A Study on Groundwater Levels Following Rewetting of Drained Wetlands in Southern Sweden

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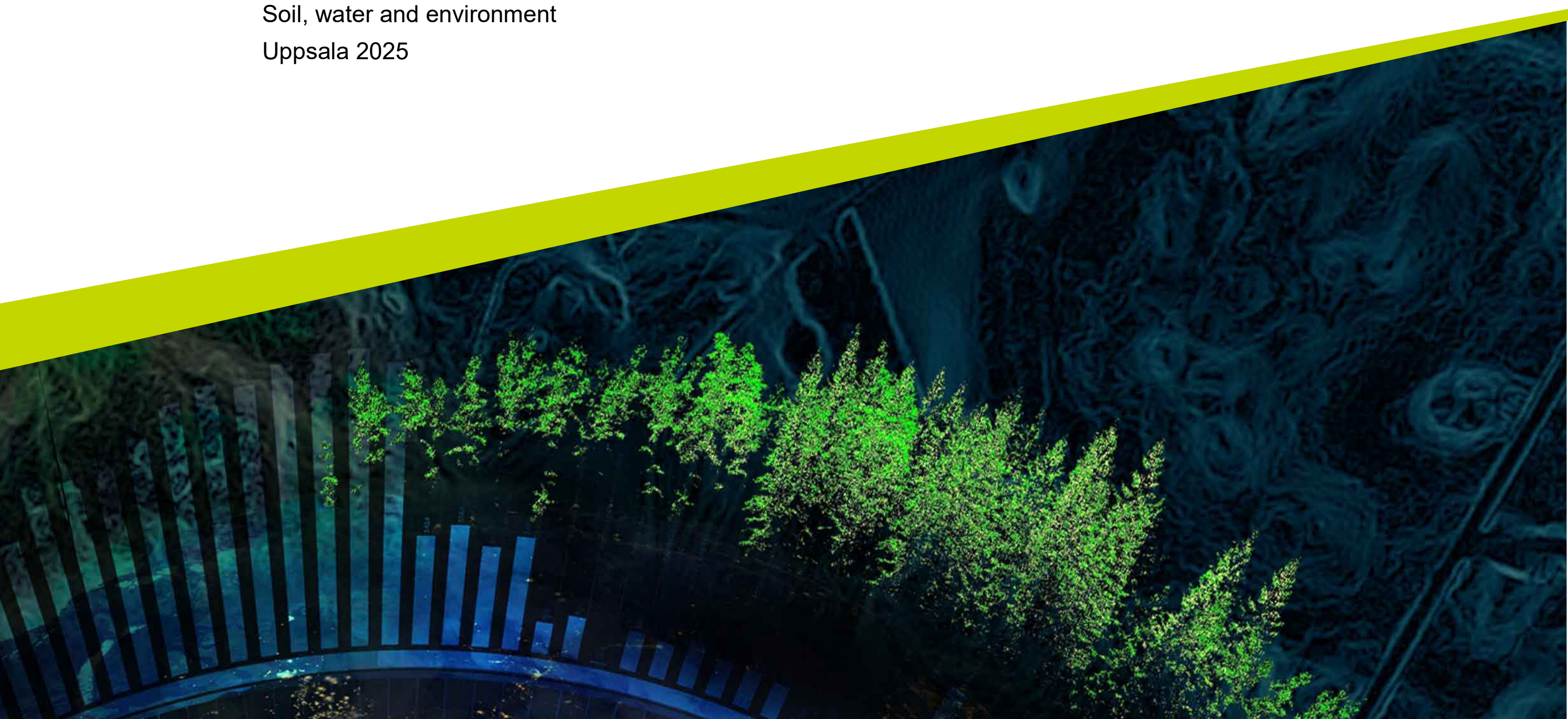

A Study on Groundwater Levels Following Rewetting of Drained Wetlands in Southern Sweden

En studie på grundvattennivåer efter återvätning av dränerade våtmarker i södra Sverige

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Abstract

In light of recent hot and dry summers, restoration of degraded wetlands has been considered as an opportunity for increasing water availability in the landscape. Despite the lack of evidence-based outcomes of rewetting on hydrological functions, the Swedish government continues to allocate funds for further implementation. This study addresses this gap by investigating responses in high temporal resolution groundwater levels (GWL) to rewetting of two historically drained wetlands within Östergötland County, southern Sweden. To assess hydrological alterations, a Before-After-Control-Impact approach was employed, using a drained but non-rewetted wetland as the control. The aim of the study was to investigate GWL changes following rewetting, both within the peatlands and in adjacent areas, and identify factors determining these responses. The results showed spatial variation of rewetting effects, both within and across sites. While one of the rewetted wetlands showed increased and stabilized GWL, providing reasons to think that restoration improved hydrological functions, the other exhibited limited responses. To improve restoration outcomes, this study emphasizes the importance of considering both local conditions for planning, implementing and monitoring rewetting efforts, along with data quality assurance as an essential step prior to further application. Recognizing that the results of restoration were not consistent in this study may not be a limitation of rewetting itself, but rather a reflection of the sometime irreversible changes that historical intensive drainage has imposed on these ecosystems.

Keywords: Ditch blocking, Drainage, Groundwater level, Wetland hydrology, Restoration

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1. Introduction

As one of the most degraded ecosystems globally, wetlands are commonly defined as areas of land where water is present near, within, or above the ground surface for extended periods of the year (Gunnarson & Löfroth 2009; Ramsar Convention on Wetlands 2018). Pristine wetlands and their properties, which are closely linked to prevailing hydrological conditions, support processes that contribute to important functions in the landscape (Thorsbrink et al. 2019; Hambäck et al. 2023). One key function is flow regulation facilitated by the capacity of wetlands to store and retain water, which helps modulate peak flows during wet periods and sustain base flow during dry spells (Kadykalo & Findlay 2016) This process is particularly relevant as extreme weather events are expected to become more common with climate change (IPCC 2023). Wetland hydrology also influences biodiversity by creating habitats for specialized plant and animal species (Bobbink et al. 2006), and contributes to water purification capacity, and nutrient retention (Powers et al. 2012; Sileshi et al. 2020). In terms of climate benefits, the recurring water logged conditions slow down microbiological processes, enabling long-term carbon sequestration (Adhikari et al. 2009). Understanding key hydrological processes in wetlands is, thus, important for predicting the potential impacts of climate change, as well as effects of restoration and management strategies.

At northern latitudes, peatlands are the most dominant type of wetlands (Bring et al. 2022). In Sweden, specifically, the topographical and climatological circumstances have provided favorable conditions for peat formation (Thorsbrink et al. 2019). This process is characterized by incomplete decomposition of plant residues due to anoxic conditions, resulting in accumulation of organic material (Moore 1989). Consequently, Sweden is one of the most peat-dense countries globally, with peatlands covering at least 10% of the land area (4.3 million hectares) (Gunnarson & Löfroth 2009; Bring et al. 2022). However, a large proportion of peatlands in Sweden have been affected by drainage to improve conditions for agriculture, forestry, and peat extraction (Morin et al. 2023). Ditching was primarily carried out during the 19th century, with an estimated network length of approximately one million kilometers, equivalent to 28 times around the world (Laudon et al. 2022). Today, new land drainage is generally prohibited in most of southern and central Sweden to limit further loss of wetlands (Swedish Environmental Protection Agency 2009). Drainage lowers the groundwater level (GWL) and may initially enhance stormwater retention by creating additional storage capacity in the peat, but this effect is temporary. Over medium term, water is gradually lost from the catchment, and with continued dewatering, the peatland begins to mineralize and subside (Holden et al. 2006). The subsidence, involving reduced pore volume and increased bulk density, reduces the ability of the land to store water (Regan et al. 2019), meaning the initial hydrological benefits of drainage are eventually lost. The impact of drainage is likely to be greatest near the ditch, decreasing outwards by about half within ten meters and becoming negligible after another few tens of meters (Bring et al. 2022).

One important aspect of wetland hydrology is the seasonality in the hydrologic cycle. In southern Sweden, rises in GWL are predominant in winter, primarily due to recharge of snowmelt and rain. Spring is also characterized by snowmelt-driven rises, although declines can occur simultaneously due to increasing evapotranspiration. During summer, high evapotranspiration typically leads to further declines in GWL (Nygren et al. 2020). Climate change is expected to alter groundwater dynamics at high latitudes, where reduced snow accumulation, earlier melting, and increased winter rainfall are shifting recharge patterns from spring snowmelt to winter rain. This, combined with a longer growing season that impedes recharge, has led to observed reductions in groundwater storage in Sweden (Taylor et al. 2013; Nygren et al. 2020).

Recent hot and dry summers have highlighted the scarcity of groundwater in the landscape, which may in some cases be mitigated by utilizing the water retention capacity both within and adjacent to wetland areas (Thorsbrink et al. 2019). Wetlands, especially peat forming types, can serve as important sources of baseflow, which is the portion of streamflow sustained by groundwater discharge, particularly during dry periods (Jillian Labadz et al. 2010). This occurs as water slowly drains from the peat and maintain flow in nearby streams and rivers when rainfall is low. High water tables in wetlands support this process, while drained or degraded ones contribute less (Menberu et al. 2016). By storing and gradually releasing water, peatlands help regulate streamflow, reducing flood peaks, and supports ecosystems during drought (Karimi et al. 2024). This possibility has reinforced the interest in hydrological functions of such ecosystems (Bring et al. 2020). Following the severe drought in 2018, the Swedish government allocated funds to restore wetlands, aiming to enhance water availability across the landscape (Swedish Environmental Protection Agency 2023). As a restoration measure, rewetting has gained recognition as it directly addresses the hydrological conditions essential to many wetland functions lost in degraded states (Kløve et al. 2017). In drained peatlands, ditch blocking is a common rewetting intervention (Holden et al. 2017). It is based on the principle that runoff through channel flow will slow down and return the land into wet conditions, which is indicated by raised GWL (Lundin et al. 2017). When permeable soil types such as sand or gravel are present adjacent to the peat, these raised levels may also extend into surrounding areas, potentially contributing to broader landscape scale improvements in water availability (Thorsbrink et al. 2019).

Despite these governmental efforts, limited scientific data exists on the desired outcomes of peatland restoration regarding groundwater. While GWL time series are fundamental for evaluating changes in groundwater dynamics, monitoring at restoration sites is often limited by costs and time constraints, particularly given the requirement of long-term measurements (Wilson et al. 2010). Additionally, measurement errors and data quality issues can further challenge detailed assessment of restoration outcomes (Rau et al. 2019; Retike et al. 2022). Furthermore, some studies have focused on the hydrological impacts of rewetting drained peatlands in Scandinavia. Generally, rewetting led to increased GWL (Laudon et al. 2023; Karimi et al. 2024; Stachowicz et al. 2025). However, as groundwater dynamics appear to be influenced by local hydrogeological and meteorological conditions (Bourgault et al. 2019; Nygren et al. 2020), additional monitoring studies are necessary to gain further understanding of outcomes across diverse settings (Bring et al. 2022).

1.1 Thesis aim

The continued allocation of governmental funding to restoration projects in Sweden, even though there is a lack of scientific evaluation, raises questions about the certainty of current policies. To support evidence-based restoration of historically drained wetlands, this study aims to investigate GWL responses to rewetting, both within the peatlands and in adjacent areas, and seeks to identify the factors determining these changes.

GWL data were assembled from three historically drained wetlands, two of which had been rewetted, to compare pre- and post-rewetting conditions. The third wetland has not been rewetted, thus, a Before-After-Control-Impact (BACI) approach was employed to evaluate hydrological changes resulting from the restoration efforts. Recognizing that quality control of GWL measurements is an essential step prior to further application, this study demonstrates how deviating data were identified and treated. Another aim was also to assess the sufficiency of the GWL data to inform the effectiveness of rewetting on hydrological outcomes in a way that can guide future restoration efforts.

I hypothesized that rewetting of drained wetlands would improve their hydrological functions and climate adaptation potential, indicated by a rise and stabilization of GWL.

2. Materials and methods

The study sites were located in Östergötland county, southern Sweden (Figure 1A), and included two historically drained wetlands that have been rewetted, one in Örbacken nature reserve and one in Kärnskogsmossen nature reserve. To evaluate the impacts of rewetting on hydrological conditions, a drained but non-rewetted wetland in Vålberga nature reserve was used as a control site.

2.1 Climatic context

Östergötland county is located in the hemiboreal zone of Sweden, which has a warm temperate climate characterized by deciduous forest as the naturally dominant vegetation type (Lindbladh et al. 2014). The mean temperatures for the coldest and warmest months (30 years mean from 1991 to 2020) are -2°C and 17-18°C, respectively. The recorded mean annual precipitation is 500-600 mm (SMHI n.d.b). Meteorological data were obtained from nearby weather stations, which measured local conditions at hourly intervals (SMHI n.d.a). Air temperature and precipitation data were obtained from Kettstaka A weather station for the Kärnskogsmossen site, while data for the Örbacken and Vålberga sites were collected from Linköping-Malmslätt station (Figure 1B).

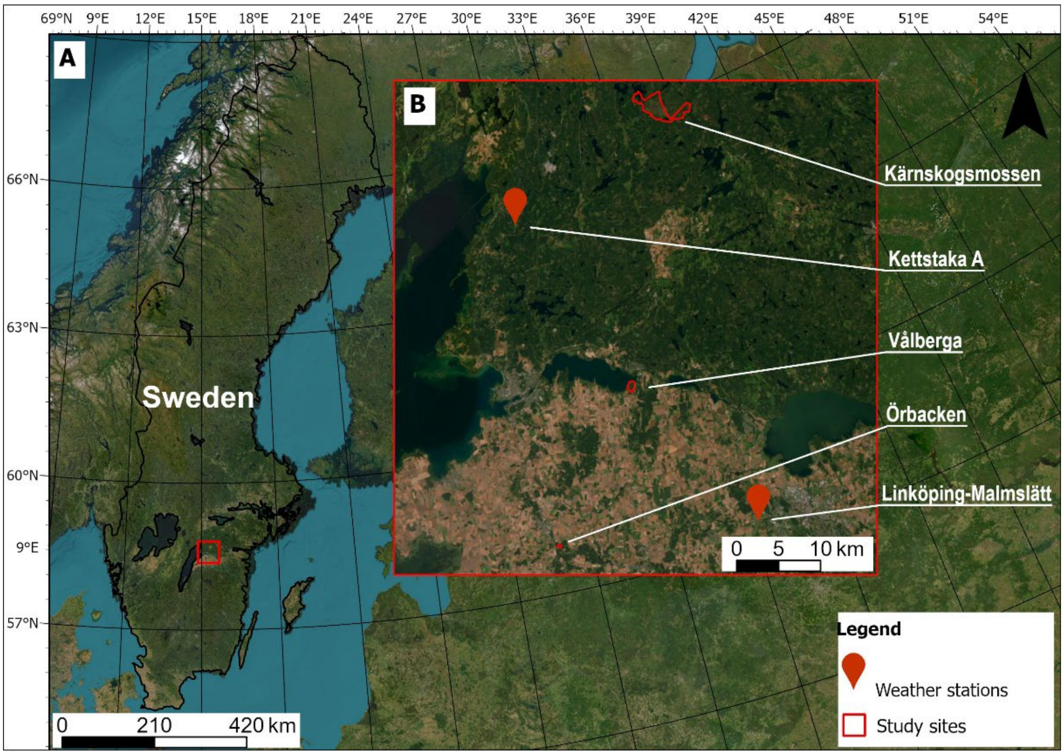

Figure 1. A) Geographic location of the study sites in Sweden. B) Outline of each nature reserve, in which the wetlands are located in, along with the relative positions of the weather stations. Basemap: World Imagery (Esri 2009) .

The meteorological conditions at the wetlands during the study period, including air temperature and precipitation, are presented in table 1 and figure 2.

Table 1. Monthly mean air temperature and monthly cumulative precipitation at the study sites Kärnskogsmossen, Örbacken and Vålberga in the period November 2022 to March 2025 (Swedish Meteorological and Hydrological Institute n.d.a).

Study site	Temperature (°C)			Precipitation (mm/month)		
	Mean	Min	Max	Mean	Min	Max
Kärnskogsmossen	6.0	-16.9 (Jan-2024)	27.0 (Jun-2024)	59.1	5.6 (Feb-2025)	229.8 (Aug-2023)
Örbacken and Vålberga	6.6	-3.5 (Jan-2024)	17.32 (Jun-2023)	50.8	5.1 (Mar-25)	215.8 (Aug-2024)

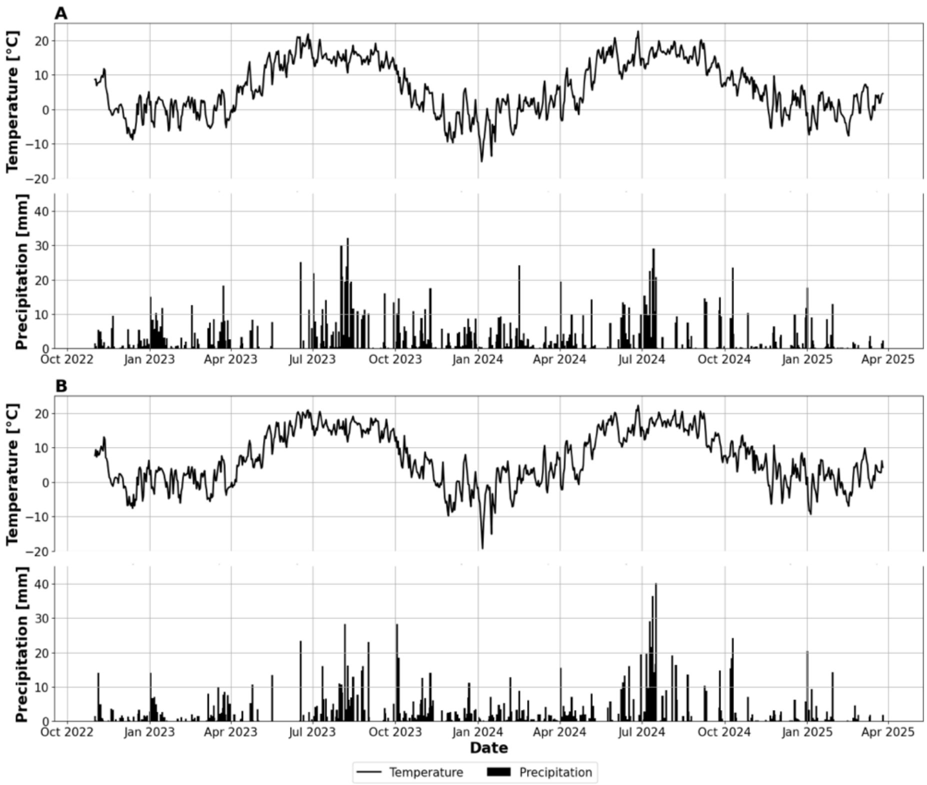

Figure 2. Time series of daily mean air temperature and total daily precipitation during the monitoring period. A) Data from the Kettstaka A weather station, representative of the Kärnskogsmossen site. B) Data from the Linköping-Malmslätt weather station, representative of both the Örbacken and Vålberga sites.

2.2 Study sites

The local geology of the study sites is characterized by them being situated below the highest coastline, meaning they were historically submerged under sea level. This post-glacial submergence exposed the areas to waves and currents, leading to the erosion of material from adjacent glaciofluvial deposits (Thorsbrink et al. 2019). A common peatland setting in these areas are underlain by thin clay layers, and bordering esker aquifers. Wetlands in such locations can either originate from groundwater discharge from the esker or through the overgrowth of a lake. In both scenarios, the wetland development began with a fen stage, which is entirely or partially dependent on inflow of groundwater (Thorsbrink & Bastviken 2021), possibly from the adjacent eskers.

2.2.1 Örbacken

The drained wetland in Örbacken nature reserve (10.8 ha) is a fen type peatland, located at the foot of Örbyfältet, which is a glaciofluvial deposit situated just outside of Mjölby. The area functions as a groundwater discharge zone, where calcareous water from the esker reaches the ground surface through spring outlets

(Thorsbrink & Bastviken 2021). The fen itself has postglacial sand in adjacent areas, besides from glaciofluvial deposits (Figure 3A), and sits on granite bedrock (©SGU 2024). The topography of the fen is relatively flat but includes subtle elevation gradients (Thorsbrink & Bastviken 2021) in the east of the nature reserve. The hydrology of the wetland is partly influenced by surrounding highly productive agricultural land, but mainly by a drainage channel that runs from south, at the outflow zone of the esker, with a flow direction towards a wet forest in the northwest (County Administrative Board in Östergötland 2017). Along the main drain, there are several smaller channels. The fen is most well-developed around these channels, where the ground is covered by mosses and the soil conditions are wetter (Figure 3B). Moreover, historical land use and property maps from 1868-1877 (Figure A.1), indicate that the area was used as open grazing land combined with haymaking in the northeastern part. The main draining channel was already present during this time. Earlier restoration measures of the wetland have included tree removal to expand the fen area (Figure 3C & 3D). More recently, actions have focused on raising the water level in the main drainage ditch. An already installed ditch plug was restored 9th of July 2023 to enable regulation of the water level. To monitor GWL changes following rewetting, three piezometers were installed.

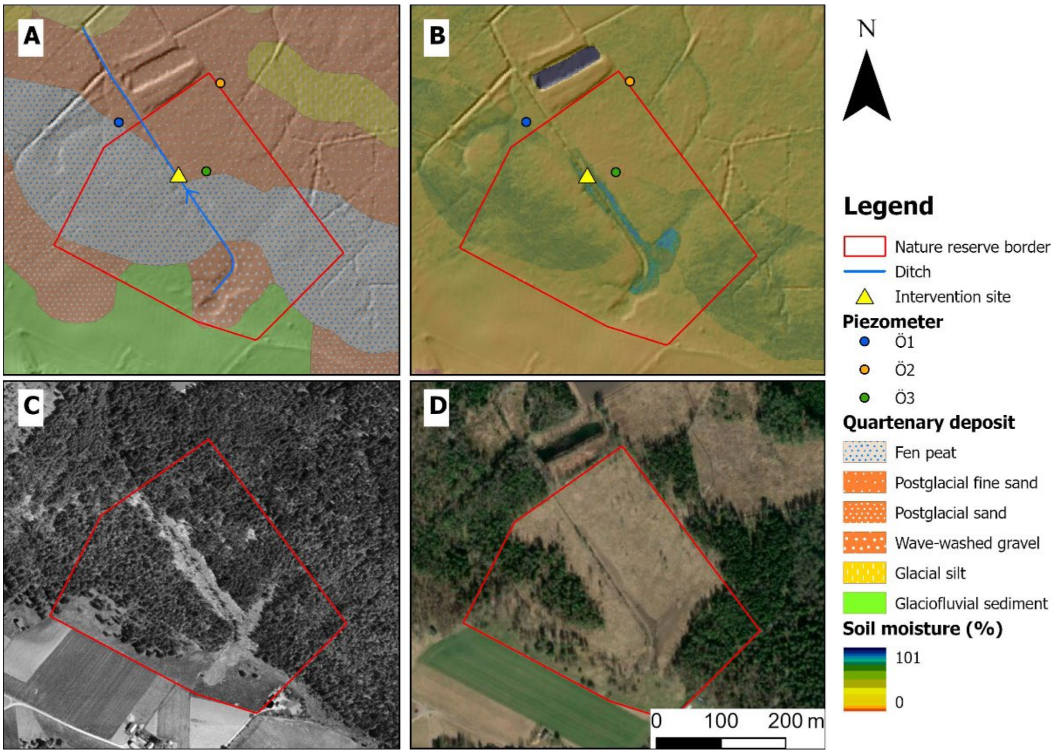

Figure 3. Site description of the drained wetland at Örbacken nature reserve. A) Map of quarternary deposits, showing location of piezometers, intervention site and drainage ditch. Quarternary deposits 1:25 000-1:100 000 ©SGU (2014). B) Map of soil wetness, showing location of piezometers and intervention site. SLU soil wetness map (Ågren et al.

2021) C) Previous land cover during 1960. Historical orthophoto 1960 ©Lantmäteriet (2025). D) Current land cover. World Imagery basemap (Esri 2009). A) and B) were blended with elevation data Grid 2+ ©Lantmäteriet (2019)

2.2.2 Kärnskogsmossen

Kärnskogsmossen nature reserve (847.7 ha) is a large mire complex and includes several mire massif types such as plateau-raised and raised bog, topogenous fen, and tarn (Figure 4E). The study area is limited to the eastern part of the nature reserve and compromises drained and/or overgrown fens or plateau-raised bogs (County Administrative Board in Östergötland 2009). An esker aquifer, composed of glaciofluvial deposits, runs through the area, which otherwise consists of sandy till in the east and fen peat in the west, (Figure 4A), all underlain by granite (©SGU 2024). The esker is covered by coniferous forest. In contrast, the lower and relatively flat area to the east is dominated by successional vegetation, including young trees, shrubs and common reed, a notable change in vegetation cover when compared with aerial imagery from 1960 (Figure 4C & D) (County Administrative Board in Östergötland 2018a). The peatland exhibits relatively high moisture conditions, while higher topographical areas are drier (Figure 4B). Although the glaciofluvial deposit has remained relatively unaffected by extraction activities, it has been excavated to allow the passage of a drainage ditch that continues in the northeasterly direction. According to historical land use maps, the northern half of the study area was characterized as open mire during late 19th century, the remaining parts were maintained through traditional mire haymaking. The intervention involved installation of 5 piezometers and a water level regulator to enable monitoring and regulation of the GWL. As a result, water level in the regultator was raised the 25th of May 2023.

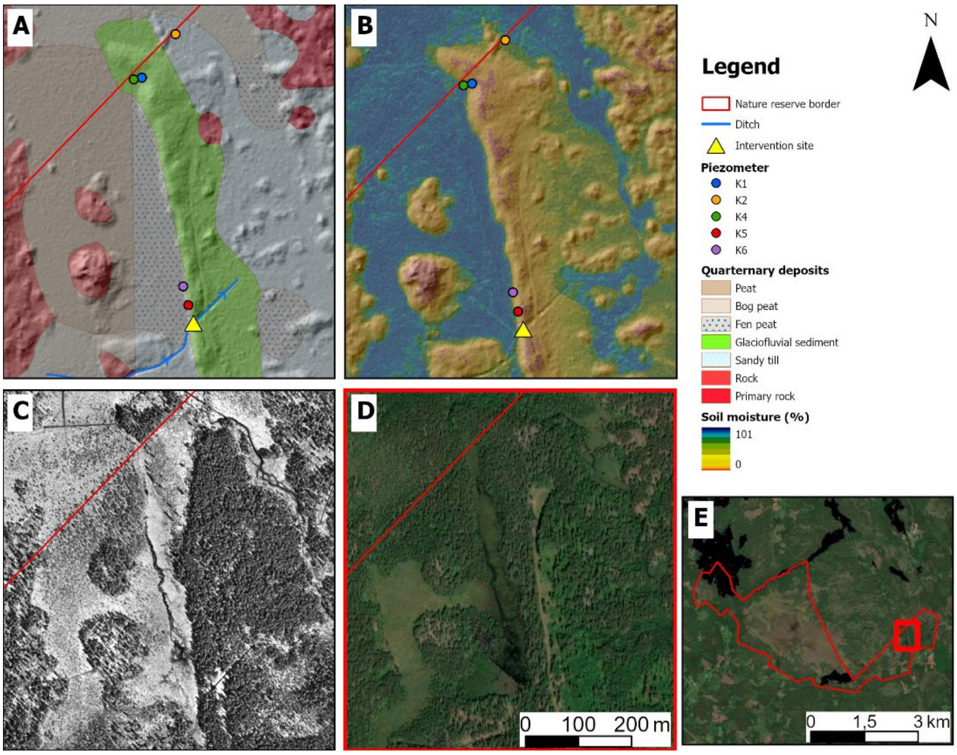

Figure 4. Site description of the eastern region of Kärnskogsmossen nature reserve, impacted by drainage. A) Map of quarternary deposits, showing location of piezometers, intervention site and drainage ditch. Quarternary deposits 1:25 000-1:100 000 ©SGU (2014). B) Map of soil wetness, showing location of piezometers and intervention site. SLU soil wetness map (Ågren et al. 2021); Elevation data Grid 2+ ©Lantmäteriet 2019) C) Previous land cover during 1960. Historical orthophoto 1960 ©Lantmäteriet (2025). D) Current land cover. E) Ouline of the Kärnskogsmossen nature reserve including delineation of the study site. A) and B) were blended with Elevation data Grid 2+ ©Lantmäteriet (2019), while D) and E) used World Imagery (Esri 2009)

2.2.3 Vålberga

Vålberga mosse nature reserve (67.3 ha) is located at the eastern end of Lake Boren and has a large and well-developed pine-dominated raised bog. The wetland is mostly forested, but there are a few smaller open areas (Figure 5D). The open areas are dominated by *Sphagnum spp.* together with some dwarf shrubs (*Calluna vulgaris* and *Vaccinum myrtilis*) (County Administrative Board in Östergötland 2018b). Bog peat has developed east of an esker aquifer, and farther east, glacial clay is found in the topographical lowland (Figure 5A), all underlain by limestone (©SGU 2024). Based on historical land use maps, Vålberga mire was an outlying land during late 19th century, consisting of entirely open bog, except for a wooded islet in the center (Figure A.3). To the east of the mire, there were also hay meadows and agricultural land. The hydrology of the mire is impacted by a main drainage ditch along its eastern edge, running from south to north, as well as several smaller ditches. This impact has led to the mire into a phase of overgrowth, characterized by an increasingly dense tree canopy, as evident when compared to historical maps (Figure 5C) (County Administrative Board in Östergötland 2022). Adjacent to the main ditch is a five-meter-wide parallel peat trench, which in turn is linked to around 15 vertically oriented peat extraction trenches, each approximately 100 meters long and three meters wide. Near the point where the main ditch drains into Lake Boren, there is a pumping station that actively regulates the water levels by pumping water from the ditch into the lake. Soil moisture is reduced adjacent to the pumping station and at topographically elevated locations (Figure 5B). Four piezometers have been installed as a preparation for future restoration efforts.

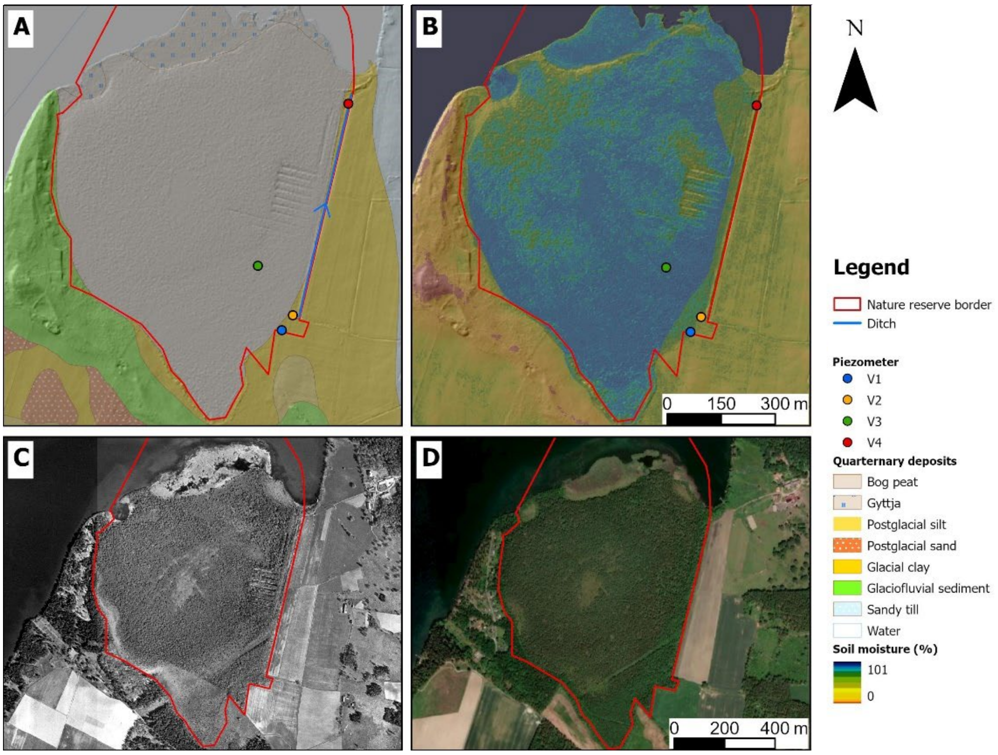

Figure 5. Site description of the drained wetland at Vålberga nature reserve. A) Map of quarternary deposits, showing location of piezometers, pumping station and drainage ditch. Quarternary deposits 1:25 000-1:100 000 ©SGU (2014); Elevation data Grid 2+ ©Lantmäteriet (2019). B) Map of soil wetness, showing location of piezometers and intervention site. SLU soil wetness map (Ågren et al. 2021) C) Previous land cover during 1960. Historical orthophoto 1960 ©Lantmäteriet (2025). D) Current land cover. World Imagery (Esri 2009). A) and B) were blended with Elevation data Grid 2+ ©Lantmäteriet (2019).

2.3 Piezometers installation and groundwater level monitoring

GWL monitoring was initiated in 2022 by the County Adminitrative Board in Östergötland through installation of piezometers. Piezometers are devices that measure the pressure of groundwater at specific points, typically consisting of a tube inserted into the ground to allow water levels to infiltrate, reflecting the hydraulic head at that location. These were strategically placed across the study sites, taking measurements at six hour intervals. The strategic placement implies that the piezometer locations were selected to support investigation of potential impact on GWL in adjacent areas to the blocked ditches. More details of the location of piezometers are provided in appendix B.

Continuous GWL recording was conducted using TD-Diver™ automatic pressure transducers equipped with GSM transmitters, enabling real-time data tracking in collaboration with the company Unoson Environment AB. Data were compensated for barometric pressure using the TD-BaroDiver®, with the adjustment automatically calculated through the Diver-Office software. From this compensation process, the water column depth above the pressure transducers were obtained. Manual GWL measurements, carried out during the installation period, were then used to calibrate the automatic measurements.

While the installation of the piezometers took place in September 2022, consistent and calibrated data collection began on 1st of November 2022, and continued until 26th of March 2025. The collected raw data set included GWL time series spanning roughly eight months pre-rewetting and slightly less than two years post-rewetting.

2.4 Data analytics

Statistical analysis, data processing, and summary statistics were performed using Python (version 3.12.7) (van Rossum 2025) and Grok (xAI 2025) used to support script development. A workflow of using Grok in script development is provided in appendix C. The pandas library (version 2.2.2) was used for data manipulation and analysis, while the matplotlib package (version 3.9.2) was employed for plotting and data visualization.

2.4.1 Data processing

The initial data set included raw GWL time series of 12 piezometers across three wetlands from November 2022 to March 2025. These observations were recorded with limited quality screening. Thus, a workflow was set up for pre-processing of GWL time series, adopted from Retike et al. (2022). First, potential errors in the GWL time series were identified by visual inspection. Second, for more thorough data exploration, a quality screening method, using a sliding window, was applied to the GWL time series. This approach served three key purposes: 1: compare short-term behavior across piezometers located in the same study site; 2: identify anomalies and/or differing behavior between piezometers; and 3: systematic flagging of differences. A window size of five time steps, corresponding to 30 hours given the six-hour measuerment interval, was considered to provide sufficient balance between capturing short-term dynamics and minimizing noise.

This investigation was performed by plotting the standard deviation of absolute trends against a range of window sizes. Using this sliding window, the slope of the GWL change between five consecutive time steps was calculated for each piezometer (incline, decline, or stability), enabling comparison of short-term dynamics and identification of relative patterns. The method detected anomalies or differing behavior of the time series and extra attention was given to periods without precipitation, during which changes might indicate data errors. Additionally, a threshold was applied to flag when relative trends in GWL between piezometers differed more than five cm, such as when one piezometer showed an incline or decline while the other remained stable or moved in the opposite direction. The four-eyes principle (Nihei et al. 2002) was applied, ensuring that each time series was reviewed by two people with separate roles: the Corrector and Controller. The Corrector was responsible for identifying errors in groundwater time series through visual inspection and the quality screening method. Behaviors were classified as errors only when they showed a clear deviation from the patterns recorded by other piezometers within the same study site. If corrections were necessary, the Corrector and Controller jointly determined the action of treatment after careful consideration of the origin, extent, and potential impact of the differing behaviors. Following the pre-processing steps, the final dataset was compiled, containing GWL expressed in centimeters and corresponding timestamps for each measurement. Negative values indicate depths below the ground surface.

2.4.2 Data analysis

The study employed a Before-After-Control-Impact (BACI) design to assess the outcome of rewetting on GWL, with impact being the restoration effort and control being the drained Vålberga site. Potential changes in GWL at the rewetted sites were assessed against GWL dynamics at the control site.

Statistical and comparative analyses were conducted on high-frequency GWL measurements from the three study sites. To ensure analytical consistency, two equal time intervals were defined for each site, both before and after rewetting. These intervals were adapted to utilize the available data pre-rewetting data and aligned to cover the same time of the year to ensure seasonal comparison. For Örbacken and Vålberga, data were divided into intervals set to 250 days each, spanning from November 1 to July 7 (2022-2023 and 2023-2024). At Kärnskogsmossen, due to earlier restoration, shorter 205-day intervals were used, covering November 1 to May 24 (2022-2023 and 2023-2024). To determine whether rewetting led to significant changes in median GWL, a non-parametric paired Wilcoxon signed-rank test ($\alpha = 0.05$) (Bauer 1972) was applied to daily average GWL data. To enable comparison across sites with varying absolute GWL, the data were rescaled using min-max (0-1) feature scaling. The test was conducted separately for each piezometer within each wetland, comparing GWL from the pre- and post-rewetting periods. To assess whether differences in precipitation or air temperature could explain potential groundwater changes, similar Wilcoxon signed-rank tests ($\alpha = 0.05$) were performed on both total daily precipitation, only including days with precipitation, and daily mean air temperature. Additional assessments included comparison of monthly mean GWL and total monthly precipitation to examine whether changes in average conditions support the patterns observed at the daily scale.

To evaluate the impact of wetland rewetting on how quickly GWL rise and decline in the case of a rain event, the Richards Pathlength index (RPI) was computed for both control and rewetted sites over the defined pre-and post-rewetting periods. This index serves as an indicator of hydrological flashiness, where higher values reflect greater variability and rapid fluctuations in GWL over time (Baker et al. 2004). The index is derived by calculating the total pathlength of the groundwater time series, standardized by the length of the time series according to the equation:

$$RPI = \frac{\sum_{i=1}^{n-1} |H_{i+1} - H_i|}{n-1}$$

where H_i is the rescaled GWL at time step i, and n is the total number of observations. Although the original formulation includes additional standardization by the median GWL, this step was omitted in the present analysis due to prior rescaling of the data using min-max normalization (Heudorfer et al. 2019). This analysis employed the Pastas package (version 1.8.1) (Collenteur et al. 2019) in Python.

An exceedance frequency analysis was performed to evaluate the proportion of time during which a GWL is exceeded before and after rewetting. This method used a flow duration curve approach and did not rely on daily averages but used the full temporal resolution of the dataset. The shape of the flow duration curve reflects the variability of flow in a system: a steep slope indicates high flow variability, while a flatter slope suggests more stable flow conditions over time (Smakhtin 2001). To interpret different aspects of the flow regime, the flow duration curve was divided into three segments following Karimi et al. (2024). The first segment, representing exceedance probabilities of 0 – 20%, corresponds to high flows typically associated with heavy rainfall events. The middle segment (20 – 70%) reflects mid-range flows resulting from moderate rainfall, and the final segment (70 – 99%) indicates baseflow conditions, which are critical for sustaining flow during dry periods.

3. Results

3.1 Quality control of groundwater level data

3.1.1 Data pre-processing and treatment of errors

During the pre-processing of the groundwater time series, several types of differing behaviors and errors were identified among the piezometers. Table 2 summarizes the main anomalies identified in the dataset, descriptions of each behavior and its respective treatment, along with references to representative examples. The first indication of a potential error in the data was a behavior in the time series that was not observed at any other piezometer within the same study site. The identified deviations were categorized into sudden and sharp shifts in GWL, jagged or toothed patterns, logger malfunctions, influence from nearby pumping, and diurnal fluctuations. The GWL shifts were characterized by sudden and sharp changes, often followed by a similar shift of the opposite sign later in the time series. To restore continuity with adjacent periods, these were addressed by adding or subtracting the corresponding level change to the affected data portion. The jagged and toothed pattern consisted of continuously changing GWL from high to low that differed from adjacent periods. This behavior was exclusively observed for piezometer K1 in Kärnskogsmossen. As no manual measurements from the monitoring period were available as reference data, these occurences were left unedited. Behavior due to instrument malfunction was distinguished by a continuously stable GWL. Subsequent data from the identified start of the malfunction was deleted. Prior to visual inspection of the time series, it was known that a pumping station was situated in the Vålberga control site. Consequently, piezometer V4, located in the proximity of the station, showed major influence from the pumping through rapid GWL changes ranging up to 60 cm. The entire time series was removed from the dataset. Diurnal fluctuations in the groundwater table appeared in some time series. These fluctuations were left unedited.

Table 2. Summary of differing behavior between adjacent piezometers identified from the pre-processing of groundwater time series and their respective treatment. Adopted from Retike et al. (2022).

Differing behavior	**Description of behavior (representative visual example)**	**Treatment**
Shift in groundwater level	Sudden, sharp level changes for a certain time period (Figure 6A).	Adjusted the data portion affected by the level change mathematically to compensate for the shift.

Jagged/toothed level pattern	Levels continuously change from high to low (Figure 6B).	Ignored the problem, since neither the higher nor lower record could be assumed to be correct.
Malfunction of automatic level logger	Logger records constant groundwater level for a significant amount of time (Figure 6C).	Identified the start of the malfunction and deleted subsequent data.
Influence of nearby pumping	Regular drop of water level, followed by fast recovery that differ from adjacent piezometers (Figure 6D).	Deleted the data that were severly affected by pumping.
Diurnal groundwater level fluctuations	Cyclic groundwater level fluctuations (Figure 6E)	Ignored as the range of level fluctuations was a few centimeters and might represent daily fluctuations associated with transpiration cycle.

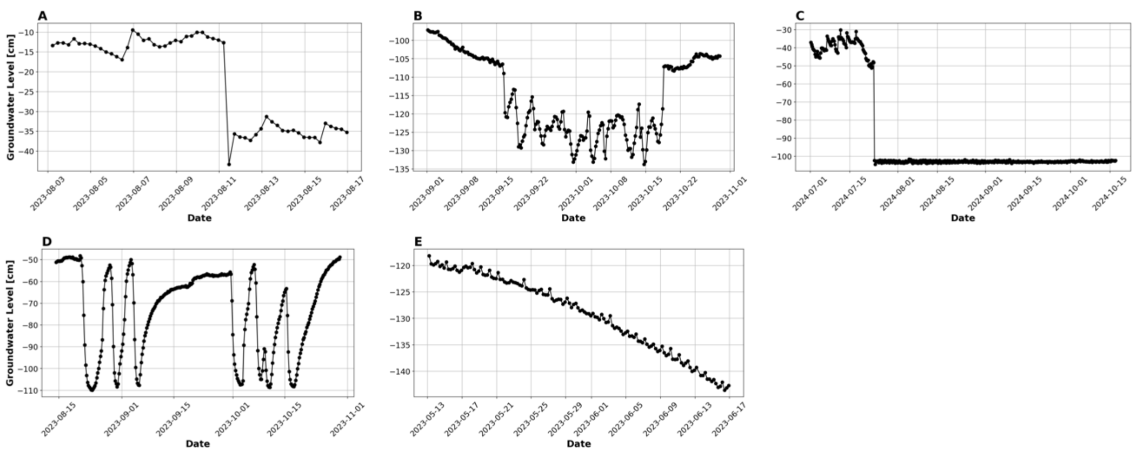

Figure 6. Represenative examples of GWL time illustrating piezometers that exhibited behavior differing from adjacent instruments. Titles indicate the study site and piezometer label. A) Shift in GWL in Ö3. B) Jagged/toothed level pattern in K1. C) Malfunction o f automatic level logger in Ö3. D) Influence of nearby pumping in V4. E) Diurnal GWL fluctuations in K1.

3.1.2 Processed time series and observed groundwater level fluctuations

The pre-processed groundwater time series are presented in figure 7. Red dashed lines indicate the timing of rewetting interventions at Örbacken and Kärnskogsmossen. In Örbacken (Figure 7A), piezometers recorded relatively stable GWL between summer seasons, during which water drained and declining levels were observed. Piezometer Ö2 recorded the most substantial decline in the hydraulic head during the summer of 2023, gradually falling below depths of 150 cm, followed by a rapid recovery. The summer of 2024 displayed more varied dynamics, where declines were less distinct and recoveries occurred more frequently, often returning to levels similar to those measured before the summer period. Piezometer Ö1, located in the wet forest area of the study site, recorded water levels above the soil surface. A notable rise in the groundwater table was observed at Ö3 post-rewetting. In Kärnskogsmossen, piezometers K2, K4, K5, and K6 recorded similar temporal patterns (Figure 7B), with rises and falls occurring around the same time. In contrast, K1 differed from this pattern and exhibited less frequent variation in the groundwater head. Seasonal regularity was weakly expressed across the site throughout the monitoring period. For instance, the amplitude of GWL fluctuations varied between the two summer periods. In 2023, drier conditions were probably present as deeper depths to the water table were recorded, particularly at K1, while the summer of 2024 was wetter. Following the rewetting event in late May 2023, piezometers K4, K5 and K6 recorded a sustained increase in the GWL compared to pre-rewetting conditions. At the control site Vålberga, GWL at piezometers V1 and V2 exhibited similar dynamics (Figure 7C), characterized by synchronized fluctuations with occasional rapid declines followed by recovery. A similar pattern was present in the data from piezometer V4, which was excluded from the final dataset due to a more pronounced influence from pumping activity (Figure 6D). In contrast, V3 showed less dynamic behavior and less frequent change of the GWL. Across all piezometers at this site, seasonal patterns with drier conditions during summer months were observed. However, the shape of the curves varied. During summer of 2023, GWL declined gradually over an extended period, whereas following summer sustained a short dry phase before shifting toward peak wet conditions.

Figure 7. Pre-processed groundwater time series recorded at six-hour intervals by piezometers at A) Örbacken, B) Kärnskogsmossen and C) Vålberga. Red dashed line represents the date of rewetting.

3.2 Effect of rewetting on groundwater levels

To assess the impact of rewetting on GWL across the piezometers at the study sites, pairwise comparisons of normalized daily mean GWL were conducted for the defined periods before and after rewetting. In every case, a significant change in median GWL was calculated between the periods (Figure 8). The wide range and number of outliers demonstrate the highly dynamic hydrology of the wetlands. Almost all piezometers across the sites showed an increase in median GWL in the post-rewetting period, except for piezometer Ö2 at Örbacken (Figure 8A), where a slight decrease was observed. Although, the lower end of the boxplot was higher, indicating that conditions were wetter in the post-rewetting period. The central tendency of the GWL across the rest of the piezometers showed an upward shift, with whiskers and individual circles extending to higher levels in the post-rewetting period. The largest shifts in were observed at piezometers K4, K5, and K6 at Kärnskogsmossen (Figure 8B). At the control site, Vålberga (Figure 8C), an increase in median GWL was also observed during the corresponding post-rewetting period, despite the absence of hydrological treatment. Summary statistics for GWL during the pre-and post-rewetting periods, along with respective p-values are provided in appendix D table A.1.

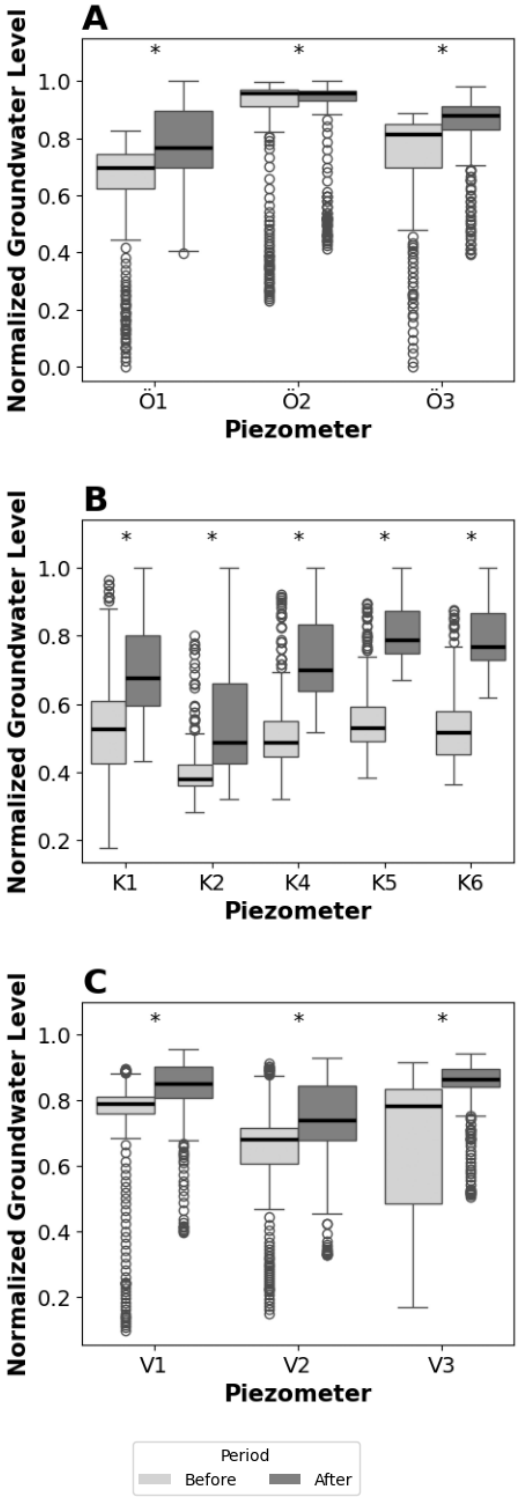

Figure 8. Boxplots showing the distribution of normalized daily mean GWL at individual piezometers during defined pre- and post-rewettning periods across the study sites. A) Örbacken, B) Kärnskogsmossen and C) Vålberga (control site, not rewetted). Boxes represent the interquartile range (IQR), whiskers extend to 1.5IQR. Circles outside the

whiskers show extreme measurments. Solid line represents median value. Asterisk denotes significance level after Bonferroni correction ($p \leq 0.0045$, ns $p > 0.0045$).*

Further assessment of rewetting effects on hydraulic heads compared monthly mean GWL and monthly cumulative precipitation between the pre- and post-rewetting periods (Figure 9). At the rewetted sites, Kärnskogsmossen and Örbacken, GWL generally rose after rewetting, or did not distinctly fall below pre-rewetting levels. At Örbacken, GWL remained relatively unchanged from November to May across both periods, with a slightly higher GWL at piezometer Ö1 post-rewetting (Figure 9A). In June and July, GWL were more stable in the post-rewetting period, since they did not reach the same depth as before rewetting. It is important to note that the July data only comprised eight days of recordings, given that Örbacken was rewetted on the 9th. The higher GWL in July 2024 is also coupled with increased precipitation. Similar pattern was observed at the Vålberga controls site, with more stable GWL in June and July 2024 (Figure 9C). In general, the differences in GWL across the periods was larger at Vålberga compared to Örbacken. In Kärnskogsmossen (Figure 9B), piezometers K4, K5 and K6 showed a clear increase in hydraulic head following rewetting. However, in January, the differences in monthly mean GWL between the two periods decreased across all piezometers in Kärnskogsmossen. Piezometers K1 and K2 generally showed increased GWL in the post-rewetting period when those months exhibited increased precipitation. In cases of heavier rainfall during the pre-rewetting months, there were no notable differences in the GWL. Monthly cumulative precipitation varied between the two periods, with some months having more precipitation post-rewetting and others receiving less.

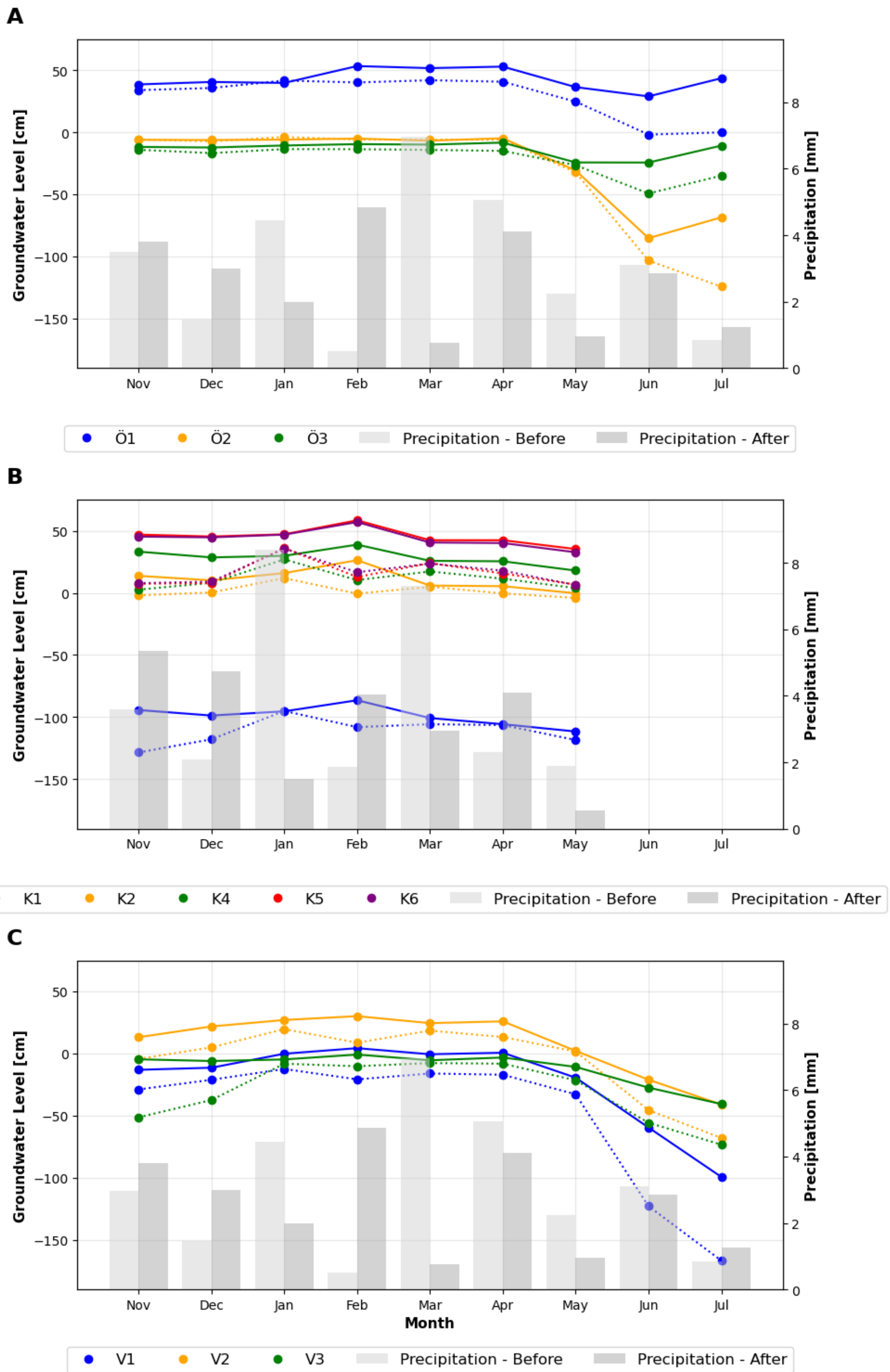

Figure 9. Monthly mean groundwater levels and total monthly precipitation from the pre- and post-rewetting periods in A) Örbacken, B) Kärnskogsmossen and C) Vålberga, which was not rewetted. Dotted lines represent groundwater levels in the pre-rewetting period, while solid lines indicate levels in the post-rewetting period.

Groundwater depth duration curves for each piezometer during the pre- and post-rewetting periods are presented in figure 10. The curves illustrate the exceedance frequency of a normalized GWL. For instance, a 10% exceedance frequency indicates that the GWL is at or above that level 10% of the time, meaning that the remaining 90% of GWL observations are at a deeper depth. Overall, the analysis revealed that the groundwater tables were closer to the surface more frequently in the post-rewetting period. The smallest change was observed at piezometer Ö2 (Figure 10A), which recorded similar GWL approximately 85% of the time, consistently at or above a non-normalized value of -70 cm. The remaining right-hand tail of the curve was shifted upwards in the period following rewetting, representing GWL during low rainfall conditions. This overall dynamic, with an upward shift in the right-hand tail in the post-rewetting period, was generally observed at piezometers across Örbacken and Vålberga (Figure 10A & 10C). Notable increases in hydraulic head were observed at piezometers K5 and K6 at Kärnskogsmossen (Figure 10B). For example, K6 recorded levels above 15 cm for 50% of the pre-rewetting period, whereas post-rewetting, it exceeded 40 cm during the same percentage of time. A similar behavior was observed at K4, although the difference was less between the levels across the two periods. Furthermore, the overall shapes of the duration curves remained relatively unchanged.

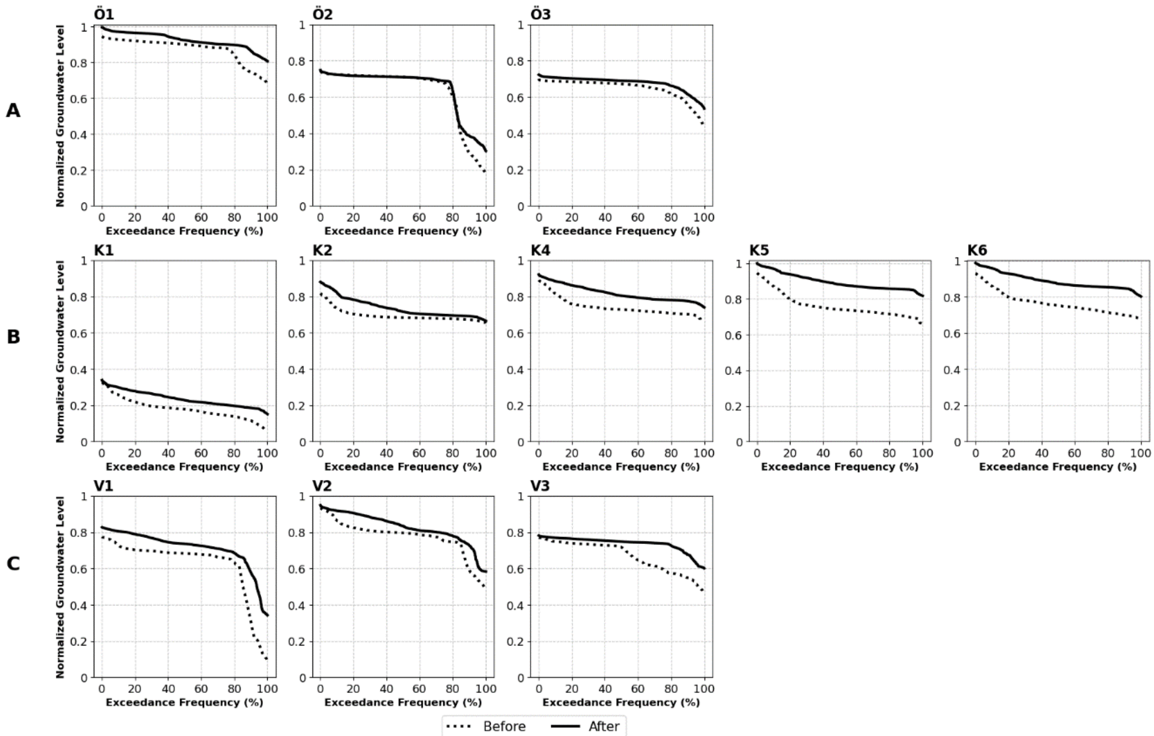

Figure 10. Groundwater depth duration curves of normalized GWL fluctuations during the pre- and post-rewetting periods. A) Örbacken, B) Kärnskogsmossen and C) Vålberga. Titles indicate the piezometer label.

3.3 Analysis of meteorological conditions

Analysis of potential differences in precipitation between the pre- and post-rewetting periods was conducted by comparing median monthly and cumulative precipitation for each site. At Kettstaka A, representative of Kärnskogsmossen, the cumulative precipitation increased slightly from 315 mm during the pre-rewetting period to 340 mm in the post-rewetting period. The median monthly precipitation increased from 30 to 56 mm. At the Linköping-Malmslätt station, representing Örbacken and Vålberga, a larger change was observed. The cumulative precipitation increased from 272 mm in the pre-rewetting period to 396 mm in the post-rewetting period. The median monthly precipitation also increased from 26 mm to 46 mm. Although, statistical analysis using a pairwise Wilcoxon test indicated no significant difference in daily precipitation at Linköping-Malmslätt nor Kettstaka A weather station ($p > 0.05$) (Figure 11). For this test, only days with precipitation were compared. Similarliy, no significant change was detected in air temperature between the pre- and post-rewetting periods ($p > 0.05$) (Figure 12).

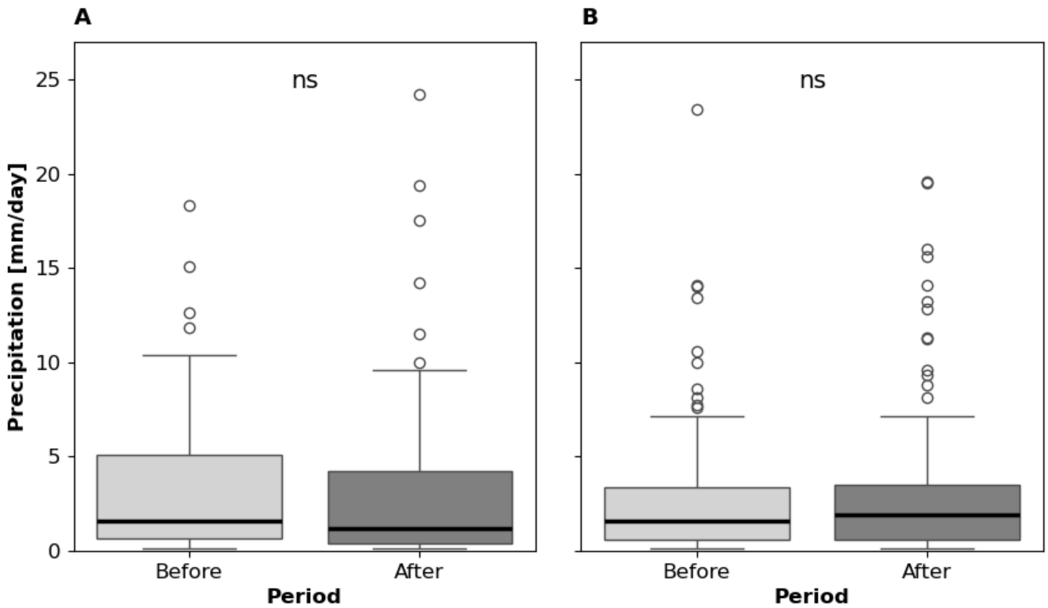

Figure 11. Boxplots showing the distribution distribution of daily rainfall, only for days with precipitation, from two weather stations nearby the study sites during defined pre- and post-rewetting periods. A) Data from the Kettstaka A weather station, representative of the Kärnskogsmossen site. B) Data from the Linköping-Malmslätt weather station, representative of both the Örbacken and Vålberga sites. Boxes represent the interquartile range (IQR), whiskers extend to 1.5IQR. Circles outside the whiskers show extreme events. Solid line represents median value. Asterisk denotes significance level after Bonferroni correction ($p \leq 0.05$, ns $p > 0.05$)*

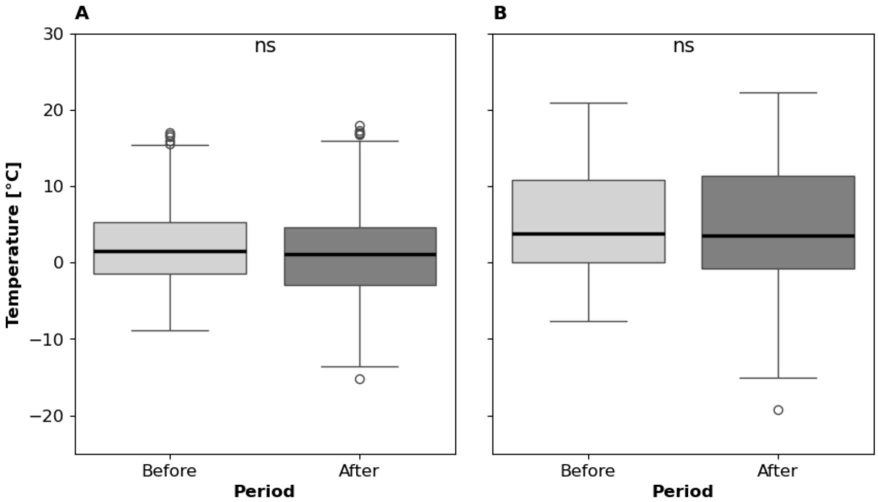

Figure 12. Boxplots showing the distribution of daily mean air temperature from two weather stations nearby the study sites during defined pre- and post-rewetting periods. A) Data from the Kettstaka A weather station, representative of the Kärnskogsmossen site. B) Data from the Linköping-Malmslätt weather station, representative of both the Örbacken and Vålberga sites. Boxes represent the interquartile range (IQR), whiskers extend to 1.5IQR. Circles outside the whiskers show extreme events. Solid line represents median value. Asterisk denotes significance level after Bonferroni correction ($p \leq 0.025$, ns $p > 0.025$)*

3.4 Flashiness assessment through Richards Pathlength index

The RPI showed varying trends across the piezometers within each site when comparing the pre- and post-rewetting periods (Figure 13). At the rewetted site Örbacken, changes in index values were generally minor, where the most notable increase from 1.20 to 1.61 was calculated at piezometer Ö1. Rises in the RPI, generally reflecting rapid responses to rainfall events, were also observed at each piezometer for the control site Vålberga, despite the absence of hydrological treatment. At Kärnskogsmossen, most piezometers exhibited lower index values after rewetting, indicating that GWL became less flashy after rewetting by slower rises and declines. An exception was K1, where a slight increase was calculated. Piezometers K4, K5 and K6 all showed similar decreasing trends in index values between pre- and post-rewetting. The most notable change among all piezometers occurred at piezometer K2, decreasing from 5.00 to 4.01.

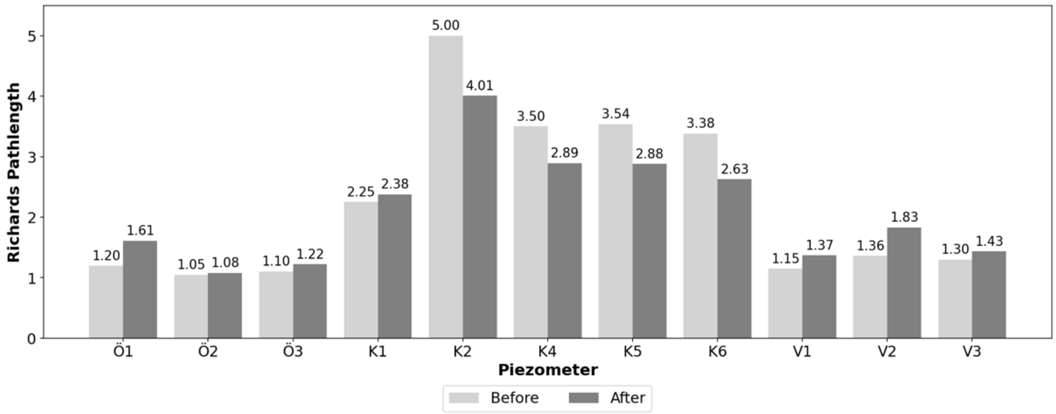

Figure 13. Richards Pathlength index across all piezometers at each site during the pre- and post-rewetting periods.

4. Discussion

In this section, I will present the main findings of the study regarding observed groundwater dynamics following rewetting. I will explore how site-specific characteristics, including hydrogeology, topography, and drainage history, may influence the spatial variability in hydrological responses. Additionally, guidance for interpretation will be provided by assessing shortcomings of the study. Finally, the section will conclude with suggestions for stakeholders, emphasizing the importance of data quality assurance and goal-oriented approaches for hydrological interventions.

4.1 Meteorological context

The analysis of meteorological conditions during pre- and post-rewetting periods showed no significant change in air temperature nor precipitation across any weather station. However, at the Linköping-Malmslätt station, there was a notable increase in cumulative precipitation over the post-rewetting period from 270 mm to 396 mm. This station was representative of meteorological conditions at both the rewetted Örbacken site and the Vålberga control site. Since seasonal variability in precipitation can influence GWL, independent of rewetting efforts, with wetter periods generally leading to higher GWL (D'Acunha et al. 2018; Menberu et al. 2018), any changes to groundwater dynamics in Örbacken may not only be due to rewetting. Conversely, rises in GWL at Vålberga may be explained by increased rainfall in the post-rewetting period.

4.2 Groundwater dynamics following wetland rewetting

4.2.1 Increases in groundwater level at Kärnskogsmossen

The results from Kärnskogsmossen indicate an increase in GWL following rewetting, particularly at piezometers K4, K5, and K6 (Figure 8B). In addition to higher GWL, these piezometers also displayed more stable levels during the post-rewetting period compared to pre-rewetting conditions (Figure 9B). This stability was notable across different rainfall conditions, including periods of high, moderate, and low rainfall (Figure 10B). Visually, extreme summer fluctuations appeared to be reduced (Figure 7), further supporting this interpretation. In addition, decreases in the RPI values at these piezometers indicated slower changes in response to rainfall or other events. These findings align with my hypothesis, and suggest that groundwater supply increased through raised GWL, and hydrological buffer capacity was improved as GWL stabilized in the post-rewetting period (Thorsbrink et al. 2019).

Exceedance frequency analysis reinforced these findings. At Kärnskogsmossen, the groundwater duration curves for the three most impacted piezometers showed a slight flattening, which is associated with less variability and more consistent GWL (Smakhtin 2001). The low-flow conditions (70-99%) were improved (Figure 10B), during which post-rewetting GWL stayed elevated and did not decline to the depths recorded in the pre-rewetting period. This is also consistent with my hypothesis that rewetting will improve hydrological functions, thereby enhancing water retention capacity and contribute to climate change adaptation.

Previous studies have found that rewetting can result in rapid rises and greater stability in GWL (Wilson et al. 2010; Haapalehto et al. 2011; Menberu et al. 2018; Laudon et al. 2023; Karimi et al. 2024). Karimi et al. (2024), for example, suggested that stabilized GWL during dry periods were due to improved retention of spring snowmelt of their rewetted peatland in the boreal region of northern Sweden. Similarly, Wilson et al. (2010) found that ditch blocking increased water storage, as seen through raised GWL, lower peak flows, and slower water movement. However, it is important to note that this study did not include flow or discharge data like the previously mentioned studies, meaning that inferred improvements in water storage at Kärnskogsmossen are based on GWL patterns. Therefore, while the results may suggest improved retention capacity, they do not confirm this directly.

The remaining piezometers at Kärnskogsmossen, K1 and K2, showed more moderate response to rewetting, or was not clearly distinguishable from the changes observed at the control site. Piezometers K5 and K6, being near the intervention site, responded rapidly and synchronized as anticipated (Bring et al. 2022). Interestingly, piezometer K4 also recorded a rapid rise in GWL, even though it was located about 500 meters from the intervention site and close to K1 and K2. This observation suggests that local hydrogeological conditions, such as the presence of the glaciofluvial ridge and sandy till in adjacent areas to the peatland, likely influenced the spatial extent of the rewetting impact. Soils with high porosity generally facilitate a slow rise in groundwater level because a larger volume of water is needed to raise the GWL, compared to a soil with low porosity (Corona et al. 2023). In this context, K1 and K2 were situated in glaciofluvial deposits and sandy till respectively. While glaciofluvial deposits can have varying pore structures depending on their composition, deposition conditions, and post-depositional changes, the settings at K1 and K2 appear to have a pore structure that resulted in a slow response (Strobel 1993). This contrasts with K4, which likely benefited from the intersection of peat and glaciofluvial sediments. This, along with its similar elevation to the rewetting site, potentially facilitated greater hydrological connectivity and allowed for a rapid rise in GWL, despite its distance from where the intervention was implemented.

The contrasting responses of piezometers K1 and K2 compared with K4 reinforce how local hydrological features can create spatial variability in responses to rewetting, even within relatively small areas. Other studies have estimated the impact distance of rewetting that further underscore the variability of how far rewetting effects can extend. Sorrell et al. (2007) found that ditch blocking in a gentle sloping fen raised GWL within 15 meters but had small effects beyond 30 meters. Conversely, Ruseckas & Grigaliūnas (2008) reported increased GWL within 980 meters from the intervention site in a raised bog in Lithuania, suggesting a broader influence depending on peatland type and hydrology.

4.2.2 Limited response in groundwater levels at Örbacken

In contrast to Kärnskogsmossen, GWL changes at Örbacken were less distinguishable from those observed at the Vålberga control site. For instance, the more stable GWL observed in June 2024 compared to previous year occurred at both sites (Figure 9), implying that external factors, such as increased precipitation, may have driven the observed stability. Similarly, the study conducted by Bourgault et al. (2019) also reported a strong positive correlation between precipitation and GWL across their studied peatlands.

The limited GWL response at Örbacken may be explained by several site-specific hydrogeological and topographic conditions, described by an assessment of the area conducted by Thorsbrink & Bastviken (2021). Firstly, the topography of the site may be relatively flat but the subtle elevation gradients was considered to control shallow groundwater flow directions. A small topographic rise located between the blocked ditch and the adjacent forest in the east was believed to direct the shallow groundwater either westward toward the ditch or northeastward, thus limiting lateral hydrological connectivity across the site. Given that piezometer Ö2 was installed northeast of this elevated area, this topographic rise may explain why no clear GWL response to rewetting was recorded. Secondly, to the northwest of the site, a raised bank of excavated material was situated west of the ditch, also in proximity to piezometer Ö1. According to Thorsbrink & Bastviken (2021), this bank may have a damming effect, which influences lateral groundwater flow, potentially explaining the relatively unchanged GWL observed at Ö1 following rewetting. These features likely contribute to a delayed or spatially limited increase in GWL. Thus, the observed groundwater pattern may reflect site constraints rather than a lack of intervention effectiveness. This aligns with findings by Menberu et al. (2016), who reported that effectiveness of ditch blockage can depend on the type of peatland. After restoration, they observed the largest increase in GWL in mires, followed by fens. Given that Örbacken is a fen type peatland, its hydrological response would accordingly be expected to be weaker than that of a mire.

Futhermore, it is also possible that Örbacken exhibits delayed hydrological recovery that is not captured within this monitoring length, due to its long history of drainage. Prolonged drainage leads to peat subsidence and alters surface topography by creating a downward slope towards the drain, which in turn affect water movement and retention (Holden et al. 2017). This deformation of the peat surface, coupled with the slow process of peat accumulation, can extend the recovery period, as found by Liu & Lennartz (2019) and Regan et al. (2019). Karimi et al. (2024) noted that while GWL recovered quickly, full restoration of peat structure and hydrological function remained incomplete three years post-rewetting. Similarly, Holden et al. (2011) found that six years after rewetting, restored sites still differed hydrologically from undisturbed controls.

While piezometer data provides valuable insights into GWL changes following rewetting, it may not always capture the full extent of hydrological responses. For instance, in a drained Norwegian raised bog, studied by Stachowicz et al. (2025), no evident responses in individual piezometer readings were detected four years after rewetting. However, they found plant and vegetation-based indicators in the that suggested a shift in hydrological conditions, such as flooded forest vegetation and trees showing signs of dying. These findings imply that important ecological or hydrological responses may occur outside of immediate vicinity of monitoring points, or in ways not detectable through GWL data alone.

Several factors may contribute to varied GWL outcomes following rewetting of drained wetlands. This study found that hydrological response differed both within individual sites and between sites across Östergötland county in Sweden. These varying responses align with a study conducted by Wilson et al. (2010), which emphasize that both local and landscape-scale conditions play critical roles in shaping hydrological recovery following rewetting interventions. At the local scale, monitoring points located at elevations similar to the blocked ditch showed a more rapid GWL response. In contrast, areas that were more elevated or less hydrologically connected showed weaker responses. At the landscape scale, Wilson et al. (2010) reported that differences in GWL recovery were likely driven by variations in peat structure, slope, and catchment size. The heterogeneity observed in GWL response across the current study sites may thus be partly explained by similar controlling factors, such as local topography, proximity to the ditch, and differences in peat structure. This highlights the need to consider local hydrogeological conditions when planning as well as evaluating wetland rewetting, since outcomes can differ widely and the same method may not work the same way in every site (Parry et al. 2014). Additionally, recovery may take considerably longer than the duration of many monitoring programmes (Wilson et al. 2010), which addresses the need for long-term studies of wetland processes following rewetting.

In summary, the data and analyses of this study showed varied groundwater responses to wetland rewetting both within and across sites, possibly due to factors related to site-specific conditions. Some findings support my hypothesis that rewetting improves hydrological functioning and climate adaptation potential, but others were contrasting. While previous studies have reported immediate increases in GWL and enhanced water storage capacity following rewetting, those effects were not as evident here. Importantly, the effects of rewetting are not uniformly positive. It has been reported that raising GWL can increase concentration of dissolved organic carbon, mercury, nutrients, but also increasing emissions of methane (Koskinen et al. 2017; Laudon et al. 2023). However, as other processes like beaver dams and tree harvesting have the potential to induce increased GWL (Čiuldienė et al. 2020; Shah et al. 2022), such negative effects alone may not justify avoiding rewetting. A drained wetland without any action taken toward rewetting is likely to continue to degrade under future climatic pressures (Loisel & Gallego-Sala 2022).

4.3 Guidance for interpretation

When interpreting the findings of this study, several shortcomings should be considered. First, a paired Wilcoxon signed-rank test was used to assess changes in GWL before and after rewetting. Although this is a commonly used non-parametric method in similar hydrological studies (Kreyling et al. 2021; Karimi et al. 2024; Stachowicz et al. 2025), there is a potential of misleading interpretation of hydrological shifts when results are summarized through changes in the median. Because there is a possibility that changes in the median do not fully capture underlying distributional changes (Potter et al. 2010). For one piezometer, the Wilcoxon test indicated a decrease in median GWL in the post-rewetting period compared to pre-rewetting. However, the distribution of GWL at this piezometer showed an upward shift at the lower end, suggesting that GWL during drier conditions were higher in the post-rewetting period. This outcome demonstrates that the Wilcoxon test does not necessarily identify where changes occur within the distribution, and potentially underrepresent meaningful hydrological improvements that do not affect the median. Therefore, relying on summary statistic to explain changes in the hydrological extremes risks oversimplifying responses. This is particularly important in this context, as changes in the extremes may indicate improved capacity of the system to buffer against high and low flows during extreme weather events. To mitigate the effects of this shortcoming, statistical testing was combined with exploratory and distribution-focused methods, such as the flow duration curve analysis.

Second, the RPI was used to assess the variability in GWL fluctuation patterns before and after rewetting. A sensitivity analysis, performed by Heudorfer et al. (2019) on groundwater indices, suggested that RPI values reach stable sensitivity after a time series length of five to six years. In this study, however, the pre- and post-rewetting periods of which the RPI was calculated corresponded to a time series length of either seven or nine months, depending on when the wetland was rewetted. This shorter duration of the time series, compared to the suggested stability threshold, introduces a limitation regarding the robustness of the RPI results. The calulated index values may not have stabilized, potentially leading to higher uncertainty than what would be expected from longer periods. Thus, the changes in flashiness following rewetting, based on RPI, should be interpreted with caution, as the values may not reflect the true change across the rewetted wetlands.

Third, although meteorological data were obtained from nearby weather stations, microclimates can vary over short horizontal distances. Some factors influencing these variations are local topography, land cover, proximity to water bodies, and soil characteristics (Aalto et al. 2022). Given the settings of the study sites, for example, Vålberga is located adjacent to a lake, and the Kärnskogsmossen site is part of a larger mire complex, it is possible that microclimatic variability exists that would lead to discrepancies between station data and actual on-site conditions. Consequently, the spatial coverage of precipitation and air temperature measurements was limited. This introduces some uncertainty when interpreting the relationship between meteorological drivers and observed GWL dynamics across the study sites. To mitigate the influence of this shortcoming, hydrological responses, such as the timing of GWL rises following precipitation events were assessed through visual inspection. However, future studies would benefit from incorporating on-site meteorological monitoring, such as tipping-bucket loggers (Taylor & Alley 2001).

Another shortcoming relates to the length and timing of the monitoring period. Rewetting interventions were implemented in early summer of 2023, yet calibrated GWL monitoring began only in November 2022, providing less than a full year of pre-rewetting data. This limits temporal coverage of annual seasonal variability, which is an important aspect given the distinct seasonality in the hydrologic cycle and its influence on GWL dynamics (Nygren et al. 2020). To enable statistical comparison while also accounting for seasonal patterns, the pre- and post-rewetting intervals were adapted to match available pre-rewetting data. However, this meant that certain seasonal GWL dynamics, particularly those during summer and early autumn, were only partially represented in some of the analyses. This shortcoming is addressed by Liu et al. (2024), who highligths the importance of pre-restoration data to establish baseline variability and reference conditions. The temporal coverage of the pre-rewetting data should be designed to capture relevant hydrological processes indicative of effective restoration. For example, if the main goal of a wetland rewetting project is to enhance water availability during drought periods, baseline conditions should ideally be captured before intervention.

4.4 Conclusions and suggestions for stakeholders

4.4.1 Quality assurance of groundwater level time series

The results from the pre-processing workflow indicated that GWL time series are susceptible to various types of errors. As the identified errors aligned with those addressed by Retike et al. (2022), the results may also indicate that the errors are commonly associated with GWL monitoring. Data quality was improved through visual inspection and an adopted method for identifying differing behavior in the GWL time series.

Factors influencing data quality and leading to necessary corrections often stemmed from errors in measurement and data recording, or anthropogenic impact. Distinguishing between artifacts in the data and natural groundwater dynamics is necessary to not weaken the analytical outcomes of peatland restoration. Because if errors were simply removed without investigating their origin, extent, or potential impact on the analyses, spatial or temporal coverage of the data may be reduced (Rau et al. 2019).

The applied methodology for quality assurance may offer a broader perspective that reinforce the necessity of distinguishing between artifacts and true groundwater behavior. The adopted quality screening method flagged several differing behaviors in the time series that mirrored the complex dynamic of groundwater fluctuations. This reflects the uncertainty of this mathematically based method for comparing short-term trends (incline/decline/stability) in the data to identify errors. In the case of separating genuine data issues from unusual but valid behavior, the value of human judgement through the roles of the Corrector and Controller was irreplaceable, which is also addressed by Gschwandtner & Erhart (2018). However, the adopted quality screening method efficiently flagged anomalies, while visual inspection utilized the ability for analyzing as well as understanding such anomalies. As suggested by Ali et al. (2019), the combination of automated and visual methods may represent an efficient approach to identify errors in time series data.

Findings of this study, regarding quality control to enhance validity of analyses, suggest that regular manual measurements could have mitigated effects from common errors in the GWL time series. This because manual measurements would have provided an external reference for both calibrating automated data loggers and verification of applied data corrections. The findings also highlight the importance of multiple monitoring points, as these provide redundancy for instrument failure and support detection of differing GWL behaviors.

4.4.2 Was rewetting a success?

Findings of this study suggest that rewetting drained wetlands has the potential to improve hydrological conditions. However, claiming that rewetting resulted in successful outcomes through significantly elevated and stabilized GWL, remains uncertain given the shortcomings of the study. Effectiveness was demonstrated to vary both within and across sites. This variability highlighted how local factors, related to hydrogeology, drainage impact, topography, and climatic context, likely influenced outcome, which may be delayed or spatially heterogenous. Thus, improved rewetting outcome begins with understanding the site-specific conditions. Should the Vålberga control site be rewetted in the future, the insights gained from this study are hoped to be helpful. Nonetheless, further consideration of intended goals with the intervention may be needed, as there are reasons to think that return to pristine state cannot be expected.

When planning rewetting efforts, it is important to be clear about intended goals. Specifically, there is a critical distinction between environmental restoration, rehabilitation, and mitigation, each reflecting different expectations for ecological recovery. Restoration refers to practices of renewing degraded, damaged, and destroyed ecosystems by active human action, aiming to return them to their historical natural state (Perrow & Davy 2002). However, given that wetlands are among the most degraded ecosystems globally, full restoration in this sense may not be achievable. Rehabilitation acknowledges this limitation and accepts that a complete return to the original state is unlikely. Instead, interventions seeks to improve ecological function, stabilize hydrology, and support the development of a self-sustaining ecosystem that reflects some characteristics of the historical landscape (Cooke 2005). In contrast, mitigation focuses primarily on reducing environmental harm, without necessarily aiming for ecological recovery to a pristine reference condition (Friends of EbA 2022).

In highly disturbed wetlands, with peat subsidence and altered hydrological properties (Holden et al. 2017), rewetting alone may not be sufficient to restore the ecosystem to its pristine state. There is a possibility that some drained wetlands have crossed hydrological thresholds, meaning that removing the source of disturbance and rely on natural succession to recover the ecosystem is unlikely to be effective (Liu et al. 2024). Instead, interventions may need to be viewed within a rehabilitation framework, which suggests that rewetting may improve hydrological conditions and initiate partial recovery, but it may not fully restore historical ecosystem functions.

Recognizing this distinction may not be a limitation of rewetting itself, but rather a reflection of the complex, sometimes irreversible changes that historical intensive drainage has imposed on these landscapes (Regan et al. 2019; Laudon et al. 2022). Emphasizing realistic goal-oriented interventions allows stakeholders to focus on achieving meaningful hydrological improvements. Only by assessing the progress toward these established goals can the success of rewetting outcomes truly be determined.

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Popular science summary

Governmental funding continues to be allocated toward wetland restoration projects to enhance water availability in the landscape and support climate change adaptation. Undrained wetlands play an important role in regulating water flow, storing water, and sustaining baseflow during dry periods. Although, there is limited scientific evaluation of restoration outcomes regarding groundwater, thus, rewetting effectiveness remains uncertain. This study investigated the groundwater level (GWL) responses following rewetting, aiming to provide scientific support for better-informed rewetting decisions.

The study compared GWL both before and after rewetting, then contrasted any changes in dynamics with a non-rewetted site to assess the impact. GWL data were collected from three historically drained wetlands in Östergötland County, southern Sweden: two rewetted sites (Örbacken and Kärnskogsmossen) and one control site (Vålberga) that was not rewetted. High-frequency GWL measurements were analyzed using statistical and comparative methods to determine whether rewetting led changes in groundwater dynamics. The analysis included quality control of GWL data, assessment of meteorological conditions, and index-based classification to evaluate the variability in groundwater level fluctuation patterns.

This study found that rewetting drained wetlands can raise GWL and make them less variable, which was consistent with my hypothesis, but the outcomes were dependent on site-specific characteristics. Kärnskogsmossen exhibited a change in groundwater dynamics following rewetting, that suggested improved hydrological functioning. However, Örbacken showed a more limited response where the behavior was not distinctly separable from those prior to rewetting. This emphasizes the need for careful planning and consideration of local factors related to topography and hydrogeological conditions in wetland restoration projects.

This study builds upon previous studies that have investigated the hydrological impacts of rewetting drained wetlands. While some studies have reported immediate increases in GWL and enhanced water storage capacity following rewetting, this study found that the effects can be more variable depending on local conditions. It aligns with the broader understanding that wetland restoration can be a complex process influenced by multiple factors, including peat structure, topography, adjacent mineral deposits, and regional climate. The thesis also acknowledges that rewetting can have some negative effects, such as increased concentrations of nutrients, dissolved organic carbon, and methane emissions.

Ultimately, knowledge generated from this research benefits a wide range of stakeholders. For instance, policymakers and governmental agencies are provided scientific evaluation of outcomes, while the research community gain from a growing body of knowledge on wetland hydrology and restoration effects.

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Appendix A

Historical land use during late 19th century

The historical land use and property map ©Lantmäteriet (2022) is slightly shifted, resulting in that delineation of nature reserves and location of interventions sites are not accurately aligned with the basemap.

Figure A.1. Historical map of Örbacken nature reserve during late 19th century, showing that it was managed through haymaking in the southwestern region while remaining part used as open grazing land. The water channel existed during that time.

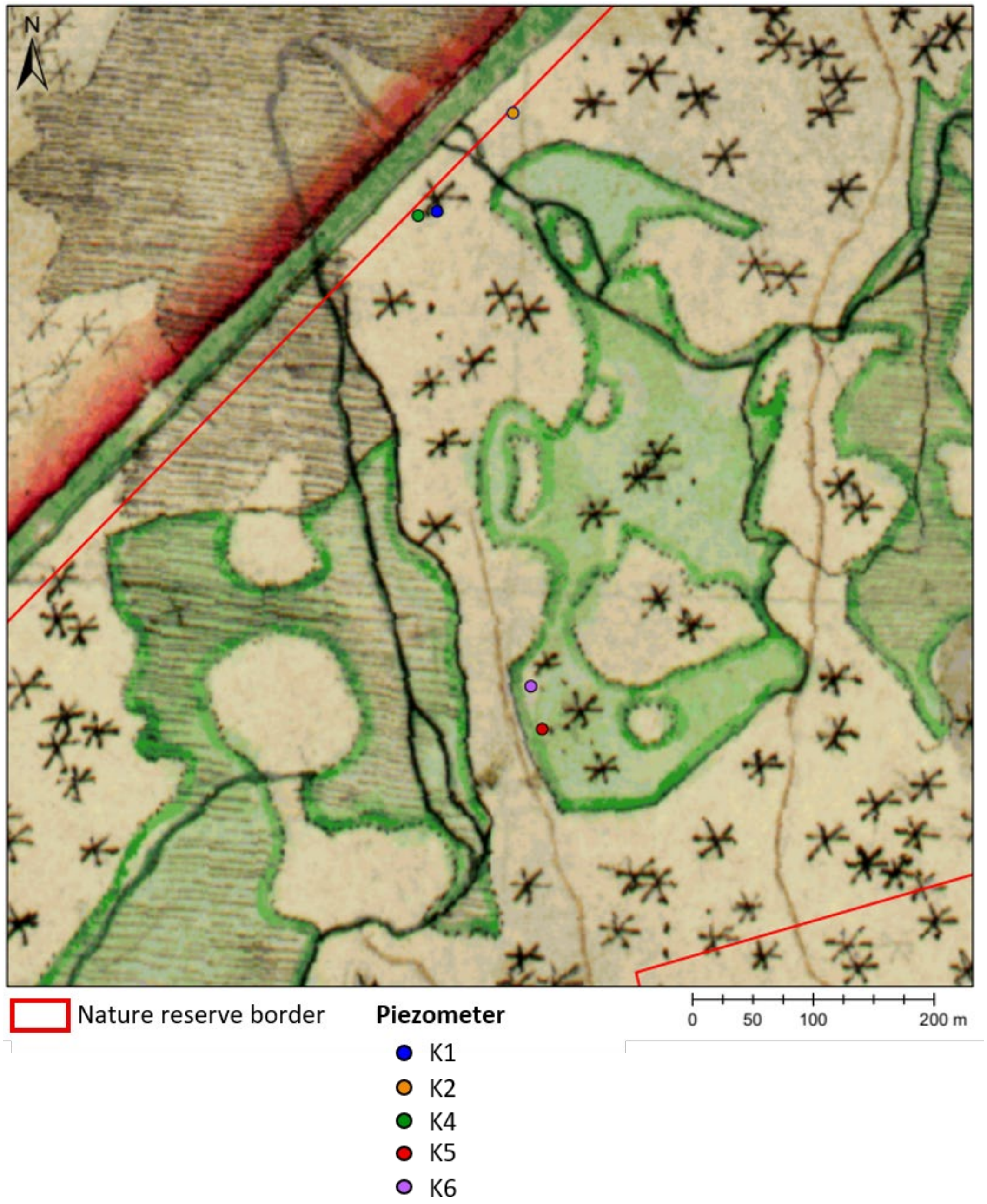

Figure A.2. Historical map of the study region in Kärnskogsmossen nature reserve during 19th century, showing that it was characterized by open mires in the northern half while remaining parts were maintained through traditional mire haymaking. The water channel had a northward flow direction during late 19th century, contrasting to the current direction crossing the intervention site.

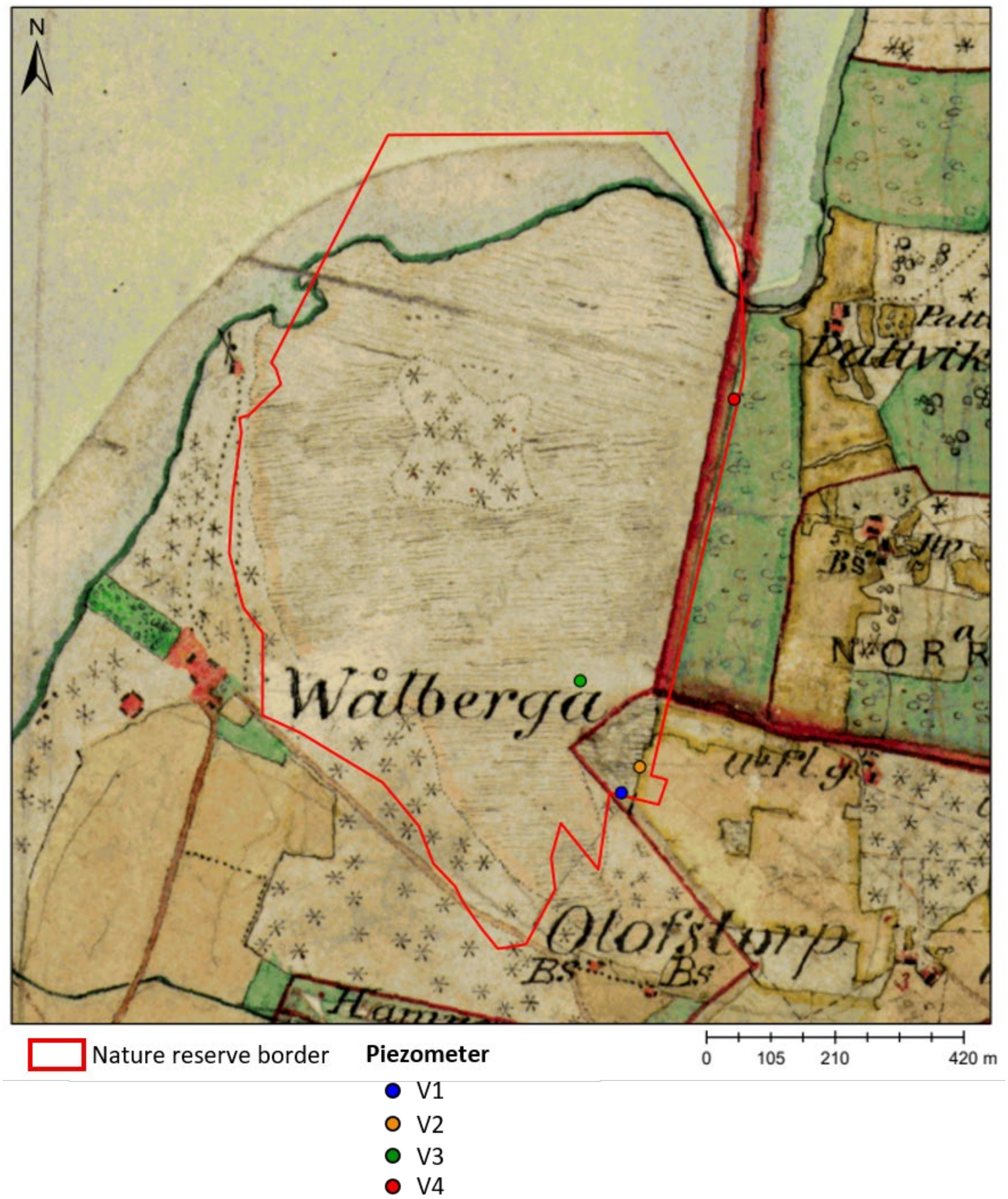

Figure A.3. Historical map of the Vålberga nature reserve, showing that the bog was much more open during late 19th century, except for a wooded islet in the center.

Appendix B

Details on piezometer setting

The environmental setting of the piezometers are shown for Örbacken (Figure A.4), Kärnskogsmossen (Figure A.5), and Vålberga (Figure A.6). Images of piezometers, sourced from the County Administrative Borad in Östergötland, are shown together with Orthophoto RGB 0.25 m 2006-2018 ©Lantmäteriet (2025)

Figure A.4. Environmental settings of piezometer Ö1, Ö2, and Ö3 in Örbacken.

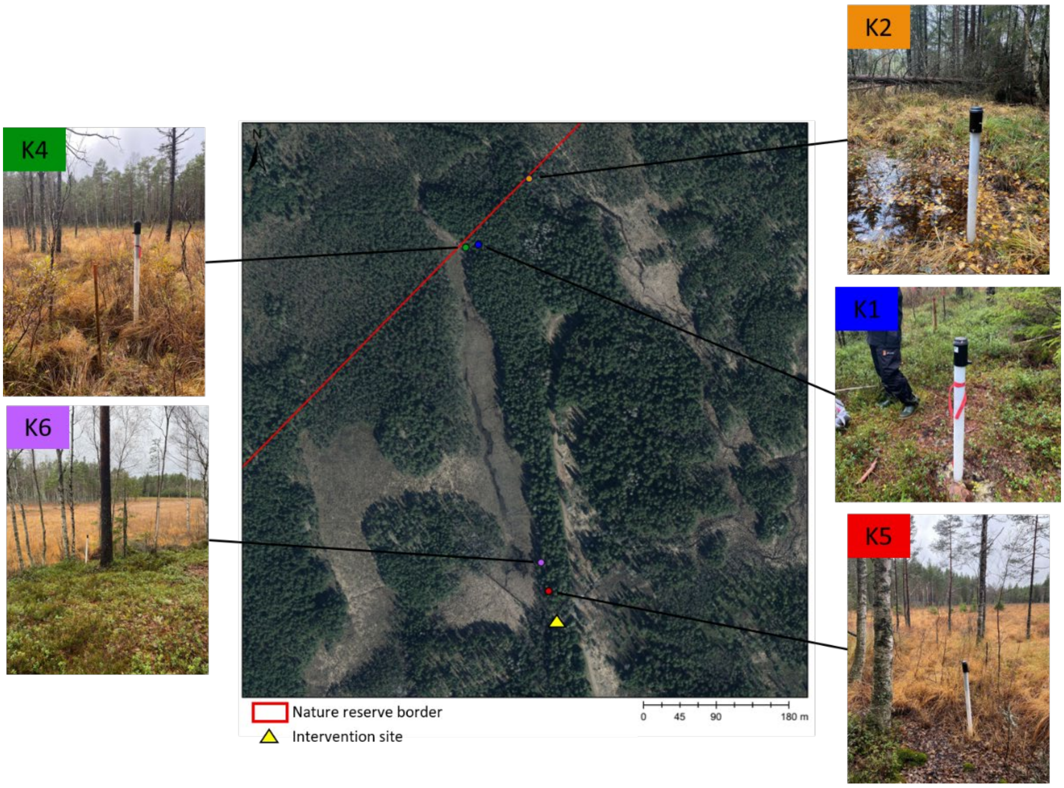

Figure A.5. Environmental settings of piezometer K1, K2, K4, K5, and K6 in Kärnskogsmossen.

Figure A.6. Environmental settings of piezometer V1, V2, V3, and V4 in Vålberga.

Appendix C

Workflow of using Grok

Grok, an artificial intelligence model by xAI, was used to assist with creating scripts. The workflow involved iterative prompting to refine coding for exploring, visualizing, and analyzing GWL data. The workflow involved four main steps:

1. An existing script or detailed description of desired functionality was provided to Grok.
2. Specific prompts were used to obtain targeted methods for data analysis. These related to context, goal, "dos", "don'ts", and instructions of how the output should be presented.
3. Grok's responses with modified code and explanations were tested with GWL data. Follow-up prompts with additional needs were provided to align with analysis method goals.
4. The outcome of the provided scripts were applied within the study. Grok's role was limited to coding support while analytical decisions were made by me.

This workflow enhanced productivity in developing scripts in Python and contributed toward detailed analysis of GWL data.

Access to scripts

GitHub link: https://github.com/johannaringstam/thesis-project-scripts.git

Appendix D

Summary statistics of groundwater levels

Titles before and after in table A.1 refer to the defined pre- and post-rewetting periods. For Örbacken and Vålberga, these intervals ranged from November 1 to July 7 (2022-2023 and 2023-2024). For Kärnskogsmossen, which was rewetted earlier in the year, the intervals ranged from November 1 to May 24 (2022-2023 and 2023-2024).

Table A.1. Summary statistics of GWL at each piezometer during the pre- and post-rewetting periods. P-values were computed from the non-parametric paired Wilcoxon signed-rank test.

Site	Piezometer	Grounwater level [cm]								p-value
		Min		Max		Mean		Median		
		Before	After	Before	After	Before	After	Before	After	
Örbacken	Ö1	-12.3	16.0	46.6	59.0	31.2	42.7	37.4	42.3	<0.001
	Ö2	-127.7	-98.4	-0.2	0.6	-24.2	-20.3	-6.3	-6.5	0.0014
	Ö3	-68.1	-42.5	-10.4	-4.4	-20.8	-13.9	-15.1	-11.0	<0.001
Kärnskogsmossen	K1	-137.1	-118.3	-79.4	-76.8	-111.3	-98.7	-111.6	-100.4	<0.001
	K2	-7.3	-4.8	28.2	42.0	1.7	11.4	-0.6	6.8	<0.001
	K4	-4.5	11.3	43.7	50.0	11.8	28.9	9.0	26.0	<0.001
	K5	-5.5	28.7	55.6	67.9	16.1	45.7	11.7	42.6	<0.001
	K6	-1.5	25.5	52.4	65.5	17.1	44.2	14.7	41.0	<0.001
Vålberga	V1	-171.0	108.1	0.2	13.5	-37.7	15.0	-22.5	-9.2	<0.001
	V2	-72.9	-47.7	40.6	43.0	0.2	13.8	5.8	14.7	<0.001
	V3	-42.7	-75.9	2.0	-0.8	-8.9	-26.4	-14.1	-6.1	<0.001