronosequence | intermediate | |
| 62 | Chronosequence | intermediate | |
| 29 | Chronosequence | old | |
| 26 | Chronosequence | old | |
| 33 | Chronosequence | old | |
| 24 | Chronosequence | old | |
| 65 | Chronosequence | old | |
| DA | Degerö | very old | natural |
| DB | Degerö | very old | natural |
| DC | Degerö | very old | natural |
| S1 | Stormyran | very old | natural |
| S2 | Hålmyran | very old | natural |
| S3 | Hälsingfors Stormyran | very old | natural |
| S4 | Hälsingfors open forest | very old | drained |
| S5 | Hälsingfors dense forest | very old | drained |
| RW | Svartberget (Russian Well) | very old | natural |
| SM | Svartberget (Shallow Mire) | none | natural |
| TB1 | Trollberget E | none | recently restored |
| TB2 | Trollberget W | none | recently restored |

The peatlands located on the coast northeast of Umeå are part of a chronosequence; a set of peatlands within a restricted geographical area that share similar attributes but are of different age. This chronosequence was created by the post-glacial uplift that causes the coastline around the Gulf of Bothnia to continuously rise. The peatlands have in previous studies been dated (Renberg and Segerström 1981) and divided into three different age classes (Wang et al. 2020; Wang et al. 2021); young (younger than 1000 years, n = 5), intermediate (1000–2000 years, n = 5) and old (older than 2000 years, n = 5). Due to their close location to each other, the peatlands are subject to similar underlying geology (mineral soil), atmospheric deposition, and climate patterns.

The peatlands in the municipality of Vindeln are located within the research sites Kulbäcksliden Experimental Forest, Trollberget Experimental Area, and near Svartberget research station.

The research area of Kulbäcksliden includes 4 mires (Degerö Stormyr, Hälsingfors Stormyran, Stortjärn, Hålmyran), as well as one drained peatland forest (Hälsingfors forest), that are studied within this project. All sites are at 260-300 meters above sea level, hence slightly above the highest coastline (Externwebben SLU 2022). Degerö Stormyr is an intensively studied peatland complex that consists of mires with different vegetation compositions but that is dominated by Sphagnum moss and half grass. The deepest peat layers at Degerö Stormyr have been dated to 8000 years old and the peat thickness is 3-4 m on average and approximately 8 m at most (Nilsson et al. 2008). It is underlain by a relatively impermeable layer of mineral glacial till and gneissic bedrock (Malmström 1923). The mire located at Trollberget Experimental Area was recently (fall 2020) restored through blocking of a drainage ditch (which has been present for approximately 100 years) to re-establish wetter conditions. The mire is equipped with two logger pairs, one located on the restored mire (TB2) and one located downstream of where the ditch has been blocked (TB1), hence at a section that is still drained by the ditch (although it is overgrown with vegetation and likely has limited drainage capacity), allowing for comparison between the sites. Lastly, two mires located close to the Svartberget research station are included in this study. For one of these mires (RW), the conditions have been altered through deepening of the water outlet, which potentially could result in similar effects as drainage.

In order to be able to investigate peat volume change capacity for mires of different ages, the mires described above were divided into four different age classes. For the mires on the chronosequence, the three age classes *young*, *intermediate* and *old* created by previous studies (Wang et al. 2020; Wang et al. 2021) were used. Apart from Degerö, the mires around Vindeln have not been systematically dated. Nevertheless, they are evidently older than the oldest chronosequence mires, and they are thought to be between 4000 and 8000 years old. They have in this project thus been grouped into the additional age class *very old*. There are two mires, however (Trollberget and Svartberget (Shallow Mire)), for which the age is unknown and they are thus not included in any age class. All sites have been probed to determine the peat depth where the water level loggers were installed (see Figure 3 for the depths and comparison between sites).

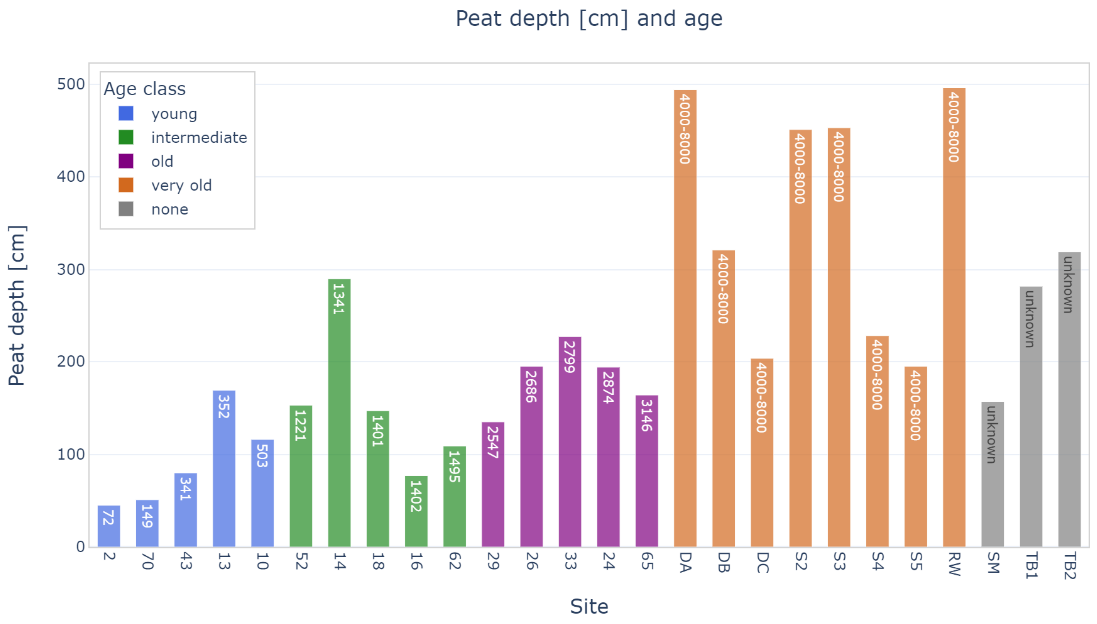


**Figure 3:** Probed peat depth at the sites where the water level loggers were installed. The sites are sorted for increasing age and the age for each site is shown as numbers [years] on the bars.

## 3.2 Data description

### 3.2.1 Groundwater level measurements

This thesis is based on time series measurements of groundwater levels at the studied peatland sites during May – November 2021, using pairs of Odyssey® Xtreem Capacitance Water Level Loggers. Water level was measured both relative to a fixed elevation (the absolute groundwater level) and relative to the mire surface (the relative groundwater level). From these measurements, it is possible to obtain the absolute water level relative to the mineral soil underneath the peat layer, the water level relative to the mire surface (i.e. the water table depth), and the absolute mire level. The data collection was not a part of this thesis project but its execution will be outlined in the following sections for understanding of the origin of the data.

***Capacitance-based water level loggers***

The groundwater level data used was measured by Odyssey® Xtreem Capacitance Water Level Loggers (Figure 4). This measuring device consist of a Teflon-coated sensor cable held down by a weight that measures the capacitance outside the cable in order to convert it to water level height. A capacitor is made up of two conducting plates or cylinders, separated by a material with insulating properties called a dielectric. The recorded value of the capacitor is directly proportional to the area of the two plates. In the Xtreem sensors, Teflon is used as the dielectric. In the Xtreem sensors, one plate is the measuring element covered in Teflon (Teflon is the dielectric) and the other plate is the water in which the sensor is immersed. Since the recorded value is proportional to the area of the plates, the variation in capacitance is directly proportional to the variation in water table height of the water which is in contact with the Teflon sensor (Dataflow systems LTD 2020).

Data recorded by the loggers were collected from the field using a smartphone application that directly uploads the data to a data portal (the Dataflow Xpert Portal). The loggers had been calibrated in a lab before installation in the field according to instructions in the user manual (Dataflow systems LTD 2020). The sensor cable was marked in two places (one mark close to each end) and then lowered into a container filled with tap water up to each mark. The value recorded by the logger at each mark was entered into the Dataflow Xpert Portal together with recorded logger temperature, allowing the software to calibrate the logger according to the measurements. The length of the Teflon sensor was 1 m except for site 70, 20, 43, and 16 which had a sensor of 0.5 due to the shallow depth of the mire.

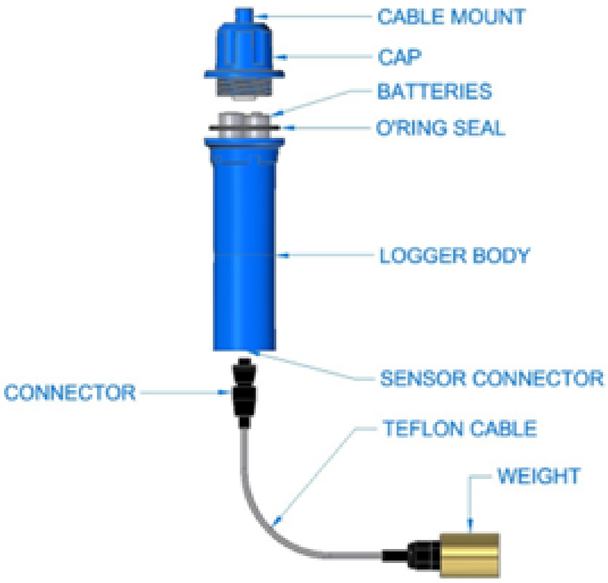


**Figure 4:** Illustration of the Odyssey® Xtreem Capacitance Water Level logger used for groundwater level measurements (Dataflow systems LTD 2020).

***Logger set-up***

The loggers measuring water level at the studied mires were set up as part of an internship project at the beginning of summer 2021. The idea of the method used is to determine the level position of the mire surface by obtaining the water level from two different types of setups. Each site was hence equipped with two Odyssey loggers as shown in Figure 5 and 6; one fixed relative to the mineral soil layer beneath the peat by a construction with metal poles anchored in the underlying layer, and one attached to a plastic grid placed on top of the mire surface. This allows measurements of the water level relative to the fixed substratum below, and of water level relative to the moving peat surface. The loggers and the sensor were protected by a screened PVC tube which allows water to pass through but without solids and dirt which could damage the sensor. By knowing the length of different components of the setup ($L_{1\text{-}3}$, absolute groundwater level ($GWL_{\mathrm{A}}$) relative mineral soil layer below, relative groundwater level ($GWL_{\mathrm{R}}$) (or water table depth), as well as the surface position of the mire ($Z_{\mathrm{mire}}$) relative to the mineral soil could be calculated (Equation 4, 5, 6).

Each unique peatland has one pair of loggers installed to measure the water levels, with a few exceptions. Degerö Stormyr was equipped with a triplet of logger pairs on three separate but nearby sites on the mire (DA, DB, DC). Hälsingfors forest was equipped with one logger pair on a site with an open forest (S4) and one pair on a densely forested site (S5). The recently restored mire at Trollberget was equipped with one logger pair on the restored mire while a second pair was installed on a site downstream of where the drainage ditch had been blocked.

$$GWL_{\mathrm{A}} = H_{\mathrm{A}} + L_{\mathrm{A1}} - L_{\mathrm{A2}} - L_{\mathrm{A3}} \tag{4}$$

$$GWL_{\mathrm{R}} = L_{\mathrm{R1}} - L_{\mathrm{R2}} - H_{\mathrm{R}} \tag{5}$$

$$Z_{\mathrm{mire}} = GWL_{\mathrm{A}} + GWL_{\mathrm{R}} \tag{6}$$

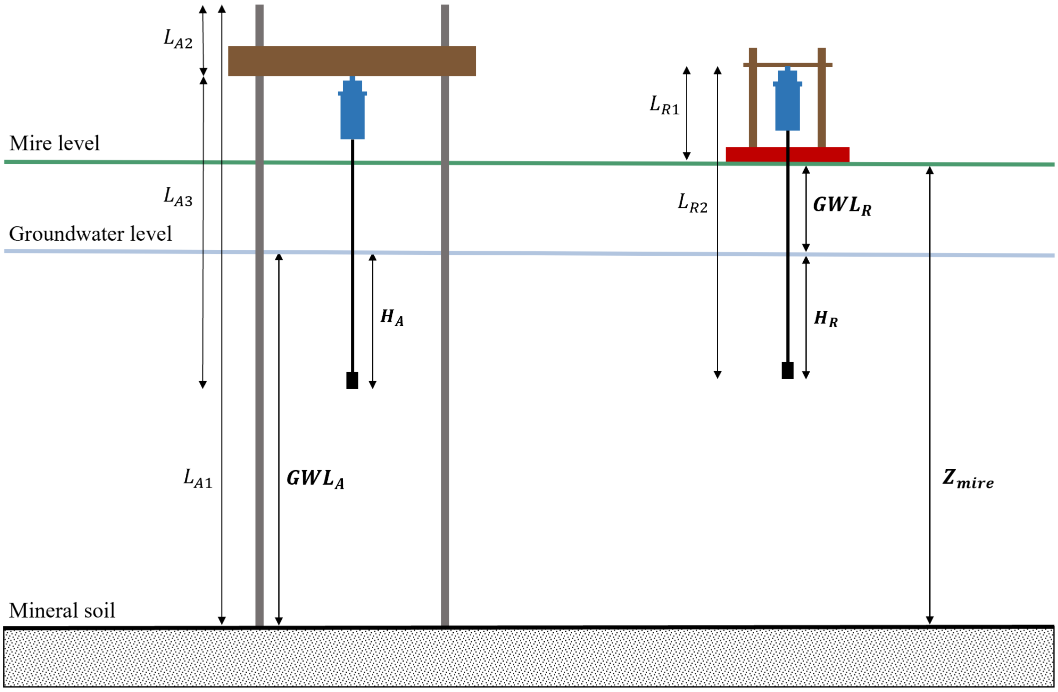


**Figure 5:** Illustration of the groundwater level measurement setup with a pair of loggers. One logger measures the absolute groundwater level ($GWL_{\mathrm{A}}$) by being fixed to the underlying mineral soil, and one logger measures the relative groundwater level ($GWL_{\mathrm{R}}$) by being attached to a grid floating on the mire surface. $GWL_{\mathrm{A}}$ and $GWL_{\mathrm{R}}$ are calculated from the distances $L_{A1}$: length of left metal tube, $L_{A2}$: distance from the top of the left metal tube to the top of the blue logger case, $L_{A3}$: distance from top of the blue logger case to the bottom of the weight, $L_{R1}$: distance from the top of the blue logger case to the bottom of the red grid, $L_{R2}$: distance from top of the blue logger case to the bottom of the weight, and also $H_A$ and $H_B$: the height of water measured by the sensor relative the bottom of the weight.

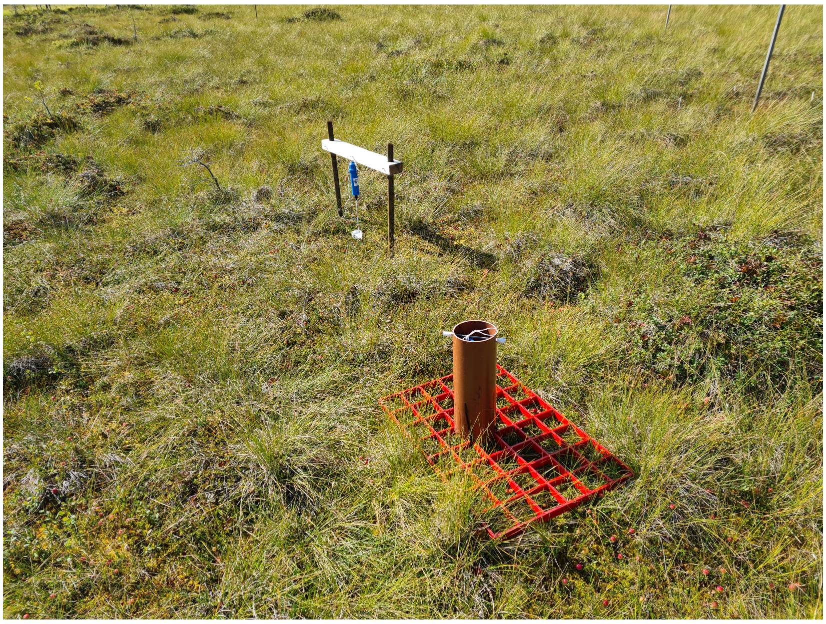


**Figure 6:** Photo of the groundwater level measurement setup with a pair of loggers at one of the mires on the chronosequence (site 29).

### 3.2.2 Quality control and pre-processing of data

The above-described field measurements resulted in a dataset of water level measurements recorded in mm at 10-minute intervals (UTC+2) between May and November 2021 (the exact time period differs between sites). The original data was controlled for quality and pre-processed in several steps as described in the following paragraphs.

Initially, the raw data were manually screened to determine plausibility, for example by inspecting time series graphs. To structure the quality control, data points were flagged using different classes. Data points that strongly deviated from the expected value were either classified as *outlier*, *offset*, *suspicious*, or *error* depending on the possible explanation and character of the deviation. Some data points were recorded before the installation date, and the water level might require an unknown amount of time to stabilize after the disturbance caused by the installation. Therefore all data points recorded on the day of installation and before were flagged as premature. Premature, outlier, suspicious, and erroneous data were removed from the dataset. Data points flagged as offset were corrected based on manual groundwater level measurements as explained further below. All other data points were flagged as valid and kept as there were no circumstances that indicated that the measurement should not be valid. The classes are outlined and described in Table 2 below.

Due to varying installation periods, collection campaigns, and functioning of the loggers, the final quality-controlled dataset consisted of time series of varying lengths for each of the studied sites. The time period with recorded data, as well for what time period data was removed and kept is illustrated in Figure 7. One of the loggers for site S1 did not record any data during the period, thus site S1 was excluded from any further investigation.

**Table 2:** During the quality control, the raw data was flagged using the classes listed in this table. The table includes a description of each class and how the data points in each class were handled.

| **Class** | **Description** | **Measure** |
|---|---|---|
| Valid | No known reason that indicates that the measurement is not valid. | Kept |
| Premature | Data points recorded by logger before the installation date. To be safe, data points recorded on the installation date were also flagged as premature, as the water level required an unknown amount of time to stabilize. | Removed |
| Outlier | Single or a few data points that deviated strongly from the other values, that were not present in measurements for the other logger, and could not be explained by a rain event. | Removed |
| Offset | Relative changes in water level were thought to be correct but the absolute level was incorrect, for example due to calibration error. See Appendix A for more detailed information. | Corrected and kept |
| Suspicious | Range of data points that deviated strongly from the expected range and that couldn't be explained by for example rain events. | Removed |
| Error | Logger malfunction, values showing 6553 which is a threshold value. Also values in between such a period. | Removed |

**Figure 7:** Illustration of the time periods of data available for each site where data has been removed during the quality control.

***Adjusting data based on offset from manual groundwater level measurements***

Available data of manual groundwater measurements obtained from the studied sites during the study period were used to check the plausibility of the data recorded by the loggers. Manual measurements had been performed using a bubbler on 1-2 occasions for each site. The bubbler was made of a plastic tube connected to a hollow metal rod. The rod was gradually lowered into the PVC tube next to the sensor cable while blowing into the plastic tube on the other end until bubbles could be heard when the rod met the water surface and its position could be recorded. The manual measurements were directly compared to the logger measurements, however, as only the date and not the specific time of manual measurements had not been recorded, the values could not be compared to a specific point in time. Instead, the average water level from logger measurements was calculated between 06.00-20.00. This value was compared to the manual measurement by taking the difference between them to obtain a correction term. A few of the loggers had *two* manual measurements. For these, the above described procedure was performed for both days to get the offsets. The correction term was then calculated as the average between the two offsets for the different days. For comparison, the daily variation (between 6.00 and 20.00) was calculated as the difference between the minimum and maximum values that day. A large span would indicate that a large difference between logger values and manual measurements could be accurate as it would depend on at what time the measurements would have been taken. The raw data measurements were then corrected by adding the correction term specified in Table 6 in Appendix before computing $GWL_\mathrm{A}$ or $GWL_\mathrm{R}$ according to Equation 4 or 5.

Two sites (S3 and S4) were also compared to water level measurements done for another project using Divers installed about 0.5 m from the Odyssey loggers. Comparing the time series data between the two loggers displayed an offset of the same size as between the Odyssey logger measurements and manual groundwater measurements, confirming that the manual measurements were likely accurate and that adjusting the raw data was a justified measure. By adjusting the data with the calculated correction term, the offset caused by the calibration error earlier described for some loggers was also corrected.

### 3.2.3 Precipitation data

To complement the groundwater level measurements and get further insight into the variation in groundwater level, precipitation data for the studied sites were downloaded from SMHI (SMHI 2022). Precipitation data from two different stations were used. Data from the station Umeå-Röbäcksdalen was used for representing the precipitation occurring at the chronosequence-mires, and data from the station Vindeln-Sunnansjönäs was used as a representation of the precipitation occurring at the sites around Vindeln. The data was aggregated into daily values and the total amount of precipitation during the measuring period 2021-06-23 - 2021-08-23 was 209 mm for Vindelns-Sunnansjönäs and 120 mm for Umeå-Röbäcksdalen.

## 3.3 Data Analysis

Analysis of the data was performed in the programming language Python. Due to the varying time periods of the dataset for the different sites (illustrated in Figure 7), different subsets of data were used depending on the analysis. If only the time period had been used for which data for all sites were available, it would have resulted in a very short time range. This would have significantly limited the analysis. The time period used for analysis is important due to the nature of the mire and water table fluctuations and its response to rain. Whether a rain event is included or not in the time series that is used for analysis can have a significant effect on the results. The goal was to keep as much data as possible in order to not lose any important information, while at the same time providing a data set that allows for a just comparison between different mires. The properties of the data used for each analysis are listed in Table 3.

**Table 3:** Properties of the dataset used for each analysis. The properties includes which parameter ($GWL_R$, $GWL_A$ or *MIRE LEVEL*), the subset time period used, and if the data has been aggregated.

| Analysis | Parameter | Time period | Aggregation |
|---|---|---|---|
| Inspection of time series graphs | $GWL_A$, $GWL_R$, MIRE LEVEL | Entire valid time period | Original data (10 min interval) |
| Statistics: median, IQR and boxplots | $GWL_A$, $GWL_R$, MIRE LEVEL | 2021-06-23 to 2021-08-23* | Original data (10 min interval) |
| Monthly statistics: boxplots | $GWL_A$, $GWL_R$, MIRE LEVEL | Entire valid time period | Original data (10 min interval) |
| Maximum peat volume change | MIRE LEVEL | 2021-06-23 to 2021-08-23* | Original data (10 min interval) |
| Linear regression and specific storage | MIRE LEVEL | Entire valid time period | Daily means |

* All sites did not have data for this entire time period so the analysis was done on data from a shorter time period: Aug 1 - Aug 23 for site S5, Jun 30 - Aug 23 for SM, and Jul 14 - Aug 23 for site TB1.

### 3.3.1 Trends in groundwater level and mire surface level

The quality controlled data was examined by visualizing the time series of mire level, absolute groundwater level, and relative groundwater level (water table depth relative to mire surface) in graphs. To clearly see how absolute and relative water level are related, the parameters were presented as the change relative to a specific date as the reference point. The change in level since the initial measurement would have been a good representation, but since the day of the initial measurement was different for the sites, August 1st was picked as the reference point as this day is included in the measurement period for all the sites (see Figure 7). The time series were also compared to precipitation during the period in order to detect any trends or patterns related to rain events. All data that had passed through the quality control was examined during this step.

The time series of mire level, absolute water level, and water table depth were also explored by calculating descriptive statistics like the median and the range of variation as the interquartile range (IQR). The interquartile range (IQR) is the most commonly used resistant measure of variability. It measures the range of the central 50 percent of the data and is not influenced by the upper or lower 25 percent (Helsel et al. 2020). These statistics were represented graphically in boxplots. In order to be able to compare these statistics between sites a subset of the data was used for this analysis. The subset time period was June 23 – August 23. Even though a few of the sites did not have valid data for this entire period, these where included using the same procedures, and any indications of the result differing due to this fact was noted. Boxplots with median and IQR were also calculated on a monthly basis using the entire available time period. This was done to display and highlight any monthly variations. The results were compared between the mire to see if there was any trend standing out. In particular, distinctions that were analyzed for were differences between the age classes, differences that could be explained by a site being drained, and differences between TB1 and TB2 in particular where noted. These results are of importance to the explanation of the results from further analysis.

### 3.3.2 Magnitude of peat volume change

The magnitude of peat volume change was represented by the maximum peat volume change, i.e. expansion or contraction, observed during the study period. To be able to compare between site the subset time period June 23 – August 23 was used. The maximum expansion/contraction was calculated as the difference between the 90th and 10th percentile of the absolute mire level data. This value was calculated for all 26 sites.

To investigate if there was any significant difference between the compression/expansion for different age classes, *Wilcoxon rank sum test* was used. The rank-sum test determines whether there is a tendency for one group to produce larger observations than another group. The assumptions that must hold for the rank-sum test are random samples, independence and ordinal scale. The test is a non-parametric test and does not require equal variance or normality of the data distribution, in fact no assumptions about the distribution is made (Helsel et al. 2020). The data was tested using Wilcoxon rank sum by using the function *ranksums()* in *SciPy* library with a significance level set to 0.05.

### 3.3.3 Linear regression and specific storage

To determine the specific storage of the studied sites, the approach described in Section 2 and Equation 3 was used. For each site the relationship between absolute water level and mire level was investigated through scatter plots of daily mean values from the entire time series. The scatters was centered around zero by subtracting the mean from each value. To be able to obtain the elastic storativity $S_\mathrm{s} \times b$ as the slope of the linear regression, there must be a reasonable linear relationship and linear fit between the water level and mire level. A linear relationship was, however, not always present, since dynamic situations as well as other processes controlling change in mire surface level may have caused the water level and mire level to not be in equilibrium. From the initial scatter plots it was observed that the linear relationship differed between the first and second half of the measuring period, as mainly drying and compression occured in the first half and rewetting, through increased precipitation, and expansion occured in the second half. Therefore, the data was divided into two subsets based in these two phases, one for the drying (compression) phase and one for the rewetting (expansion) phase.

The slope of the linear regression was thus calculated for both compression and expansion. Linear regressions with and $\mathrm{R}^2 > 0.6$ was considered as an acceptable estimation of the relationship. For those sites where this criteria holds, the slope of the linear regression ($S_\mathrm{s} \times b$ according to equation 3) was used to calculate the specific storage $S_\mathrm{s}$. To do this, $S_\mathrm{s} \times b$ was divided by the aquifer thickness $b$. If one were to divide with the total aquifer thickness, this is done with the assumption that the whole peat profile is compressible. It is likely that the old decomposed and dense peat much less compressible and has a lower $S_\mathrm{s}$. Therefore, $S_\mathrm{s} \times b$ was instead divided by the standardized depth $b$ = 0.5 m to obtain the specific storage. The aim was to compare these values within the age classes young, intermediate, old and very old as well and determine the statistical significance through Wilcoxon rank-sum test, however, this was not possible due to the final calculations resulting in too few samples in each age class.

# 4 Results

## 4.1 Temporal trends in water table change and peat volume change

By visually inspecting time series graphs of mire surface level, absolute groundwater level ($GWL_A$), and relative groundwater level ($GWL_R$), also referred to as the water table depth, several trends and characteristics of water table change and peat volume change were identified. Time series graphs for two of the sites (site DA at Degerö Stormyr and site 29 on the chronosequence) are displayed as examples of the general trends in Figure 8 and 9, while the time series graphs for the remaining sites can be found in Appendix C.

It was generally observed that the groundwater level was strongly affected by rain events, as larger rain events corresponded to immediate peaks in both $GWL_A$ and $GWL_R$ (see example in Figure 8 and 9). The mire level response to these changes in groundwater level, as well as the relation between $GWL_A$ and $GWL_R$, differed between mires. For several mires there was a clear trend of the mire surface level following the fluctuations in water level; a rise in $GWL_A$ is followed by a rise in mire level and vice versa. This trend was clear for site DA (Figure 8), DC, S3, S5, 13, 52, 14, 33, 65, TB1 (Figures in Appendix C). For other mires, however, the mire level does not appear to be affected by changes in water level, as seen by the nearly constant mire level during the measurement period despite larger fluctuations in $GWL_A$. This behaviour was clear for site 70, 18, 16, 29, 26, 24 (Figures in Appendix C). The nearly constant mire level at these sites also resulted in limited buffering of the water table depth relative to the mire surface, as seen in how closely $GWL_R$ follows the changes in $GWL_A$ (Figure 9). This is in contrast to the behavior of mires similar to site DA (Figure 8), where the change in $GWL_R$ tends to be smaller than the change in $GWL_A$, thus displaying a buffering effect by the mire level change on the water table depth relative to the mire surface. For the sites that are not mentioned above, the relationship between mire level, $GWL_A$ and $GWL_R$ was not as clear and it was difficult to draw any conclusions from visually inspecting the time series graphs. The relationship between $GWL_A$ and mire level was however investigated further through the scatter plots of which the results are described in Section 4.3.

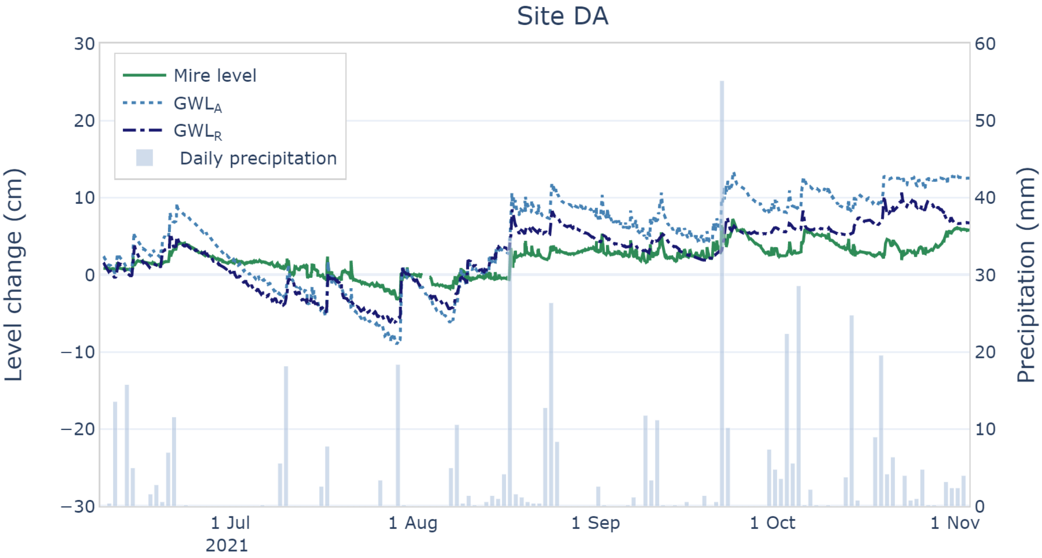


**Figure 8:** Time series of mire surface level, absolute groundwater level ($GWL_A$) and relative groundwater level ($GWL_R$) (water table depth relative to the mire surface) presented as the level change relative August 1. Positive values mean the mire surface or water level is at a higher position relative August 1. This graph is for site DA located at Degerö Stormyr, one of the *very old* mires. Also daily precipitation as rain from the station Vindeln-Sunnansjönäs.

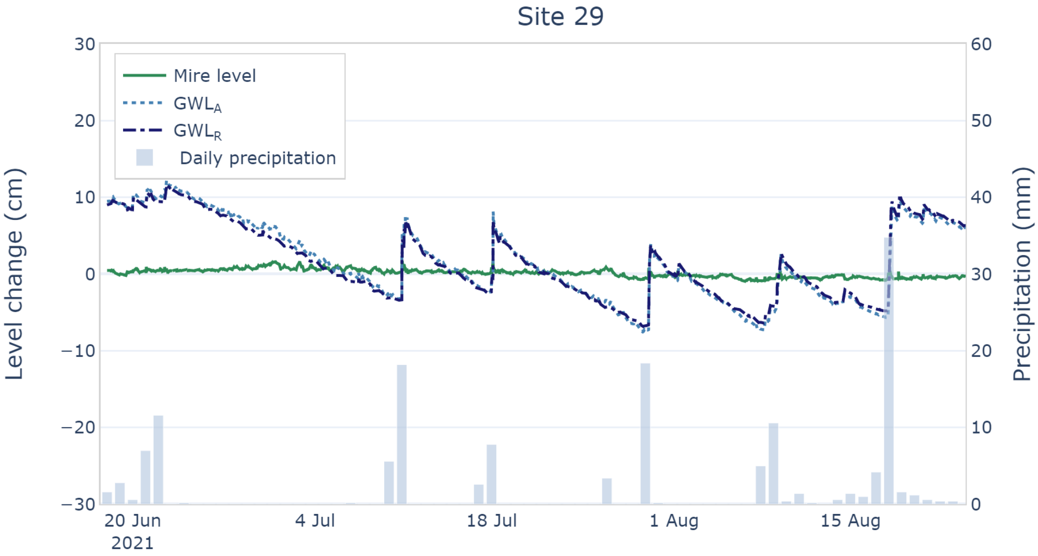


**Figure 9:** Time series of mire surface level, absolute groundwater level ($GWL_A$) and relative groundwater level ($GWL_R$) (water table depth relative the mire surface) presented as the level change relative August 1. This graph is for site 29 on one of the *old* chronosequence-mires. Also daily precipitation as rain from the station Umeå-Röbäcksdalen.

Hydrometeorological characteristics of this study period that were observed in the graphs include; an extended dry period (no rain) of approximately 18 days between June 22 and July 10 along with a steady decline in $GWL_A$; a few larger rain events causing peaks in water level with a quick rebound to the trend of decline; and an increase in the frequency of rain events in August followed by increased water levels. For the majority of the studied sites, minimum $GWL_A$ occurred on July 29th. The exceptions were the intermediate age chronosequence sites 62 and 14, located close to each other on the coast, site RW and SM with a minimum occurring on August 7th, as well as site TB1 with a minimum on July 10th. The maximum observed $GWL_A$ for the studied sites occurred either right at the beginning of the measuring period in June or at the end of the dry period in late August, depending on the available data. The absolute maximum is most likely right after snowmelt when saturated conditions occur, however, this was not captured by this measuring campaign. Another phenomenon that was observed on a few occasions was a sudden drop in mire level following an increase in the water level during a rain event, for example as observed for site 26 (Figure 8 in Appendix C). It was not possible to determine if this was more common or not for certain mires by visually inspecting the graphs, as this would require careful inspection day by day for all sites to detect every time this phenomenon occurred.

The median $GWL_R$ recorded for the chronosequence sites ranges between 2.8-14.5 cm and the variation, represented by the interquartile range (IQR) ranges between 0.7-8.7 cm. For the Vindeln-mires, the median is 3.3-47.8 cm and IQR 2.2-16.5 cm (Figure 10). The median $GWL_R$ is slightly deeper for the *old* mires compared to the *young*, but there is no indication that the $GWL_R$ IQRs vary with the age of the mire. However, some sites stand out in other aspects.

The two drained and forested sites S4 and S5 have a significantly deeper water table (median $GWL_R$ is 45.5 and 47.8 cm) and thus a large unsaturated zone, compared to all other sites. Site S2 (natural) also has a notably deep water table. The water table depth reached more than 20 cm below the surface at some point during the measurement period for additional sites as well (site 70, 16, 29, 24, 65, S3, TB2), indicating an occasional relatively large unsaturated zone. The oldest *young* mires (13 and 10) and the youngest *intermediate* mires (52 and 14) stand out by displaying a smaller variation in $GWL_R$, as shown by the small IQR:s. In addition, the *old* site 33 displays a similar small range of variation. The three sites at Degerö display a slightly different median ($GWL_R$) (7.2-13.1 cm) although they are located on the same mire. This is although in the range reported by previous studies (Yurova et al. 2007).

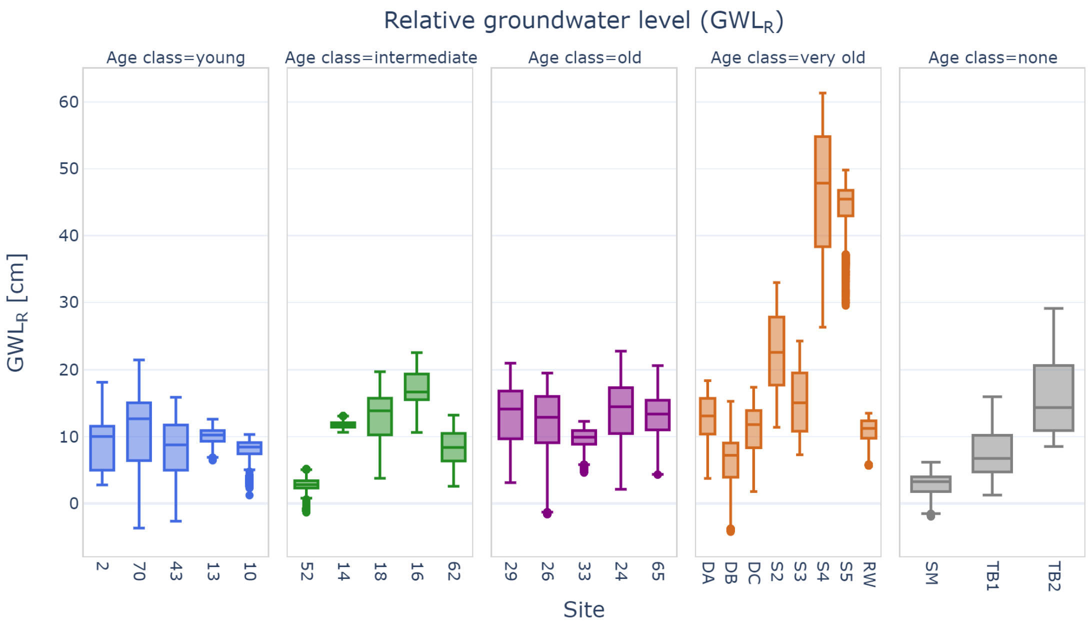


**Figure 10:** Median relative water table depth and the variation as represented by the IQR. Based on data from the period Jun 23 – Aug 23 2021, with the exception of site 16, S5, SM and TB1 that are based on data for shorter time periods.

Negative GWL$_R$ values, as seen in the whiskers for some sites in Figure 10, occur when the water table rises above the mire level as the mire is flooded. This happened on a few occasions at some sites (site DB, SM, 2, 70, 43, 52, 26, 33, and 24) mainly as a result of the more frequent rain events that occurred in August. In general, however, the water table stayed below the mire surface at all sites as can be seen in the lower median absolute groundwater levels compared to the median mire levels (Figure 11 and 12). The median mire level (ie. the peat thickness) ranges from 0.59 to 4.99 m and the median GWL$_A$ from 0.46 to 4.86 m for the studied sites. Since GWL$_A$ was measured relative to the mineral soil, it is directly related to the thickness of the peat layer, hence the mires with thick layers also have large median GWL$_A$ values.

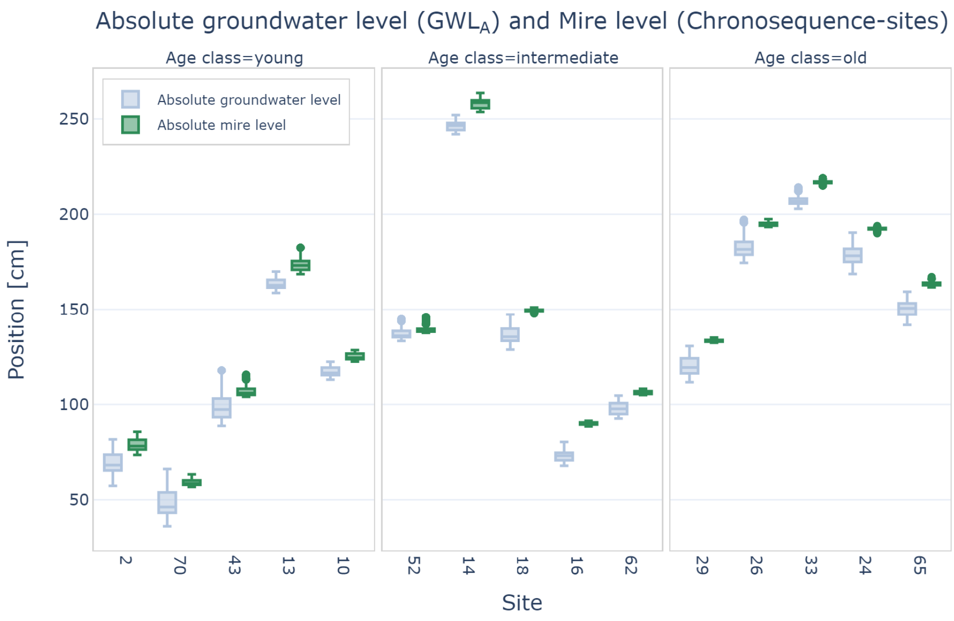


**Figure 11:** Median mire level and absolute groundwater level, and the range of variation as represented by the IQR for sites on the chronosequence. Based on data from the period Jun 23 – Aug 23 2021, with the exception of site 16, S5, SM and TB1 that are based on data for shorter time periods.

**Figure 12:** Median mire level and absolute groundwater level, and the range of variation as represented by the IQR for sites around Vindeln. Based on data from the period Jun 23 – Aug 23 2021, with the exception of site 16, S5, SM and TB1 (see caption in Figure 10 for more details).

The IQR:s for $GWL_R$, $GWL_A$, and mire level can be seen in the boxplots (Figure 11 and 12), but for easier comparison the IQR:s was also presented in a bar graph which can be found in Appendix D. The variation in mire level represented by the IQR is smaller for the intermediate and old age class compared to the young, with the exception of mire 14 (Figure 11). The mire surface level does not fluctuate as much as the absolute water level, as can be seen in the smaller IQR for the mire level (0.6-5.7 cm) compared to the water level (2.6-13.7 cm) (Figure 11 and 12). There are two exceptions though, for *young* site 13 and the *intermediate* site 14 the mire level IQR is larger than the IQR for absolute water level. Site 2, 13, and 14 stand out among the chronosequence sites with mire level IQR greater than 4 cm. Site S3 and TB1 stand out among all sites with a mire level IQR greater than 5 cm.

Another interesting observation is that the IQR for the groundwater level relative to the mire surface ($GWL_R$) is smaller than the IQR for absolute water level ($GWL_A$). This displays the buffering effect that mires surface fluctuations have on the variation in water table depth. There are exceptions though (site 26, RW, S2, S5, and TB2), where the range in water table depth is greater than the range in absolute water table height.

The median and IQR values for mire level, $GWL_A$ and $GWL_R$ are presented in Table 7 in Appendix D.

## 4.2 Maximum peat volume change

The maximum peat volume change, calculated as the differences between the 10th and 90th percentiles of mire surface level in the summer ranged between 1.24 - 10.26 cm (Figure 13). In general, it seems like the maximum volume change is smaller for older mires, although there is no clear trend of decreasing volume change with increasing age. The main finding was that there is a significant ($p < 0.05$) difference in maximum peat volume change between the *young* and *old* chronosequence mires, with the *old* mires displaying less volume change during the study period. Wilcoxon rank-sum test showed a significant difference between between *young*-*old* mires, *young*-*very old* mires, and *old*-*very old* mires (Figure 14 and Table 4). Older chronosequence sites, the sites in the *old* class as well as the three oldest in the *intermediate* class, have a similar volume change (1.3-2.1 cm) that is clearly less than the remaining younger sites. The *very old* age class however does not follow this pattern of decreasing volume change with age, thus the results do not show a general trend in that regard.

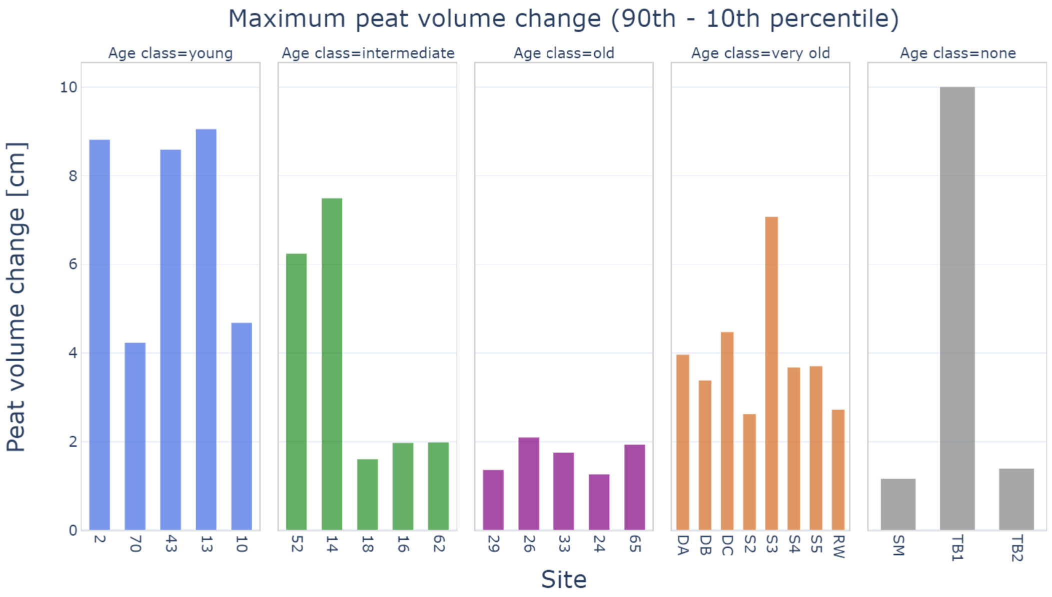


**Figure 13:** Maximum peat volume change calculated as the difference between the 10th and 90th percentile. Just like in previous analyses, the compression for site TB1, SM, S5 and 16 is calculated with data from a shorter time period than the other sites

A considerably large amount of volume change occurred for the site located on the downstream side of a blocked drainage ditch (TB1), compared to all other sites and particularly compared to the site located on the rewetted mire on the upstream side of the blocked ditch (TB2). Looking at the drained sites S4 and S5 and comparing them to other natural sites nearby (S2, S3, and Degerö) does not give any indication of drainage affecting the maximum peat volume change. Instead, the natural mire S3 stands out with a much larger compression compared to other sites.

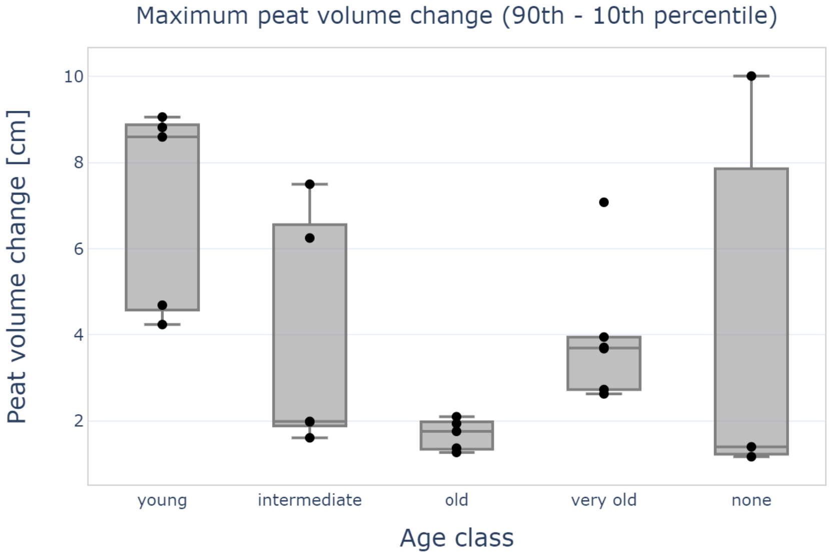


**Figure 14:** Maximum peat volume change grouped for each age class. The black markers represent the median value for each site in that age class.

**Table 4:** Results from Wilcoxon rank-sum test between maximum peat volume change for different age classes. P-values in bold indicate a significant difference ($p < 0.05$) between the two listed age classes. For this statistical test, the mire Degerö Stormyr was represented by the mean maximum peat volume change of the three sites on this mire (DA, DB, DC).

| Age class | p-value |
|---|---|
| Young - Intermediate | 0.076 |
| Young - old | **0.009** |
| Young – very old | **0.018** |
| Intermediate - old | 0.117 |
| Intermediate – very old | 0.808 |
| Old – very old | **0.006** |

## 4.3 Specific storage and relationship between water level and mire level

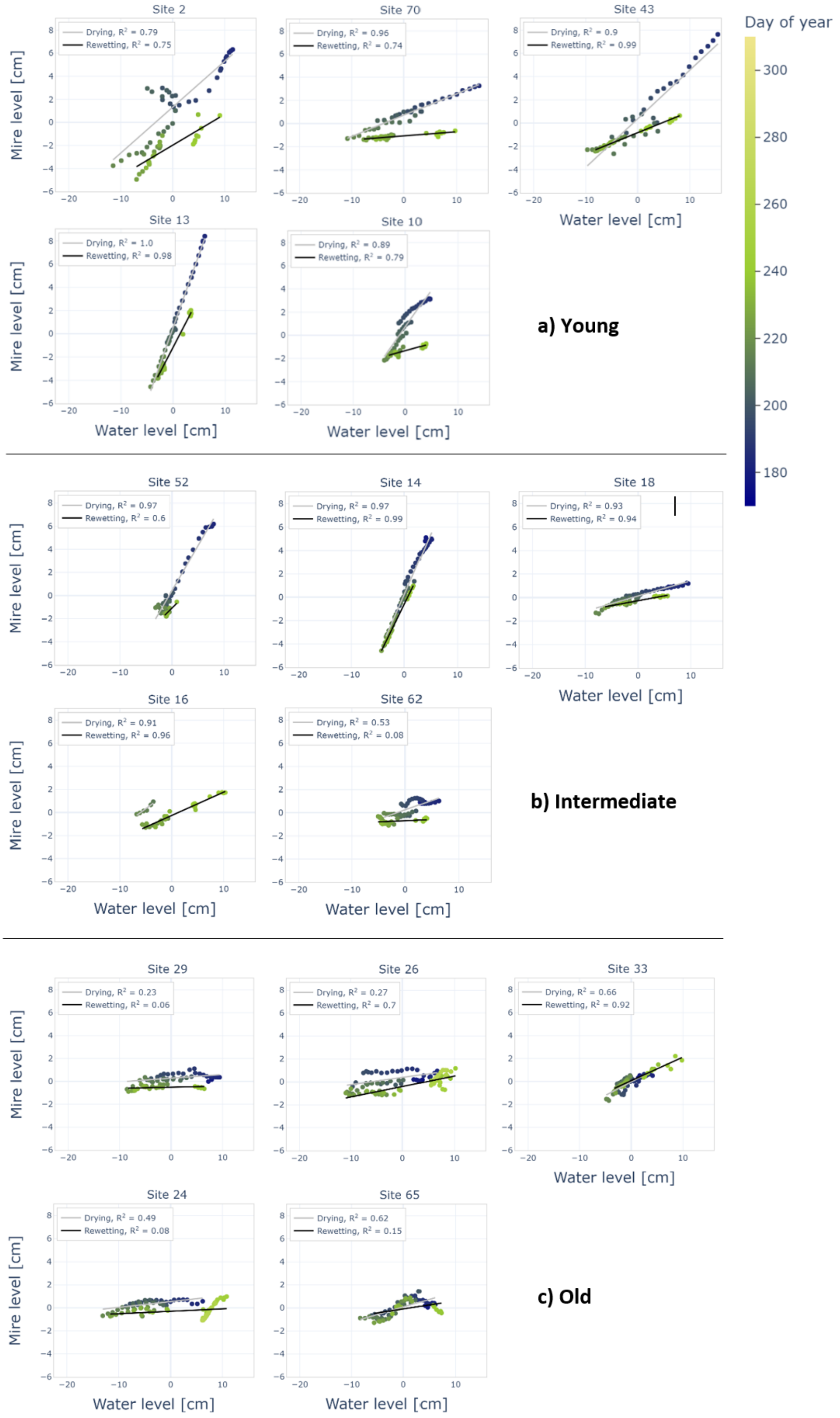
An almost perfect linear relationship between absolute groundwater level and mire level was observed for several sites (site 70, 43, 13, 10, 52, 14, 18, S3, TB1) (Figure 15). However, other sites display a more dynamic relationship. The *old* chronosequence sites 62, 29, 26, 24, 65 gives rather scattered results. The exception is 33 with a clear linear relationship.

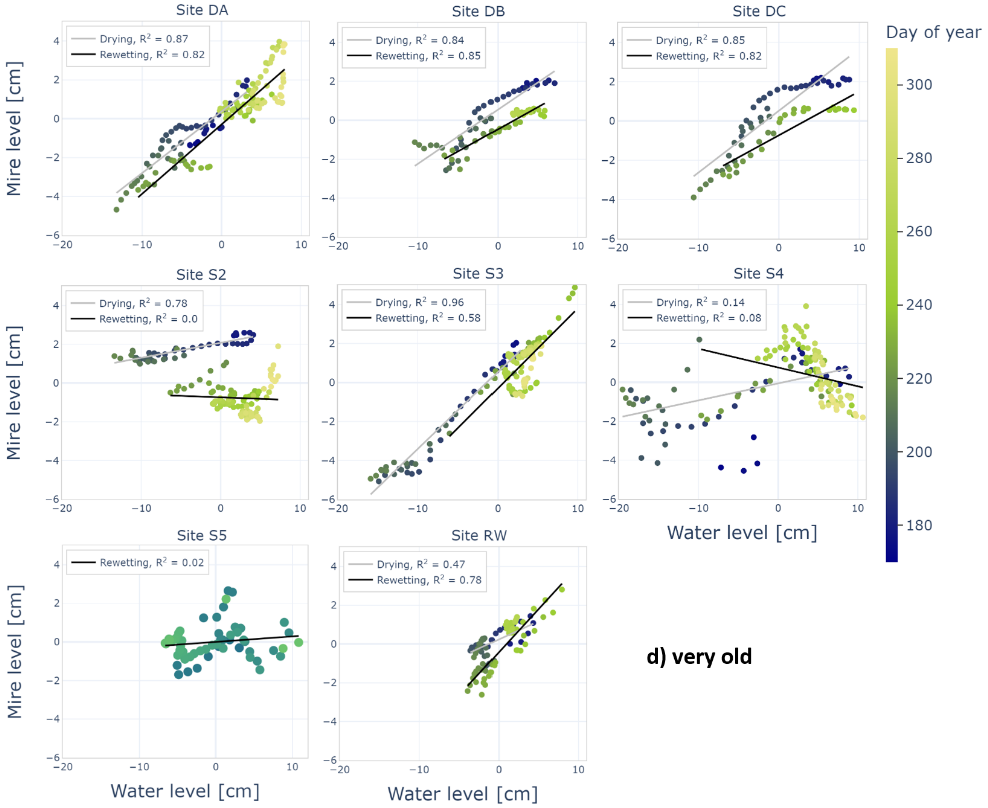
For several of the sites, a changing trend was observed towards the later part of the measuring period, with a shift in the direction of change and in the slope of the linear regression. This is most pronounced in the scatter for site 70 and 43 (Figure 15). This changing trend was identified to occur on July 30. The day before marked the driest day, i.e. the day with the lowest recorded water level, and on July 30 a rain event occurred which significantly raised the water table. The following period was characterized by generally wetter conditions. Because of this, the relationship between absolute groundwater level and mire level was further investigated for a drying and a rewetting phase, which could also be generally characterized as an expansion and compression phase based on the direction of the relationship. The compression phase consists of the days from the start of the measurements until the point in time when the lowest water levels occurred (July 29), and was characterized by a general decrease in mire level although some rain events led to a shorter time period of expansion before going back to the compressing trend.

From the scatter plots in Figure 15, it was also observed that the differences in the characteristics of these two phases also differed between mires. During the rewetting period for site TB1, DA and S3 the mire level rebounds to the same level as at the beginning of the drying period. For site 70, 42, 10, and S2, however, the mire level does not rebound, but remains at a lower level, only slightly increasing as the water level goes up during the rewetting.

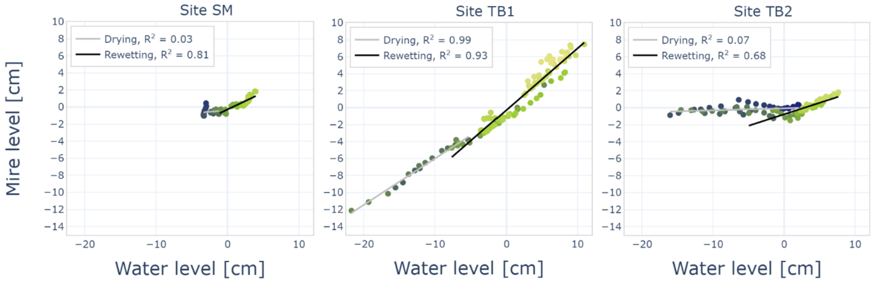
For a few of the sites, the driest point in time is not actually June 30, as mentioned in section 4.1.

Relationship between absolute groundwater level ($GWL_A$) and mire level





**d) very old**



**e) none**

**Figure 15:** The relationship between absolute groundwater level and mire level for mires of the a) *young*, b) *intermediate*, c) *old* and d) *very old* age class, and e) the mires with unknown age. The values are presented relative to the mean for each site to center the scatter around zero, and the linear regression fit and its R$^2$-value is displayed for the drying and rewetting period. The coloring indicates the day of year (day 180 was June 29 and day 300 was October 27) and highlights the direction of change. Note the y-axis range differs for the age class *very old* and *none*.

The results of the linear regression analysis are presented in numbers in Table 5. The sites that had a significant and acceptable linear fit ($p < 0.05$ and $R_2 > 0.6$) are highlighted in bold and those are the sites for which the elastic storativity was estimated as the slope of the linear regression. It was noted that the older chronosequence sites are the ones without an acceptable linear relationship for either of the phases (with the exception of site 33), as well as the two drained ”very old” sites S4 and S5.

By dividing the elastic storativity coefficient ($S_s \times b$) by the peat thickness, specific storage was obtained which can be used as an estimate of the peat elasticity. The specific storage calculated for the compression and expansion phase is visually presented in Figure 16. The values ranges from $1.5 \times 10^{-3}$ cm$^{-1}$ to $25.3 \times 10^{-3}$ cm$^{-1}$ for the compression phase and $0.7 \times 10^{-3}$ cm$^{-1}$ to $18.4 \times 10^{-3}$ cm$^{-1}$ during the expansion phase. Just as noted from looking at the graphs above, a difference between the drying and rewetting phase is observed for the specific storage as well. The specific storage is generally greater for the compression phase than the expansion phase. The exception is site DA and TB1. Since some sites did not have a sufficient linear relationship which did not allow for calculation of $S_s$, the number of samples within the age class intermediate, old, and very old were too few to determine if there is a statistical difference between the age groups through Wilcoxon rank-sum test. It can be seen, however, in Figure 16 that the specific storage is generally greater for young mires compared to old.

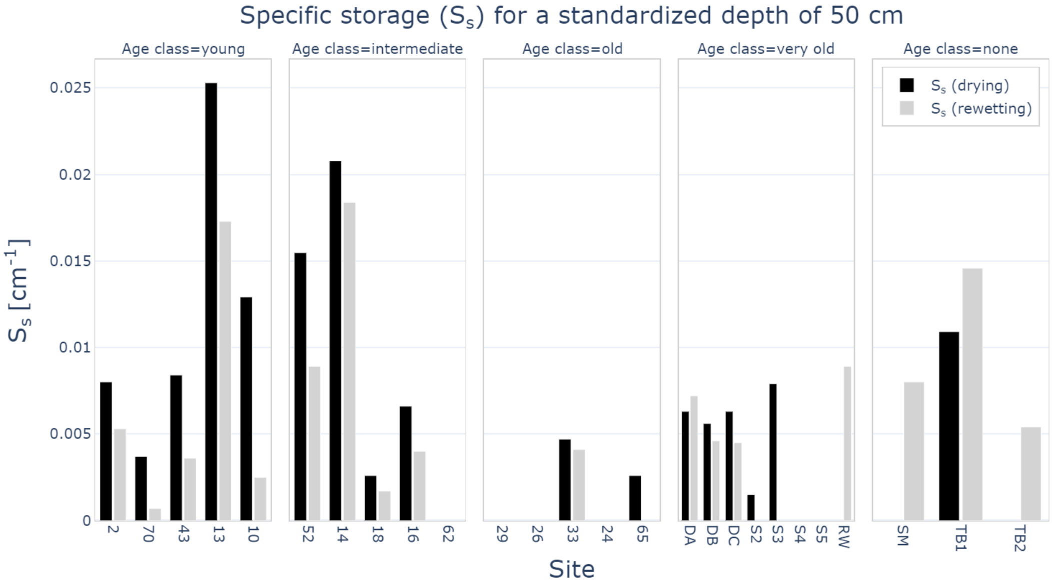


**Figure 16:** Specific storage ($S_s$) for the standardized depth 50 cm, during a drying period where peat compression generally occurred, and during a rewetting period where peat expansion generally occurred. For sites with a linear regression $R^2 \geq 0.6$, $S_s$ was not calculated, which is why a value is missing for some sites.

**Table 5:** Slope and R$^2$-value from the linear regression between absolute groundwater level and mire level, as well as specific storage S$_s$ (cm$^{-1}$ $\times 10^{-3}$) calculated from the slope and a standardized depth of 50 cm. S$_s$ was only calculated for sites with an acceptable linear fit (R$^2$ $\geq$ 0.6), these are highlighted in bold.

| | | **Compression** | | | **Expansion** | | |
|---|---|---|---|---|---|---|---|
| **Age class** | **Site** | **Slope** | **R$^2$** | **S$_s$ (50cm)** | **Slope** | **R$^2$** | **S$_s$ (50cm)** |
| young | 2 | 0.4 | **0.79** | 8 | 0.27 | **0.75** | 5.3 |
| | 70 | 0.18 | **0.96** | 3.7 | 0.04 | **0.74** | 0.7 |
| | 43 | 0.42 | **0.9** | 8.4 | 0.18 | **0.99** | 3.6 |
| | 13 | 1.26 | **1** | 25.3 | 0.87 | **0.98** | 17.3 |
| | 10 | 0.64 | **0.89** | 12.9 | 0.13 | **0.79** | 2.5 |
| intermediate | 52 | 0.78 | **0.97** | 15.5 | 0.45 | **0.6** | 8.9 |
| | 14 | 1.04 | **0.97** | 20.8 | 0.92 | **0.99** | 18.4 |
| | 18 | 0.13 | **0.93** | 2.6 | 0.08 | **0.94** | 1.7 |
| | 16 | 0.33 | **0.91** | 6.6 | 0.2 | **0.96** | 4 |
| | 62 | 0.16 | 0.53 | | 0.02 | 0.08 | |
| old | 29 | 0.03 | 0.23 | | 0.01 | 0.06 | |
| | 26 | 0.06 | 0.27 | | 0.09 | **0.7** | |
| | 33 | 0.23 | **0.66** | 4.7 | 0.2 | **0.92** | 4.1 |
| | 24 | 0.05 | 0.49 | | 0.02 | 0.08 | |
| | 65 | 0.13 | **0.62** | 2.6 | 0.07 | 0.15 | |
| very old | DA | 0.32 | **0.87** | 6.3 | 0.36 | **0.82** | 7.2 |
| | DB | 0.28 | **0.84** | 5.6 | 0.23 | **0.85** | 4.6 |
| | DC | 0.31 | **0.85** | 6.3 | 0.22 | **0.82** | 4.5 |
| | S2 | 0.08 | **0.78** | 1.5 | -0.02 | 0 | |
| | S3 | 0.39 | **0.96** | 7.9 | 0.41 | 0.58 | |
| | S4 | 0.09 | 0.14 | | -0.1 | 0.08 | |
| | S5 | | | | 0.03 | 0.02 | |
| | RW | 0.19 | 0.47 | | 0.45 | **0.78** | 8.9 |
| none | SM | 0.08 | 0.03 | | 0.4 | **0.81** | 8 |
| | TB1 | 0.55 | **0.99** | 10.9 | 0.73 | **0.93** | 14.6 |
| | TB2 | 0.02 | 0.07 | | 0.27 | **0.68** | 5.4 |

# 5 Discussion

## 5.1 Trends in water table change and peat volume change

Based on the results of previous studies (Howie and Hebda 2018; Kennedy and Price 2005; Nijp et al. 2019; Price 2003; Price and Schlotzhauer 1999) the mire level was expected to follow the fluctuations in the absolute water level. This was indeed observed for the majority of the sites when inspecting the time series graphs (for example Figure 8), as well as the relationship between absolute groundwater level and mire level (Figure 15), an indication that the studied Northern peatlands have the elastic property provided by the Sphagnum moss dominating the vegetation cover. However, for some of the mires, the mire level remained surprisingly constant despite strong responses of the water level to rain events, only rising slightly during peaks in water level (like for site 29, Figure 9).

It was also observed that the mire level changes have a buffering effect on the water table depth relative to the mire surface. From the time series graphs, it was observed that the sites with larger variations in mire level also displayed smaller changes in $\mathrm{GWL_R}$ compared to $\mathrm{GWL_A}$ (Figure 8), while for sites with nearly constant mire levels, changes in $\mathrm{GWL_A}$ resulted in equally large changes in $\mathrm{GWL_R}$, which illustrates a limited ability to buffer the changes in water table depth. Comparing the IQR of $\mathrm{GWL_R}$ and $\mathrm{GWL_A}$ also indicated that the water table depth is buffered and stabilized to some extent at most of the mires, as the range of variation is generally lower for $\mathrm{GWL_R}$ than for $\mathrm{GWL_A}$. Although this shows that a buffering effect is present, it was not quantified or carefully compared between mires. Nijp et al. (2019) reported that peat volume change buffered on average 26% and maximally 84% of the decline in absolute water level. Similar metrics could be obtained from the data presented in this thesis to more clearly quantify the water table buffering at the studied mires, to do this was however not the main focus of this thesis.

Other dynamics that were identified were sudden drops in mire level following an increase in water level on some occasions. This could be due to the accumulation of rainwater on top of the mire surface, exerting pressure on the peat matrix and causing the surface to drop (Schlotzhauer and Price 1999). This is however not thought to have any major implication on the calculated maximum peat volume change or the relationship between mire level and water level, as this only occurs on a limited number of occasions.

### 5.1.1 Relationship between absolute water level and mire surface level

The relationship between water level and mire level as illustrated through scatter plots (Figure 15) was mainly investigated to determine if it was suitable to calculate specific storage through the slope of the linear regression. However, it also gives information about the water level and mire level dynamics.

As mentioned above the, scatters plots displayed a linear relationship between mire level and absolute water level for the majority of the sites, showing that the mire level follows the fluctuations in the absolute water level. However, this was not the case for all sites, which indicates that other processes might affect this relationship. A poor linear relationship could be explained by hysteresis in the mire-surface relation (which was observed), which is not uncommon and is due to a delay in the response of peat volume change to change in water level (Waddington et al. 2010). This does however not explain why a poor relation is the case for certain mires. The relation is expected to be poor for the drained and forested mires S4 and S5 due to their very deep water tables which is a problem for the calculation of $S_s$ as explained in section 2. Deviations from a linear relationship could also be an indication of entrapped gas in the peat pores that cause the surface to rise. Ebullition tends to occur during periods of falling atmospheric pressure, which cause the entrapped gas volume to expand causing a surface level rise (Strack et al. 2006). The atmospheric pressure could for example fall prior to rain events, and it would be possible to investigate if rising mire levels occurred prior to rain events as a means to determine if ebullition was a cause of poor linear relationship for some mires, however, this was not done in this thesis. Gases can also build up over the season which might explain hysteresis relations later in the summer or fall (Waddington et al. 2010).

When comparing the age classes, the *old* age class stands out with a poor linear fit for either the drying or rewetting period, or both, for four out of five mires (Table 5). This was expected considering how three of the mires (site 29, 26, and 24) also displayed nearly constant mire levels despite larger fluctuations in water level. It thus seems like the peat volume change capacity is low for these mires.

## 5.2 Volume change capacity for mires of different age

### 5.2.1 Maximum peat volume change

The main finding of this thesis was that the magnitude of peat volume change was significantly smaller for older mires compared to younger ones, as seen in the difference in maximum peat volume change between the *young* and *old* mire age class (Table 4). This indicates that older mires have less capacity for peat volume change, however, the results from the *intermediate* and *very old* age class also need to be considered.

There was no statistically significant difference between the *intermediate* age group and the other groups in terms of maximum compression. However, the resulting compression for the sites within the group still confirms that compression is related to age. The mires within the *intermediate* age class were not uniform in terms of peat volume change. Instead, the youngest mires (52 and 14) displayed volume change in a similar magnitude as for the mires in the *young* age class, while the three oldest mires (18, 16, 62) displayed volume change of the same magnitude to that of the *old* age class (Figure 13). Why this group displays results similar to both the *young* and *old* classes of mires might be explained by the vegetation composition for the intermediate sites, which can be characterized as a transition between the vegetation at the *young* and *old* sites (Wang et al. 2021). This indicates that the vegetation composition could be an important factor for peat volume change. For these sites in particular, there is also evidence that maximum peat volume change is related to the variation in relative groundwater level (GWLR IQR), as the GWLR IQR is much smaller for the two younger sites compared to the three older. This is in line with the idea that expansion and contraction will buffer the changes in water table and keep the relative groundwater level more stable.

The *very old* age class does not follow the trend of decreasing maximum peat volume change with increasing age, as maximum peat volume change was significantly larger for the *very* *old* mires compared to the *old* (Table 4 and Figure 13). However, these mires are subject to different geographical locations and thus different conditions which complicate the comparison with the mires on the chronosequence. The most evident difference is that the *very old* mires around Vindeln likely experienced much more rain during the measurement period (209 mm compared to 120 mm measured at the representative stations). More rain means larger increases in water table as well as greater peat expansion, thus larger values of maximum peat volume change. The *very old* age group is also generally more heterogeneous, including mires of a very large age span (4000-8000 years), as well as drained sites which could be more significant to the results than differences in age. The realization from this is that the mires of the *very old* age class might not be appropriate to include when trying to correlate capacity for peat volume change and age, at least not through the metrics used in this thesis, as these mires are affected by to many independent factors.

### 5.2.2 Specific storage

As shown by the impact of different rain amounts on the difference between the old and very old age classes, the dependency on water input is a limitation of using maximum peat volume change as a representation for peat volume change and the elasticity of a mire. Therefore the specific storage was also used to determine the capacity for peat volume change and to quantify the elasticity of the mires, as this value is standardized for water level fluctuations as well as related to the related to compressibility of the peat (Price and Schlotzhauer 1999). Specific storage was calculated for a drying phase when mainly compression of the peat was occurring, and a rewetting phase when mainly expansion occurred. It was not possible to obtain a value for the specific storage for all sites because of a poor linear fit in the relationship between mire level and absolute water level. Thus no statistically significant results came out of the comparison between the age classes. However, some patterns were still observed when comparing the different age classes and these were also similar to the patterns that were observed for the maximum peat volume change. First of all, the specific storage appears to generally be greater for younger mires compared to older ones (Figure 16). In addition, the specific storage for the *intermediate* age class appears to be similarly affected by the vegetation composition, as the two younger sites have a much greater $S_\mathrm{s}$ compared to the two older sites 18 and 16 ($S_\mathrm{s}$ was not calculated for 62 because of low R$_2$). The mires of the *very old* age class also have larger specific storage than the *old* group. Maximum peat volume change and specific storage are thus related; mires with a large maximum peat volume change during the study period also have a large specific storage.

It is important to note that the resulting specific storage of $1.5 \times 10^{-3}$ cm$^{-1}$-$25.3 \times 10^{-3}$ cm$^{-1}$ for the compression phase and $0.7 \times 10^{-3}$ cm$^{-1}$-$18.4 \times 10^{-3}$ cm$^{-1}$ for the expansion phase are larger by one magnitude compared to a specific storage of $5 \times 10^{-4}$ cm$^{-1}$ reported for a Swedish undisturbed bog by Kellner and Halldin (2002) and $9.6 \times 10^{-4}$ for a cutover peat by Schlotzhauer and Price (1999). However, a reasonable explanation for why this is could not be found.

### 5.2.3 Possible explanations

The age of mires is not itself a factor that affects peat volume change, however, the presented results indicate that factors that differ between mires of different ages might influence the capacity for peat volume change. It remains unknown what these factors are, as this was not systematically investigated in this thesis. However, the available data can give some clues to other factors that are related. According to Price and Schlotzhauer (1999), the capacity for peat volume change is related to increased peat thickness. Peat thickness is a factor that is influenced by age, as peat continuously accumulates (Vitt 2008). The results in this thesis were the opposite, peat volume change was smaller for the *old* sites with a larger mire depth compared to the *young* (Figure 3). For the young and intermediate sites, however, the mires with large mire depth also had larger $S_\text{s}$ during rewetting and drying (Figure 3 and 16). The older mires could be more affected by oxidation of the peat because of deeper water tables. The relative groundwater level was slightly larger (deeper) at older mires (Figure 10), which has also been observed in another study of a chronosequence of mires (Tuittila et al. 2012). Oxidation of the peat is affecting its compressibility (Kennedy and Price 2005) and will become more pronounced with deeper water tables as oxygen can find its way down in the peat layers. The differences in peat volume change between different mires could be related to different vegetation composition and soil structure (Whittington et al. 2007), and it has been shown that the mires on the chronosequence are covered in different vegetation and that this appears to affect the peat volume change.

Although a relationship between maximum peat volume change and variation in relative groundwater level could be seen within the intermediate age class, there is no general relationship when taking all the studied mires into account.

### 5.2.4 Peat volume change during different hydrological conditions

One major finding from the calculation of specific storage for the drying and the rewetting period was that specific storage is larger during drying (compression) than during rewetting (expansion) (Figure 16). Schlotzhauer and Price (1999) also noted that expansion occurred at a smaller rate during rewetting and that peat volume change, in general, was greater during periods of water loss than during water gain. It is likely that the mire level eventually regains its full expansive state, however, this might indicate that some mires are slower in their expansion response to the elevated water levels that occur during the later part of the summer, and highlights the hydrological-feedback mechanism for maintaining wet conditions. Possible explanations are that volume change to some extent is affected by the degree of saturation, as well as dependent on the previous history of loading (Schlotzhauer and Price 1999).

Although the drying and rewetting phase was generalized to all sites, these two phases were not pronounced for all sites. Values of specific storage could perhaps have been obtained by identifying multiple phases, as specific storage is known to vary during the season depending on the conditions. These results would however be more difficult to compare between sites.

## 5.3 Volume change capacity for mires subject to different land management

By investigating the data from the mires at Trollberget, TB1, and TB1, it was possible to compare the effect of a restoration effort on the water table and mire surface dynamics. However, the results of the analysis are difficult to interpret. Contrary to what might be expected behavior of the water table position upon rewetting (raised water tables (Ketcheson and Price 2011)), the relative water table depth was greater for the restored site (TB2) than for the site that is still drained (TB1). TB1 was one of the sites that had a logger with a calibration error which was corrected for by subtracting a correction term from the measured time series and lowering it to fit the manual measurement 6. It is possible that this correction factor is wrong and thus affects the resulting median relative water table depth. It was also noted that the drainage ditch has never been cleaned and is overgrown with vegetation, so the drainage is not as effective and might not have the expected effect on the water table.

The maximum volume change during the study period was surprisingly large for the drained site (TB1), it displayed the greatest volume change of all studied sites, and much larger than for the restored site (TB2). From looking at the time series graphs it is evident that the absolute groundwater level is fluctuating more for TB1 than for TB2, also resulting in larger fluctuations in mire level. It is unclear if this is an effect due to hydrological processes or peat characteristics, or perhaps a problem with the incorrect calibration and insufficient correction. The specific storage during the rewetting period was also greater for drained TB1 compared to restored TB2. These results indicate that where the mire is still drained, there is a greater capacity for peat volume change compared to where the mire is rewetted. It should however be considered that the mires had during the time of measurements only been rewetted for a few months, so any actual changes in peat volume change capacity might not be present so early in the restoration effort. The differences seen between these two sites could be due to the specific location for where the loggers are placed, rather than differences in the hydrological conditions caused by the ditch blocking.

It was not possible to determine specific storage for the two drained mires S4 and S5 due to the poor linear relationship between the water level and mire level which is likely a result of deep water tables, and they did not stand out in terms of maximum peat volume change.

## 5.4 Limitations

The limitations of this study include varying and relatively short time period with available data. In order to obtain the true maximum peat volume change capacity, a dataset that includes the entire cycle of wetting and drying would be preferable, in order to capture when the mire level is at its lowest during the dry summer months and when it is at its highest elevation after snowmelt during the spring. It was also explained in the method (Table 3) that data from a shorter time period was used for a few of the sites that had very little data. This was the case for site S5, SM and TB1 when calculating median, IQR and maximum peat volume change. This was however not thought to have any meaningful effect on the results. The shorter time period used for S5 is a likely explanation for the smaller $GWL_R$ IQR compared to for example S4, this does however not have any implications on further results. The shorter time period for site SM means that a period with higher water levels that was captured for the close-by site RW (see Figure 33 for RW, Figure 34 for SM) are not included for SM and does not affect the median and IQR for SM. If data between Jun 23 and Jun 30 had been captured for SM, it is likely that the higher water levels observed in RW for this period would also be present at SM, hence it is reasonable to say that the median $GWL_R$ for SM should actually be less, which would maintain the observed relationship between $GWL_R$ for RW and SM (median $GWL_R$ is smaller for SM compared to RW). Site

TB1 is represented by measurements from Jul 14 - Aug 23 and did not capture the longer dry period before this date, which is included in the measurements for TB2 (see Figure 40). Thus the median $GWL_R$ for TB1 could be greater if this period would have been captured. However, monthly medians for TB1 and TB2 display approximately the same difference between the two sites (approximately 10 cm) for the months where data is available for both (July, August, September, October), so the relationship is still considered accurate.

How peat volume change is related to the age of mires was investigated by grouping the mires into different age classes and comparing these classes. Ideally the age groups should contain mires with similar characteristics apart from age. There is, however, some spread in the characteristics within the age groups, particularly in the group *very old*, like vegetation (sphagnum vs forest) and status (drained vs natural), and as already mentioned, the different geographical location compared to the chronosequence. This has an affect on the statistics and the interpretation of the results.

The results presented in this report are based on the measurements of pairs of groundwater level logger placed on the studied mires. Some data from these logger were quality controlled before analyzed and inaccuracies were identified and corrected for (these are listed in Appendix **??**, but the results could still be affected by unidentified inaccuracies. For example, validating the logger groundwater level measurements by only on manual measurement is not enough to be confident in the correctness of the logger measurements. It is important to obtain more manual measurements at the logger-sites for future analysis of the data recorded by the Odyssey loggers. The plastic grid floating on top of the mire (5 exerts pressure on the peat below and could cause a settling effect in the beginning of the time series, which is important to be aware of for the continuous use of this measurement system.

# 6 Conclusion

The water table change and peat volume change investigated within this study has highlighted several aspects of peat volume change and how the elastic property of mires might differ under different conditions.

The results indicate that the age of peatlands could be a predictor of the elasticity of mires and their capacity for peat volume change, as a significantly smaller magnitude of peat volume change was observed for old mires (older than 2000 years) compared to young (younger than 1000). This pattern was also generally confirmed by the calculation of the specific storage, which was observed to be greater for younger mires, although this could not be confirmed statistically due to the small sample size. Age is not intrinsically a factor affecting peat volume change, however, it is an implication that factors changing as the peatland evolves are important for the ability to expand and contract. Understanding these factors, which could include for example peat depth and vegetation composition, are crucial for the study of peatland ecohydrology.

The very deep water tables of two drained and forested sites did not appear to have any effect on peat volume change capacity as it was quantified in this thesis. It was not possible to quantify the specific storage as the large unsaturated zone at these two sites does not allow for specific storage to be defined based on the changes in water level and mire level. This implies that the elastic properties of drained sites need to be investigated using a different approach than what was used in this study.

The study also highlighted peatlands ability to maintain wet condition through changes in specific storage which is related to the compressibility of the peat. It was found that the specific storage, the volume of water released from storage by compression of the peat matrix, is larger during drying and compression compared to during rewetting and expansion. The dynamic behaviour for water storage properties during drying and rewetting should be included in future models.

Future research on peatland ecohydrology require a multi-scale approach that consider many aspects, including the process of peat volume change. This has implications om restoration effort that are often performed to reestablish the capacity for peat volume change and indicates that restoration efforts should be focused on regaining the properties, like vegetation composition, linked to young peatlands.

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# Appendices

## A Reported issues with Odyssey loggers

Some issues were observed for some of the loggers:

- S1-RGWL did not record any data during the measurements period. Thus Site S1 was excluded from the analysis.
- Data flagged as offset occurred for site TB1, 02, 70, and 43. This disturbance was characterized by implausible absolute readings of water level (around 3000-4000 mm) during the first half of the measurement period, while the relative changes in water level readings where reasonable and thought to be correct. This was likely due to a calibration error that was corrected during the measurement period. Rather than discarding this data it was adjusted based on manual water level measurements.
- Data has been removed from the start of the measuring period for TB1 because the TB1-AGWL did not record any data until July 13, and since both relative and absolute measurements are needed to calculate the mire level and perform the analysis, the measured data for the TB1-RGWL logger was also removed.
- For site 16, the time series graph displayed an odd behaviour for the first half of the measurement period. The mire surface decreased as the water table increased. This is thought to be result of the water level measured by the relative logger decreasing *faster* than the water level for the absolute logger.

# B Correction term for groundwater level adjustments

**Table 6:** The correction term used to adjust the raw groundwater level data based on manual groundwater level measurements performed using a bubbler.

| Logger ID | Correction term [cm] | Logger ID | Correction term [cm] |
|---|---|---|---|
| DA-RGWL | -5 | DA-AGWL | -6.5 |
| DB-RGWL | -5.2 | DB-AGWL | -6.8 |
| DC-RGWL | -3.2 | DC-AGWL | -5 |
| TB1-RGWL | -6.5 | TB1-AGWL | -397.9 |
| TB2-RGWL | -11.9 | TB2-AGWL | -9.6 |
| RW-RGWL | -2.9 | RW-AGWL | -2.6 |
| SM-RGWL | -4.1 | SM-AGWL | -6.3 |
| S5-RGWL | -22.5 | S5-AGWL | -25.5 |
| S4-RGWL | -21.3 | S4-AGWL | -24.6 |
| S3-RGWL | -10.5 | S3-AGWL | -17.7 |
| S2-RGWL | -14.8 | S2-AGWL | -10.9 |
| S1-RGWL |  | S1-AGWL |  |
| RGWL13 | 2.55* | AGWL13 | -1.7 |
| RGWL10 | -0.95* | AGWL10 | -0.8 |
| RGWL02 | -243, -0.8 ** | AGWL02 | -269, -5.2 ** |
| RGWL70 | -266.5, -12.5** | AGWL70 | -258.5, -0.4 ** |
| RGWL43 | 269.5, 417.0 , -3.8 ** | AGWL43 | -279.6, -412.5, -8.5 ** |
| RGWL62 | 0.4 | AGWL62 | 0.6 |
| RGWL14 | 2.4 | AGWL14 | -3.3 |
| RGWL16 | -280.2, -417.6, -10.7 ** | AGWL16 | -1.1 ** |
| RGWL18 | 0.8 | AGWL18 | -0.1 |
| RGWL52 | -1.1* | AGWL52 | -3.6 |
| RGWL24 | -1.1* | AGWL24 | 0.9 |
| RGWL26 | -1.1 | AGWL26 | 1.2 |
| RGWL29 | 1.2 | AGWL29 | -0.1 |
| RGWL65 | -1 | AGWL65 | -0.7 |
| RGWL33 | -2.5 | AGWL33 | -2.7 |

[*] Correction term calculated as the average offset at two points in time, since there was two manual groundwater measurements to compare.

[**] Multiple correction terms are used on different time periods for the sites where a calibration offset occured.

# C Time series graphs for all sites

**Figure 17:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site 2, one of the *young* chronosequence-sites. Also daily precipitation from the station Umeå-Röbäcksdalen.

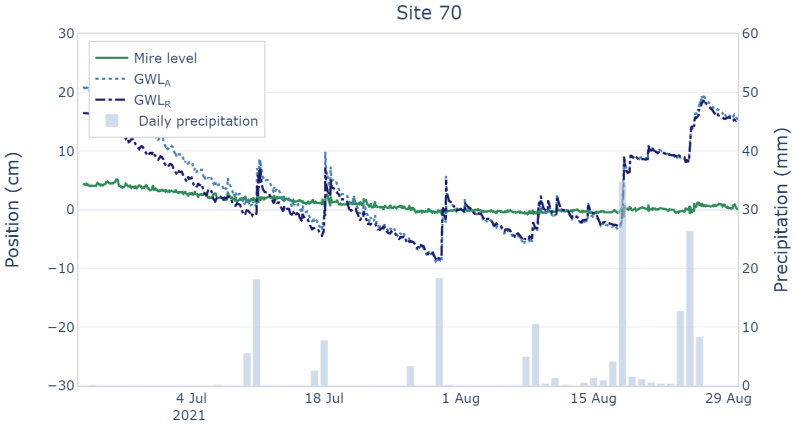

**Figure 18:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site 70, one of the *young* chronosequence-sites. Also daily precipitation from the station Umeå-Röbäcksdalen.

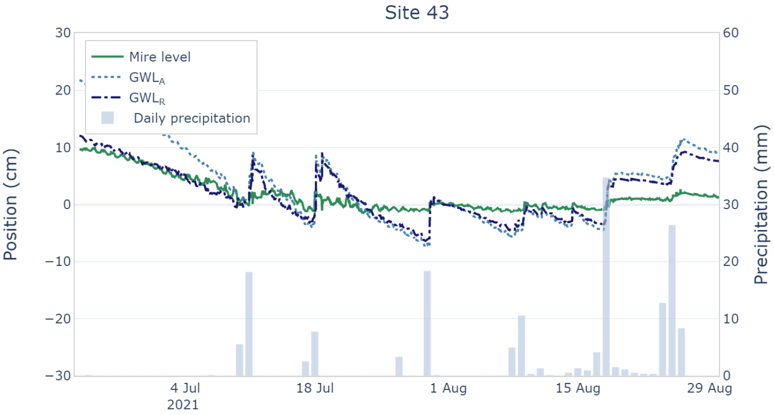

**Figure 19:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site 43, one of the *young* chronosequence-sites. Also daily precipitation from the station Umeå-Röbäcksdalen.

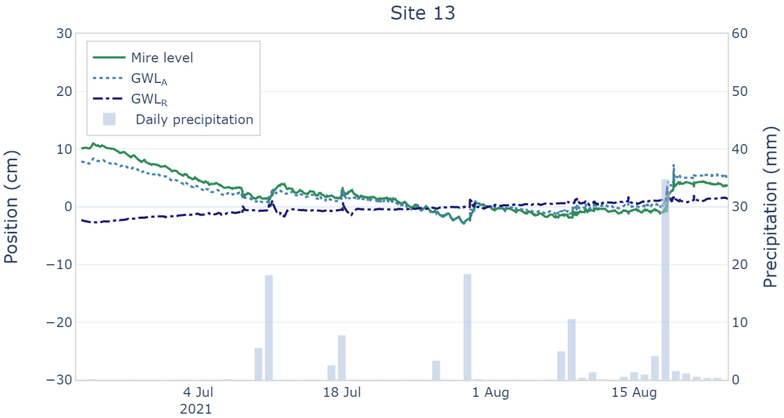

**Figure 20:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site 13, one of the *young* chronosequence-sites. Also daily precipitation from the station Umeå-Röbäcksdalen.

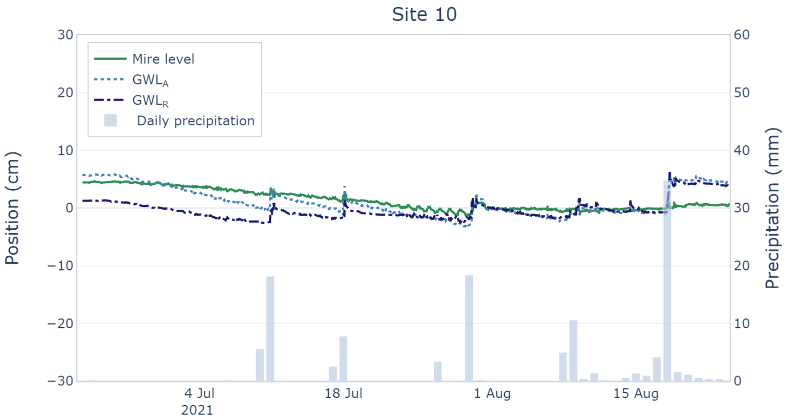

**Figure 21:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site 10, one of the *young* chronosequence-sites. Also daily precipitation from the station Umeå-Röbäcksdalen.

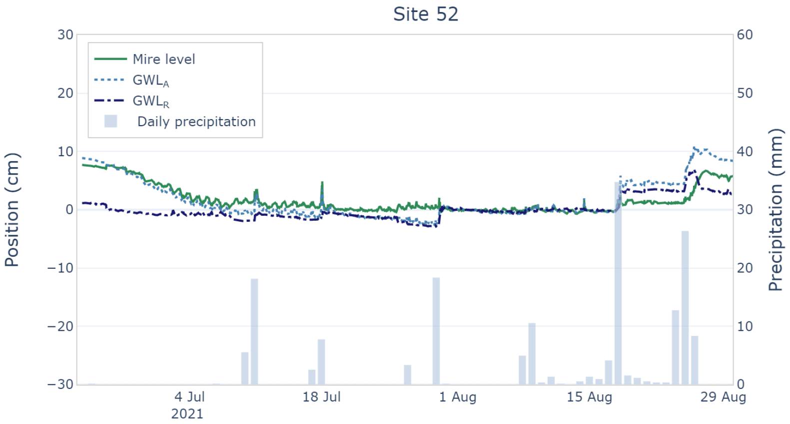

**Figure 22:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site 52, one of the *intermediate* chronosequence-sites. Also daily precipitation from the station Umeå-Röbäcksdalen.

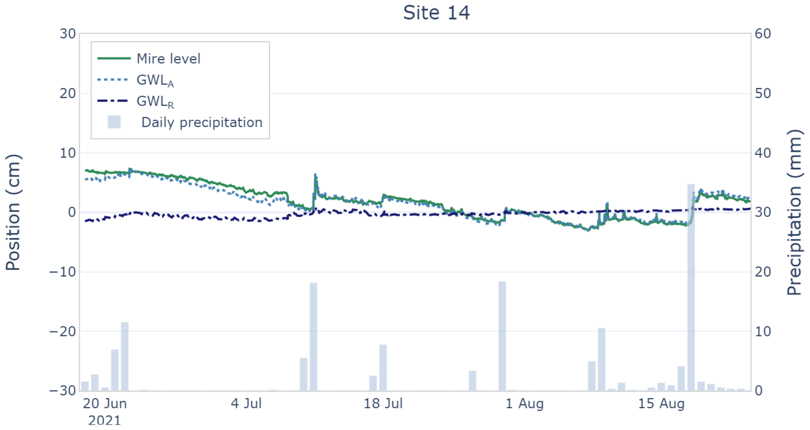

**Figure 23:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site 14, one of the *intermediate* chronosequence-sites. Also daily precipitation from the station Umeå-Röbäcksdalen.

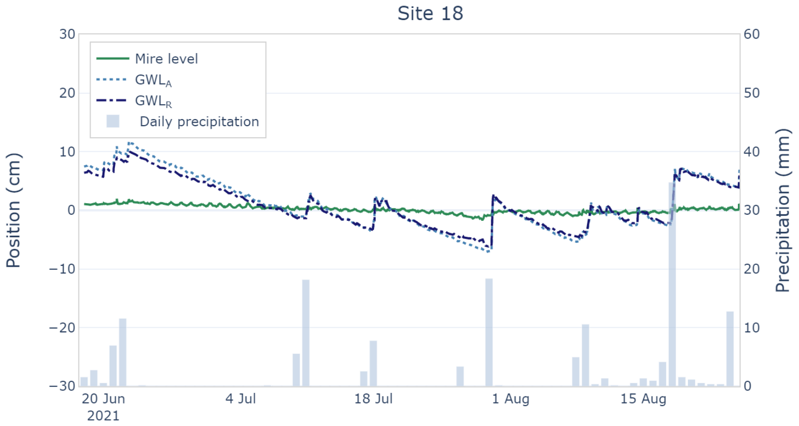

**Figure 24:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site 18, one of the *intermediate* chronosequence-sites. Also daily precipitation from the station Umeå-Röbäcksdalen.

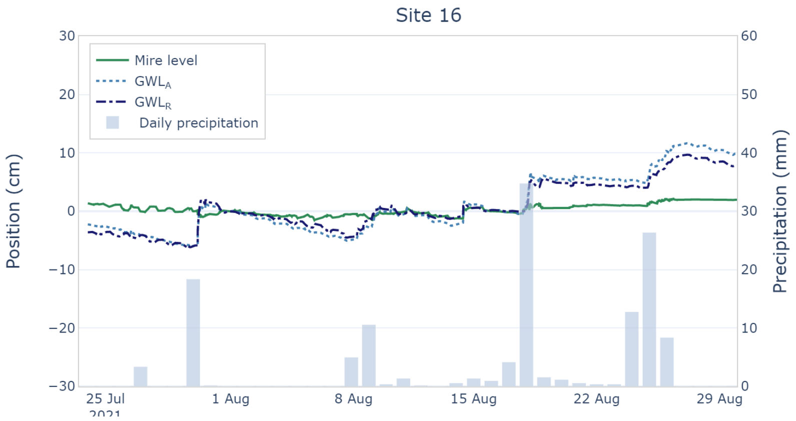

**Figure 25:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site 16, one of the *intermediate* chronosequence-sites. Also daily precipitation from the station Umeå-Röbäcksdalen.

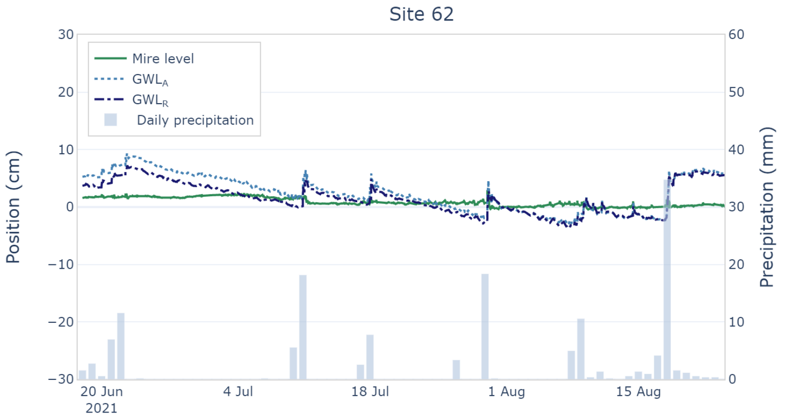

**Figure 26:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site 62, one of the *intermediate* chronosequence-sites. Also daily precipitation from the station Umeå-Röbäcksdalen.

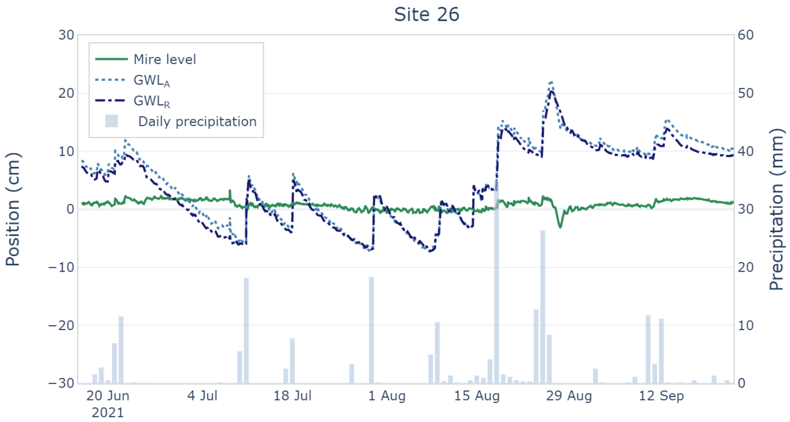

**Figure 27:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site 26, one of the *old* chronosequence-sites. Also daily precipitation from the station Umeå-Röbäcksdalen.

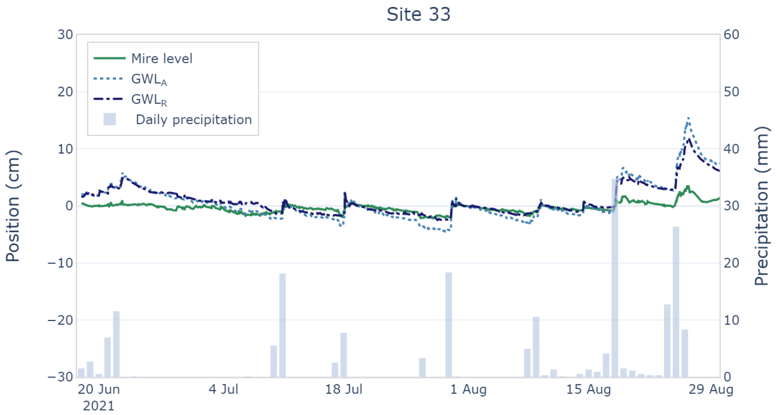

**Figure 28:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site 33, one of the *old* chronosequence-sites. Also daily precipitation from the station Umeå-Röbäcksdalen.

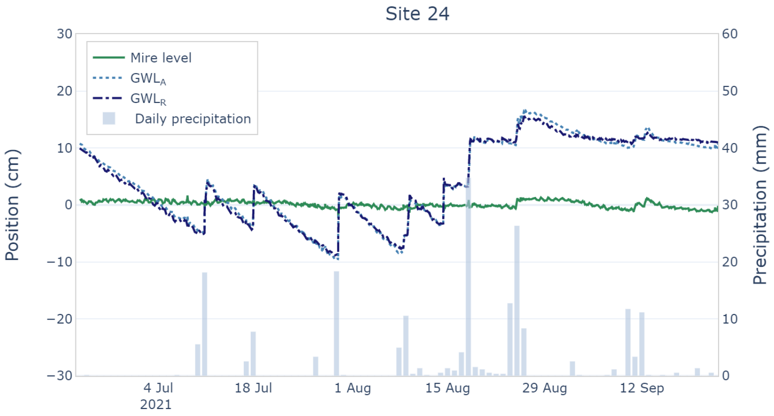

**Figure 29:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site 24, one of the *old* chronosequence-sites. Also daily precipitation from the station Umeå-Röbäcksdalen.

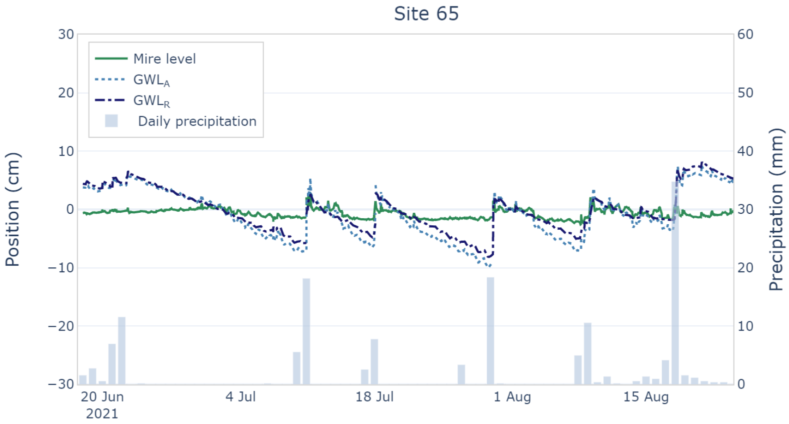

**Figure 30:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site 65, one of the *old* chronosequence-sites. Also daily precipitation from the station Umeå-Röbäcksdalen.

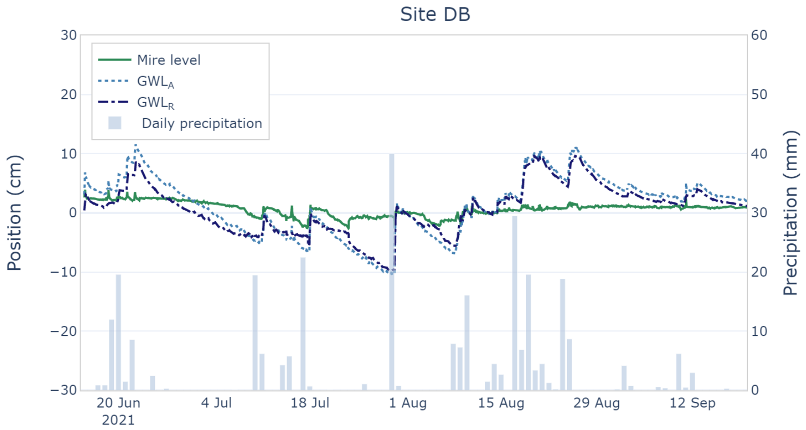

**Figure 31:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site DB located at Degerö Stormyr. Also daily precipitation as rain from the station Vindeln-Sunnansjönäs.

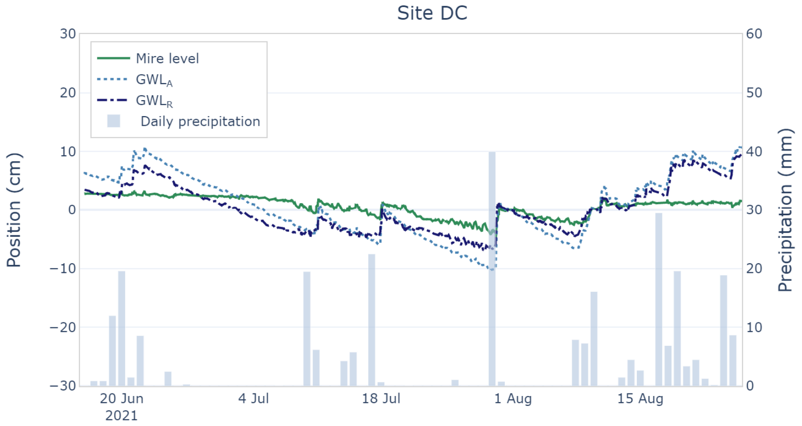

**Figure 32:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site DC located at Degerö Stormyr. Also daily precipitation as rain from the station Vindeln-Sunnansjönäs.

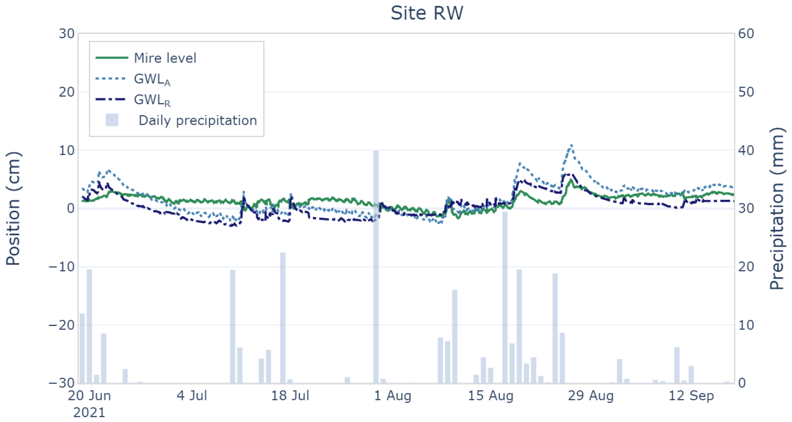

**Figure 33:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site RW located at Svartberget. Also daily precipitation as rain from the station Vindeln-Sunnansjönäs.

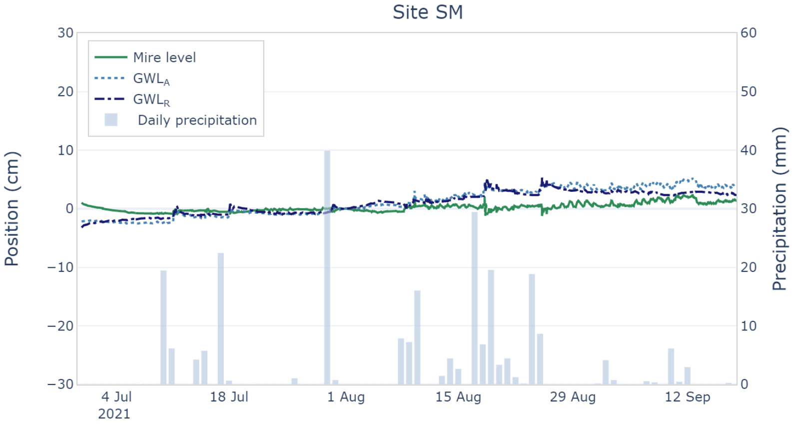

**Figure 34:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site SM located at Svartberget. Also daily precipitation from the station Vindeln-Sunnansjönäs.

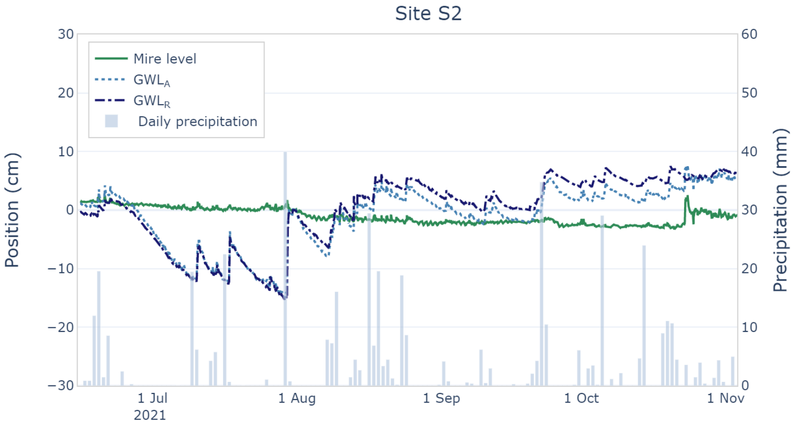

**Figure 35:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site S2 located at Stormyran. Also daily precipitation from the station Vindeln-Sunnansjönäs.

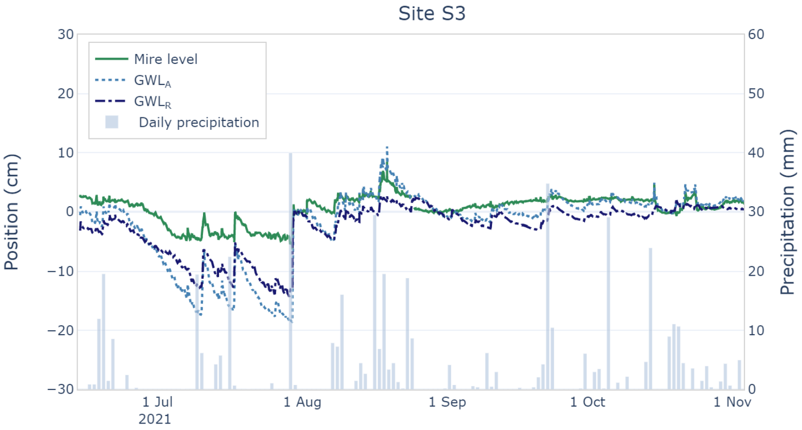

**Figure 36:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site S3 located at Hålmyran. Also daily precipitation from the station Vindeln-Sunnansjönäs.

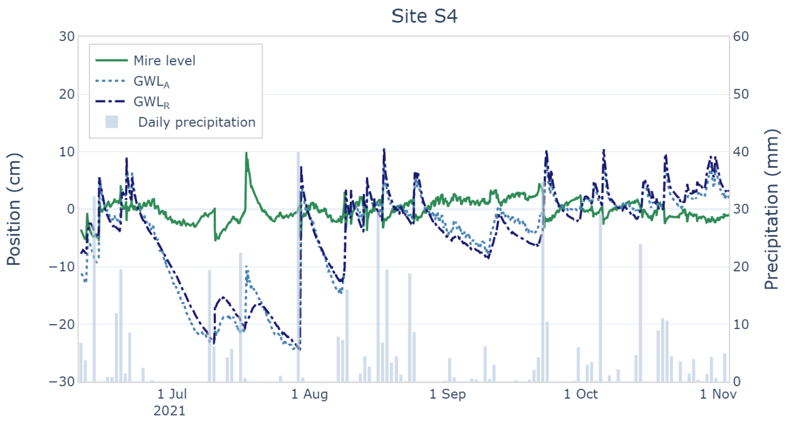

**Figure 37:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site S4 located at Hälsningfors open forest, which is a drained mire. Also daily precipitation from the station Vindeln-Sunnansjönäs.

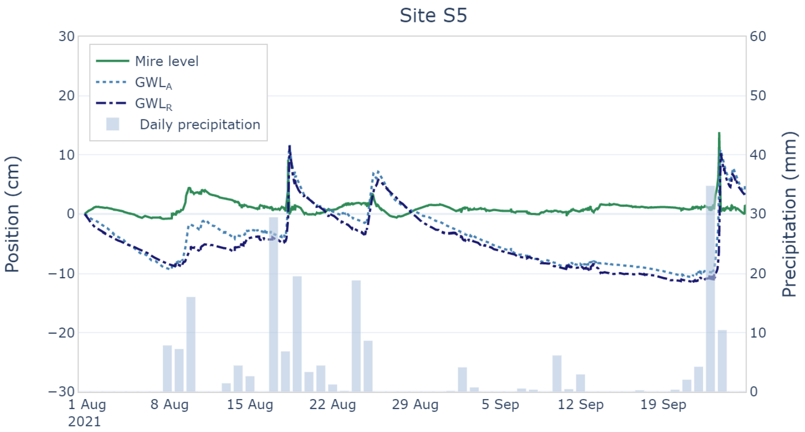

**Figure 38:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site S4 located at Hälsningfors dense forest, which is a drained mire. Also daily precipitation from the station Vindeln-Sunnansjönäs.

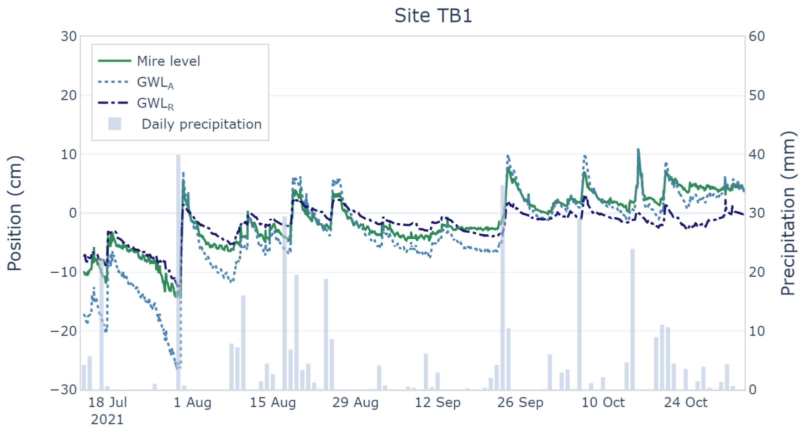

**Figure 39:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site TB1 located at a recently restored mire at Trollberget. Site TB1 is located downstream of where the drainage ditch has been blocked. Also daily precipitation from the station Vindeln-Sunnansjönäs.

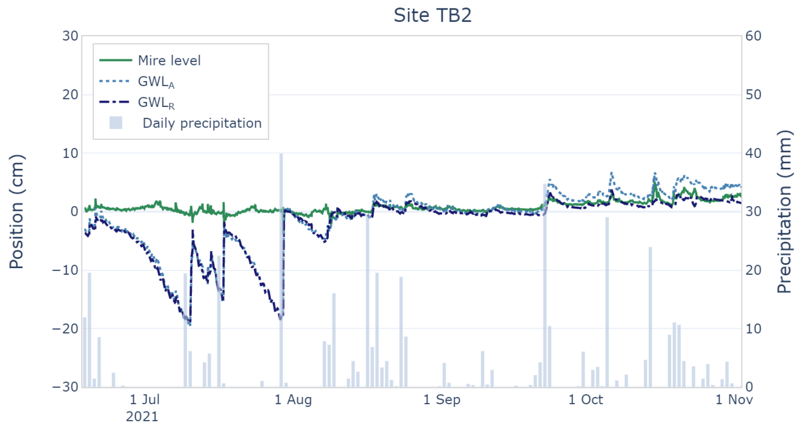

**Figure 40:** Time series of mire surface level, absolute water level and water table depth relative the mire surface for site TB1 located at a recently restored mire at Trollberget. Also daily precipitation from the station Vindeln-Sunnansjönäs.

# D Median and IQR

**Table 7:** Median and IQR values for all sites during the period June 23 – Aug 23 2021.

| **Age class** | **Site** | **MIRE LEVEL** | | **$GWL_A$** | | **$GWL_R$** | |
|---|---|---|---|---|---|---|---|
| | | **Median [cm]** | **IQR [cm]** | **Median [cm]** | **IQR [cm]** | **Median [cm]** | **IQR [cm]** |
| young | 2 | 78.23 | 5.15 | 68.27 | 8.27 | 10.03 | 6.57 |
| | 70 | 58.65 | 2.28 | 46.31 | 10.65 | 12.68 | 8.65 |
| | 43 | 106.02 | 3.23 | 97.36 | 9.79 | 8.77 | 6.76 |
| | 13 | 173.2 | 4.63 | 162.82 | 4.08 | 10.24 | 1.61 |
| | 10 | 124.55 | 3 | 116.54 | 3.94 | 8.44 | 1.68 |
| intermediate | 52 | 138.88 | 1.54 | 135.9 | 3.32 | 2.81 | 1.11 |
| | 14 | 258.49 | 4.1 | 246.54 | 3.73 | 11.76 | 0.67 |
| | 18 | 149.54 | 0.78 | 135.61 | 6.38 | 13.87 | 5.49 |
| | 16 | 90.05 | 1.17 | 73.14 | 3.91 | 16.67 | 3.86 |
| | 62 | 105.99 | 1.41 | 97.72 | 5.74 | 8.38 | 4.12 |
| old | 29 | 133.54 | 0.86 | 119.46 | 7.98 | 14.12 | 7.14 |
| | 26 | 194.78 | 1.42 | 181.61 | 6.73 | 12.9 | 6.93 |
| | 33 | 216.78 | 0.83 | 206.8 | 2.6 | 9.92 | 2.04 |
| | 24 | 192.48 | 0.72 | 178.25 | 6.87 | 14.47 | 6.86 |
| | 65 | 163.49 | 1.34 | 150.67 | 5.99 | 13.38 | 4.44 |
| very old | DA | 499.01 | 2.21 | 485.85 | 5.98 | 13.1 | 5.34 |
| | DB | 308.51 | 1.69 | 301.77 | 6.89 | 7.21 | 5.12 |
| | DC | 173.71 | 2.7 | 161.85 | 7.79 | 11.8 | 5.56 |
| | S2 | 402.27 | 1.79 | 379.27 | 9.82 | 22.62 | 10.11 |
| | S3 | 433.7 | 5.69 | 418.95 | 13.73 | 15.07 | 8.73 |
| | S4 | 308.45 | 2.21 | 260.05 | 19.1 | 47.84 | 16.48 |
| | S5 | 194.25 | 1.42 | 149.45 | 3.43 | 45.47 | 3.82 |
| | RW | 503.95 | 1.36 | 492.26 | 2.02 | 11.23 | 2.61 |
| none | SM | 144.11 | 0.62 | 140.78 | 2.8 | 3.26 | 2.2 |
| | TB1 | 284.89 | 5.25 | 278.25 | 11.19 | 6.74 | 5.49 |
| | TB2 | 245.94 | 0.75 | 231.31 | 8.98 | 14.36 | 9.72 |

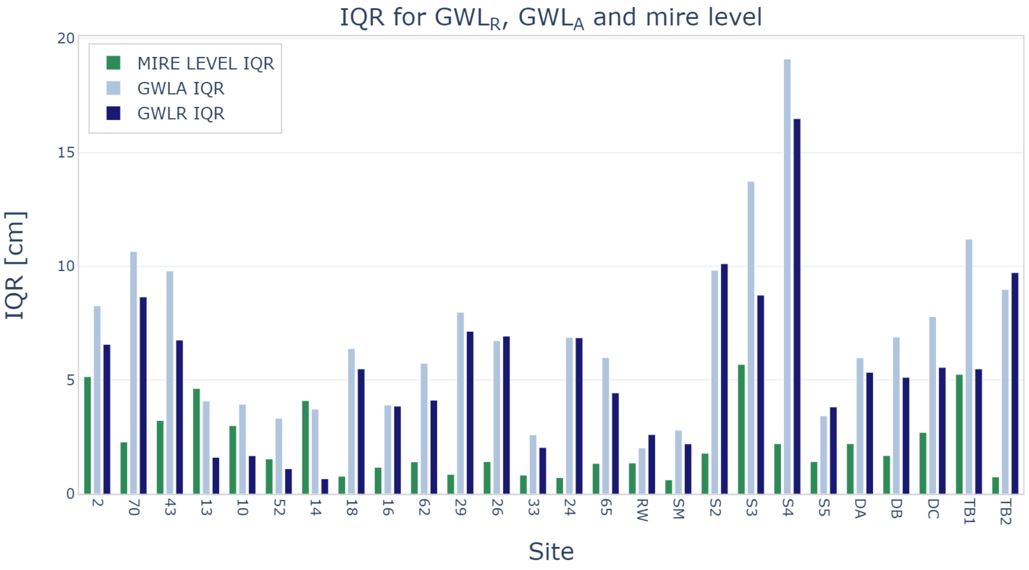

**Figure 41:** IQR:s for all sites displayed as bars for easier comparison.

# E Depth integrated specific storage

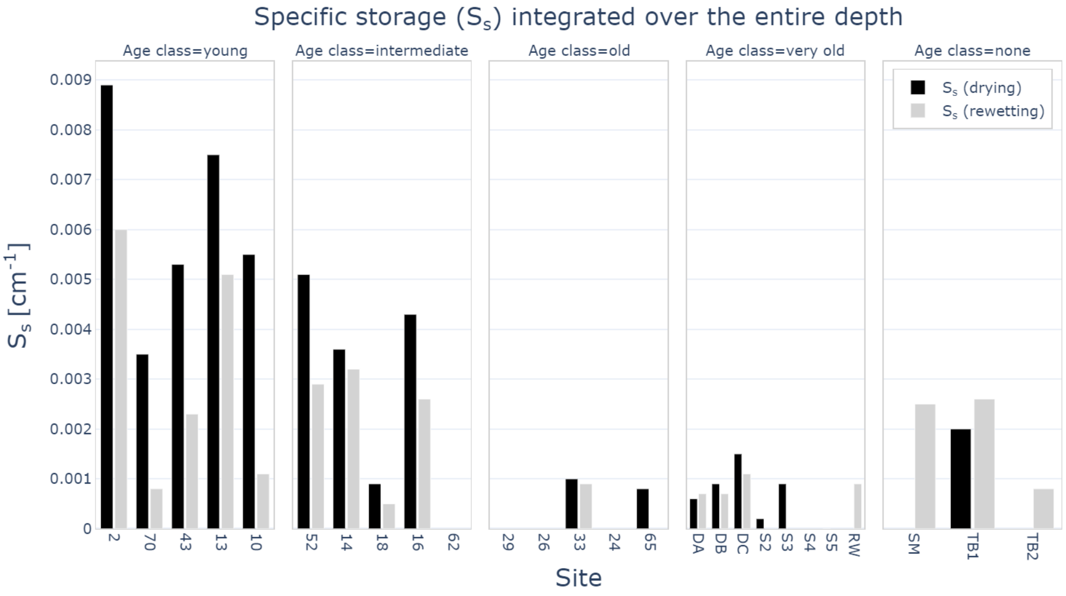

**Figure 42:** Specific storage (S$_s$) integrated over the entire depth of the mire during a drying period where peat compression generally occurred, and during a rewetting period where peat expansion generally occurred. For sites with a linear regression $R^2 \geq 0.6$, S$_s$ was not calculated, which is why a value is missing for some sites.