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How controlled drainage and peat subsidence affect the hydrology of cultivated peatlands under changing climatic conditions

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ABSTRACT

Sustainable cultivation of peatlands is challenged by drainage induced acceleration of peat decomposition, which leads to substance fluxes and peat subsidence. Controlled drainage (CD) is designed to allow sufficient drainage for cultivation practices while excessive drainage can be avoided during other times. There is a remaining research gap in the potential of CD to affect field hydrology under changing climate. In this study, the functioning of CD in a peat covered field was simulated using a hydrological model driven by climate scenarios (RCP8.5 and RCP4.5) for two locations in Finland, southern Salo and northern Ruukki. Simulation of peat subsidence was included for the near future period of 2041–2060. Different climate scenarios resulted in varying hydrological impacts, especially during winter. During the historical period, CD decreased average groundwater table (GWT) depths by 0.10–0.13 m, the impact being similar in both locations. Average summer GWT depths were decreased by 0.06–0.09 m. CD reduced average drain discharge by 32–37 mm/a in Salo and by 14–19 mm/a in Ruukki. The performance of CD remained stable in the future climate scenarios. The simulated peat subsidence rates were 0.9–1.4 cm/a without CD, and CD reduced subsidence by 14–22 %. Subsidence decreased average GWT depths, CD effect on GWT depths, and drain discharge, but increased the CD effect on drain discharge. CD has relevance in reducing peat decomposition in Nordic peatland fields under current and future climate, but more effective reduction likely requires irrigation during growing season.

1. Introduction

While covering only 3 % of global land area, peatlands store approximately 30 % of terrestrial carbon (Ciais et al., 2013; Melton et al., 2022; Page et al., 2011). The peatland areas play an important role in carbon sequestration, but land-use involving drainage compromises this potential (Nijman et al., 2024). Globally, approximately 25 million ha of peatlands have been estimated to be under agricultural use (FAO, 2020).

When peatland is drained, the amount of oxygen available for microbiological processes increases, which accelerates the decomposition of organic matter, leading to emissions of carbon dioxide (CO_2) (Brouns et al., 2014; Hooijer et al., 2012; Husen et al., 2014). Drainage has also been found to increase emissions of nitrous oxide (N_2O) and decrease emissions of methane (CH_4) (Evans et al., 2021; Maljanen et al., 2010). In boreal areas, drained agricultural peatlands have been estimated to emit 24–35 t ha^{-1} a^{-1} CO_2 equivalent of greenhouse gases (IPCC et al.,2014). The emissions show large variability depending on the site characteristics, variability in weather conditions, and field management (Gerin et al., 2023). In terms of greenhouse gas emissions from microbiological processes in soil, agriculture has been described as the most unfavorable land-use option for peatlands (Maljanen et al., 2010). Sustainable use of cultivated peatlands has been listed as one of the main land use policies to mitigate climate change (Ministry of Environment Finland, 2024). Decomposition of organic matter is linked to nitrogen mineralization, and high nitrogen loads have been reported in cultivated peatlands (Kløve et al., 2010; Lemola et al., 2000; Pham et al., 2023; Yli-Halla et al., 2022), which is a threat to aquatic ecosystems.

The main controlling factors of peat decomposition rate are soil moisture and temperature (Bader et al., 2018; Kechavarzi et al., 2007; Mäkiranta et al., 2009; Moyano et al., 2013). Several studies suggest that groundwater table (GWT) depth is a viable proxy for this rate at an annual level (Evans et al., 2021; Heikkinen et al., 2024; Huang et al., 2021; Tiemeyer et al., 2020). Evans et al. (2021) and Heikkinen et al. (2024) found a nearly linear relationship between CO_2 emissions and

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GWT depth at an annual level, higher emissions taking place with deeper GWTs. Aben et al. (2024) also found a linear relationship, with slightly better fit using mean summer GWT depths than annual mean GWT depths (r^2=0.19 and r^2=0.15, respectively). They noted that there is considerable variation within literature considering the connection between GWT depth and CO_2 emissions. Deviating from linear models, Tiemeyer et al. (2020) reported a non-linear relationship, where changes in GWT in depths larger than 30 cm hardly had an effect on CO_2 emissions. van der Poel et al.,(2025)) reported linearly increasing emissions with GWT depth until the depth of 80 cm, after which the emissions started to decrease. Overall, the literature indicates that lowered GWTs are strongly linked to increased peat decomposition.

Alongside with physical processes of consolidation and compaction, peat decomposition is linked to peat subsidence (Hooijer et al., 2012). In addition to reducing peat cover thickness, the subsidence changes the drainage depth, and consequently affects the functioning of the water management system. It increases the risk of water logging in low-lying lands (Hanson et al., 2011) and eventually requires renovation of the drainage system to maintain desired drainage depth (Kløve et al., 2017). Evans et al. (2019) reported a linear relationship between observed GWT depths and peat subsidence rates, the response being steeper in warmer climates.

In addition to the challenges related to peat decomposition and subsidence, artificially lowering GWTs increase drainage water discharge and load of solutes and fine-grained solids to surface waters (Christianson and Harmel, 2015; Kyllmar et al., 2023). Consequently, to reduce the environmental impacts (such as global warming and eutrophication) and subsidence of drained agriculturals peatlands, excessive drainage should be avoided while allowing suitable conditions for cultivation practices. This calls for flexible water management methods that can be adjusted as needed over the cropping cycle.

Controlled drainage (CD) is a subsurface drainage method in which the outlet elevation can be temporarily increased to effectively decrease the drainage depth, which can result in higher GWTs and reduced drain discharge in comparison to conventional subsurface drainage (ND). The effects of CD on field hydrology depends on the field and drainage system properties and meteorological conditions (Joel et al., 2009; Salo et al., 2021). The effects of CD have been studied on mineral soils (Salla et al., 2022; Salo et al., 2021; Wesström and Messing, 2007), but water level control studies on peatlands have often focused on methods which rely on irrigation (Boonman et al., 2022; Kechavarzi et al., 2007; Querner et al., 2012). Some positive results have been reported related to the use of CD to mitigate peat decomposition (Heikkinen et al., 2024). However, the difficulty of maintaining sufficiently high GWTs has been noted by Heikkinen et al. (2024) and Kløve et al. (2017). There is a research gap regarding the potential of CD to control GWTs and drain discharge on peatlands under different meteorological conditions, which forms a basis for guidelines for sustainable water management.

Simulation models have become widely applied tools to study hydrological impacts of hypothetical scenarios such as different water management methods and climate conditions. Spatially distributed models can be divided into one-dimensional models lacking lateral processes (Hintikka et al., 2008; Larsson et al., 2007), two-dimensional models including lateral processes in one dimension (Gärdenäs et al., 2006; Salo et al., 2021), and fully three-dimensional models including lateral processes in two dimensions (Boico et al., 2023; Warsta et al., 2013). In comparison to 3D models, 2D models can be considerably lighter computationally while still sufficient in capturing the relevant field hydrologic processes. Thus, they can be better suited for high volume simulations.

Climate model outputs are customarily used as input to hydrological models for assessments of changes in future hydrology. Air temperature and precipitation in Finland are projected to increase in the future decades, both changes being likely stronger during winters (Ruosteenoja et al., 2024). There are substantial differences between climate models, and especially future precipitation includes large uncertainties (Ruosteenoja et al., 2024). It is also uncertain how global greenhouse gas emissions will develop in the future. To deal with these uncertainties in climate impact simulations, it is recommended to use ensembles of several models and emission scenarios (Benestad et al., 2017). Huang et al. (2021) used a global dataset of peatland studies and projected greenhouse gas emissions from managed peatlands to increase in future climate. Hellmann and Vermaat (2012) reported increases in greenhouse gas emissions, peat subsidence, and nitrogen loads from cultivated peatlands in Netherlands due to lowered summer groundwater levels in a severe climate change scenario. Salimi et al. (2021) concluded water level management to be necessary to reduce CO_2 emissions under moderate and severe climate change scenarios in Sweden. These results highlight the need to study the performance of CD to manage hydrology in future climate.

The geographical focus of this study is Finland, where cultivated peatlands constitute 270 000 ha, or 11 %, of the total cultivated area in the country (Statistics Finland, 2023). These fields are estimated to be responsible for 13 % of the total agricultural greenhouse gas emissions (Statistics Finland, 2023). Typical features of agricultural hydrology in Finland are short growing season with evapotranspiration surplus, wet autumn, cold and snow-covered periods during winter, and rapid snowmelt events and low precipitation in spring. Much of the agricultural production in Finland is concentrated on the coastal area between latitudes 60 and 65, where both current meteorological conditions and future climate projections show variation (Ruosteenoja et al., 2024). Especially future changes in snow dynamics can diverge in the southern and northern hydrology. Thus, regional differences are expected to appear in future changes of field scale hydrology and CD effects.

The study had two main objectives: 1) to simulate the impacts of climate change on GWT depths, drain discharge, and the potential of CD to regulate hydrology in a cultivated peatland field during the 21st century, and 2) to simulate peat subsidence and study the hydrological implications of subsidence and the potential of CD to reduce it during 2041–2060. Climate projections with high temporal resolution (1–3 h) for two locations representing south and north of the agriculturally productive coastal area of Finland were used with RCP 8.5 and RCP 4.5 emission scenarios.

2. Material and methods

2.1. *Climate scenarios*

The climate change impact simulations were based on climate model outputs for two locations in Finland (Fig. 1), Salo and Ruukki, representing south and north of the agriculturally productive coastal area, respectively. The climate model ensemble includes two GCMs: EC-EARTH (ECE) and Geophysical Fluid Dynamics Laboratory Climate Model version 3 (GFDL). ECE is a GCM developed by a European consortium of national meteorological services and research institutes, and this study used the ECE simulations by the Irish Centre for High-end Computing (ICHEC). GFDL has been developed by the U.S. National Oceanic and Atmospheric Administration (NOAA). These two GCMs have been downscaled by two different setups of the RCM HARMONIE-Climate (HCLIM) (Lind et al., 2020; Médus et al., 2022): a ~12 km resolution HCLIM12-ALADIN (AL) and a ~3 km resolution HCLIM3-AROME (AR). The former applies a parameterized convection while the latter resolves deep convection explicitly. The climate projections described three 20-year periods: a historical reference period (1986–2005), a near future period (2041–2060), and a far future period (2081–2100). Two different emission scenarios were used as radiative forcing: the worst-case scenario RCP8.5, where greenhouse gas emissions keep increasing throughout the 21st century, and an intermediate scenario RCP4.5, where greenhouse gas emissions peak around 2040 and then decline. The model and RCP combinations, resulting in six different climate scenarios for both locations, are listed in Table 1. A key motivation to adopt these climate models in the simulations was their

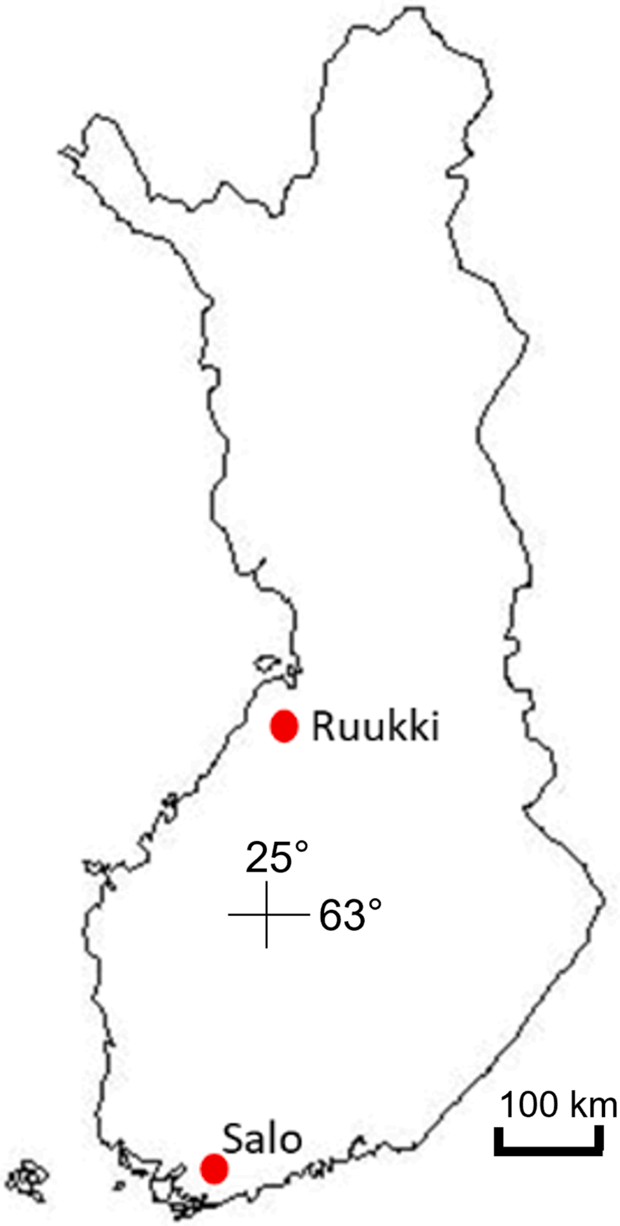

Fig. 1. Locations of Salo and Ruukki in Finland.

Table 1
GCMs, RCMs and emission scenarios used in this study.

GCM	RCM	Emission scenario
GFDL	HCLIM12-ALADIN, HCLIM3-AROME	RCP8.5
EC-EARTH	HCLIM12-ALADIN, HCLIM3-AROME	RCP8.5, RCP4.5

high temporal resolution, and for AROME, its convection-permitting feature.

The variables extracted from the climate models included air temperature, precipitation, relative humidity, wind speed and shortwave radiation with temporal resolution of 1–3 h. Average values were taken from nine (3 ×3) cells around the target locations to smooth out excessive and possibly unrealistic variability at a single cell-level (Huebener et al., 2022). Potential evapotranspiration (PET) and long-wave radiation were computed with the Penman-Monteith equation and Stefan-Boltzmann law, respectively, according to FAO recommendations (Allen et al., 1998). Air temperature and precipitation produced by the climate models for the historical period before bias correction are compared to observations in Fig. 2.

The empirical quantile mapping method (Enayati et al., 2021) with 1000 evenly spaced quantiles was used to correct temperature and precipitation biases in the climate model outputs. Due to lacking hourly observations, hourly climate model data was first aggregated to daily data using precipitation sums and average temperature, and these were compared to daily observations. The resulted daily correction factors were applied for the hourly climate model data, using the same factor for each day (Tamm et al., 2023).

2.2. FLUSH description

FLUSH is a process based hydrological model initially developed for drained agricultural lands (Warsta et al., 2013). It includes a two-dimensional (2D) overland flow domain and a three-dimensional (3D) subsurface flow domain. In the overland flow domain, precipitation is stored into soil surface depressions, from where it can infiltrate into the subsurface domain. Exceeding the depression storage capacity and the infiltration capacity generates overland flow, which is described with the diffuse wave approximation of the Saint Venant equations. In the subsurface domain, water flow is based on a dual-permeability approach including soil matrix and macropores where water flow is described with the Richards equation. Water can be exchanged between soil matrix and macropores based on pressure difference (Gerke and van Genuchten, 1993). Water retention characteristics and unsaturated hydraulic conductivities are described with the van Genuchten (1980) model. An energy-based snowpack model (Koivusalo et al., 2001) has been integrated into the FLUSH model to enable simulation of Nordic snow-affected conditions.

Water can exit the model via the drainage system, as lateral groundwater flow through the model boundaries, and as evapotranspiration. Subsurface drainpipes and open ditches function as local sinks with the following function:

$$q = AK_s \frac{H_c - (H_s + H_{control})}{\Omega} \tag{1}$$

where q [L^3T^{-1}] is the volumetric flux, A [L^2] is the area of the sink in the cell, K_s [LT^{-1}] is the saturated hydraulic conductivity of the soil, H_c [L] is the hydraulic head in the soil, H_s [L] is the hydraulic head in the drainpipe/ditch, $H_{control}$ [L] is the control effect in controlled subsurface drainage (i.e., the elevation difference between the drain outlet and drainpipe in the cell when the outlet elevation is higher than the drainpipe elevation and 0 m otherwise), and Ω [L] is the entrance resistance factor. Water can end up in the open ditches also as overland flow. Lateral groundwater outflow through the model boundaries is either determined by the soil surface gradient at the boundary or is prevented (impermeable boundary). The model does not support groundwater inflow to the model. Water is removed as evapotranspiration from the root layer based on rooting depth, potential evapotranspiration, and simulated soil moisture. The root mass distribution is calculated as a linearly decreasing function of depth from the soil surface to the rooting depth. PET demand is distributed to the soil according to the root mass distribution. Evapotranspiration is restricted by low soils moisture, following the approach by Feddes et al. (1978). The restriction increases linearly from the pressure head of −5 m to the wilting point defined as the pressure head of −150 m.

2.3. Model application and analysis of results

A single 2D FLUSH model parameterization was used to simulate the hydrology of a cultivated peatland field with both Salo and Ruukki climate scenarios. The schematization of the model setup is shown in Fig. 3. The soil and drainage parameters were based on Salla et al.

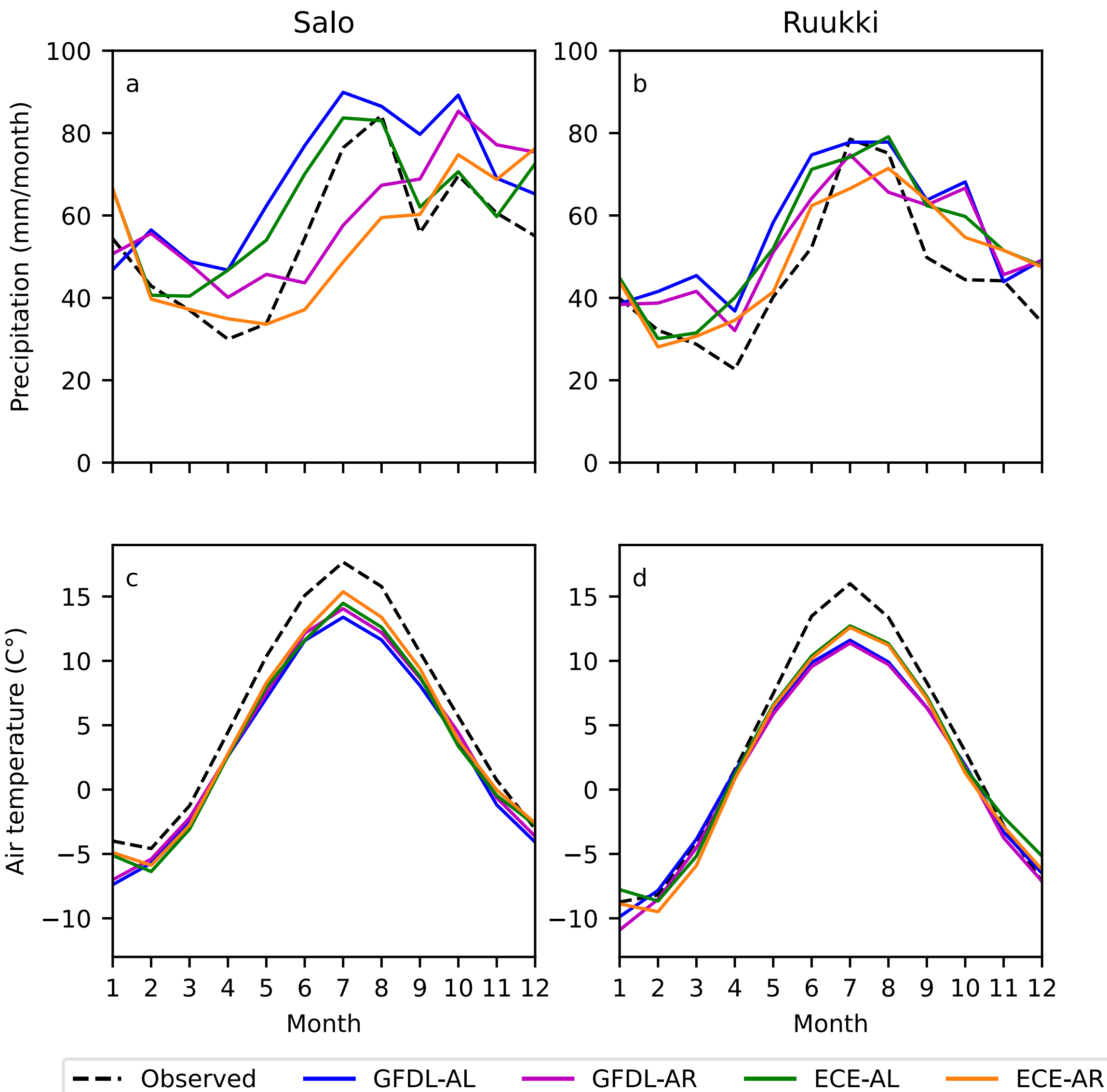

Fig. 2. Average precipitation and air temperature according to the climate models before bias correction and observations during the historical period 1986–2005.

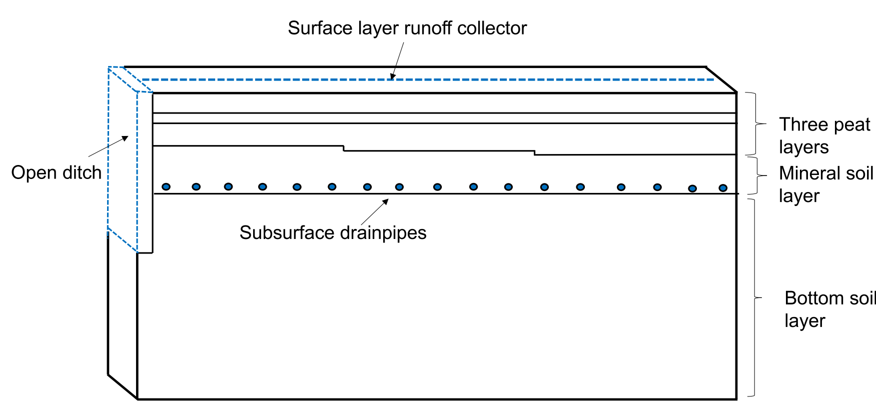

Fig. 3. Schematization of the 2D model setup. Starting from the soil surface, the thicknesses of the three peat layers were 0.25 m, 0.10 m, and 0.25–0.35 m (varied spatially). The thickness of the mineral soil was 0.40–0.50 m, and the bottom soil was 2.3 m thick.

(2024), where a 3D FLUSH setup was calibrated to describe the hydrology of an experimental peatland field block under controlled drainage in Ruukki. The field block has a cover of sedge peat mixed with coarse silt, the average thickness of the peat cover being 0.65 m. Below the peat cover, there is an acid sulphate mineral soil consisting of silty soil on top and clayey soil at the bottom. The block is drained with controlled subsurface drainage and open ditches. The 3D model setup of Salla et al. (2024) included the field block and a part of an adjacent forest area to include the hydrological connections between the field block and the forest into the simulations.

The model application used in this study described a 224 m long 2D profile (one horizontal and one vertical dimension) of the Ruukki field block which cuts across the subsurface drainpipes and the main open ditch. The areas around the block, such as a forest area toward the north (see Salla et al., 2024), were not included in the model. As a result, the block was detached from the topographical features and hydrological connections of the surrounding area at the Ruukki site, as its aim was to function as a generic description of a hypothetical peatland field instead of the particular site. Our model can be interpreted to describe a situation where groundwater levels are managed in the same way in the surrounding areas. The computational grid consisted of 112 vertical columns, each 2 m wide and 3.4 m deep. The columns consisted of 32 cells with thickness ranging from 0.02 m at the top and 0.5 m at the bottom. The grid included 17 subsurface drainpipes with 1.1 m depth and 12 m spacing. The 1.5 m deep open ditch was placed at one end of the grid, approximately 12 m from the closest drainpipe. To include surface layer runoff, a 0.1 m deep open ditch was set to cover the whole length of the grid similar to Salo et al. (2021) and Salla et al. (2022). The average slope was 0.1 % towards the main open ditch. The boundaries at the bottom and at the sides were impermeable. In the model, the subsurface drainage was controlled with the scheme in Fig. 4. The main soil parameters and model performance metrics against water table observations in Ruukki are listed in Appendix A.

The effects of climate change and controlled drainage on the field hydrology were analyzed by averaging GWT depths for each calendar month and drain discharge for each of the four seasons. The terms average GWT depth and average drain discharge refer to averages taken over a whole 20-year period (including all seasons) unless specified otherwise. The statistical significance of changes in the efficacy of controlled drainage between the time periods was assessed with the non-parametric Mann-Whitney *U* test with populations consisting of monthly means. To determine the significance, a p-value of 0.05 was used as the threshold.

2.4. Peat subsidence

Peat subsidence under CD and ND during the near future period was simulated using Eq. 2 (Evans et al., 2019), which links mean GWT depth to peat subsidence in non-tropical areas based on observed datasets:

$$S = -0.0212 d_{GWT} + 0.43 \# \tag{2}$$

where S is the peat subsidence rate (cm/a), and d_{GWT} is the mean groundwater table depth (cm). The equation was assumed to be applicable also when GWTs were below the peat cover. From the climate model ensemble, GFDL-AR RCP8.5 and ECE-AL RCP4.5 were selected to represent two extreme scenarios in terms of changes in GWT depth in the near future period. To compute the total amount of peat subsidence during the 20-year near future period, the period was simulated in four separate parts, each lasting for five years. After each 5-year simulation, the accumulated subsidence was calculated with Eq. 2, which was then applied to the peat cover by reducing the thickness of each peat layer equally, and the next simulation was conducted with the new peat cover thickness. The subsurface drain and open ditch depths were reduced accordingly. The control effect (Eq. 1) remained constant. Finally, to see how the reduced peat cover thickness affects the field hydrology, the whole near future period was simulated with the final peat cover thickness. The approach was considered reasonable as, according to our simulations tests, dividing the 20-year period to shorter intervals (instead of the 5-year intervals) would not have a marked impact on the simulations results.

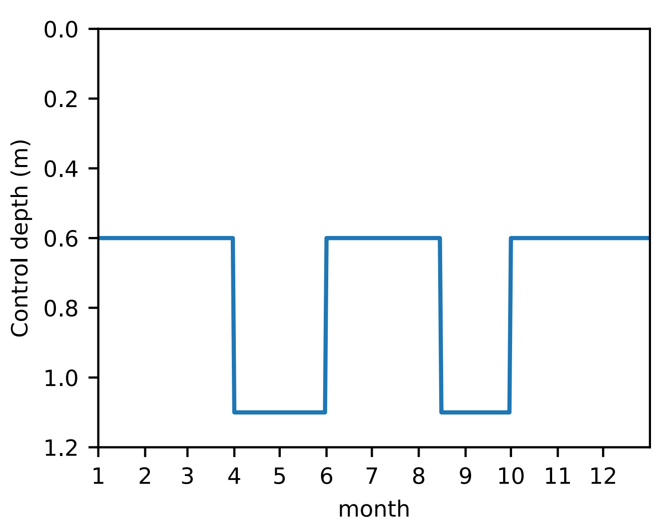

Fig. 4. The controlled drainage scheme over a calendar year.

3. Results

3.1. Climate change

The average air temperatures in the historical period in Fig. 5a-b were 5.6 °C in Salo and 2.7 °C in Ruukki. In the near future (Fig. 5c-d), the temperatures were projected to increase by 1.8–4.0 °C and 2.0–4.0 °C, and in the far future (Fig. 5e-f) by 2.5–6.8 °C and 2.8–7.1 °C in Salo and Ruukki, respectively. The highest temperature increases were seen during winter months, and the winter warming was stronger in the northern site of Ruukki. The differences between the climate models (GCM+RCM) were mainly determined by the GCMs (higher increase in GFDL than in ECE), while the differences between RCMs (AR and AL) remained low.

Precipitation was projected to increase in almost all scenarios (Fig. 6), but the changes were less consistent than in air temperature. Only ECE-AL/AR RCP4.5 projected small decreases in average annual precipitation in near future Ruukki. Average annual precipitation (652 mm in Salo, 539 mm in Ruukki, Fig. 6a-b) increased more in Salo (14–167 mm and 52–265 mm in the near and far future, respectively) than in Ruukki (from 20 mm decrease to 123 mm increase and 32–226 mm increase in the near and far future, respectively) in all projections. In both locations, the highest increase in precipitation was again produced by the GFDL-AL/AR RCP8.5 scenarios, predominantly during autumns and winters. The changes in precipitation were reflected in the changes in discharge potential (Fig. 7), and the GFDL-AL/AR RCP 8.5 scenarios were the only ones where the average annual discharge potential was projected to increase in both future periods, predominantly in autumns and winters. The future changes in discharge potential varied among the other scenarios, but generally the discharge potential was lower in the far future in comparison to the historical period.

3.2. Hydrology

The differences in historical GWTs between the two locations were characterized by higher winter GWTs in Salo and a more distinguished rise in spring GWTs caused by snowmelt in Ruukki (Fig. 8a-b). The higher winter GWTs in Salo were coupled with high winter drain discharges, whereas the drain discharges in Ruukki were seasonally more stable (Fig. 9a-b). The historical long-term average GWT depths with different climate models varied between 0.75 m and 0.77 m in Salo, and between 0.80 m and 0.85 in Ruukki. Average drain discharges varied between 271 mm/a and 283 mm/a in Salo, and between 193 mm/a and 211 mm/a in Ruukki.

The future changes in hydrology varied between different climate models and RCPs (Figs. 8–9). Generally, the GFDL-AL/AR models with

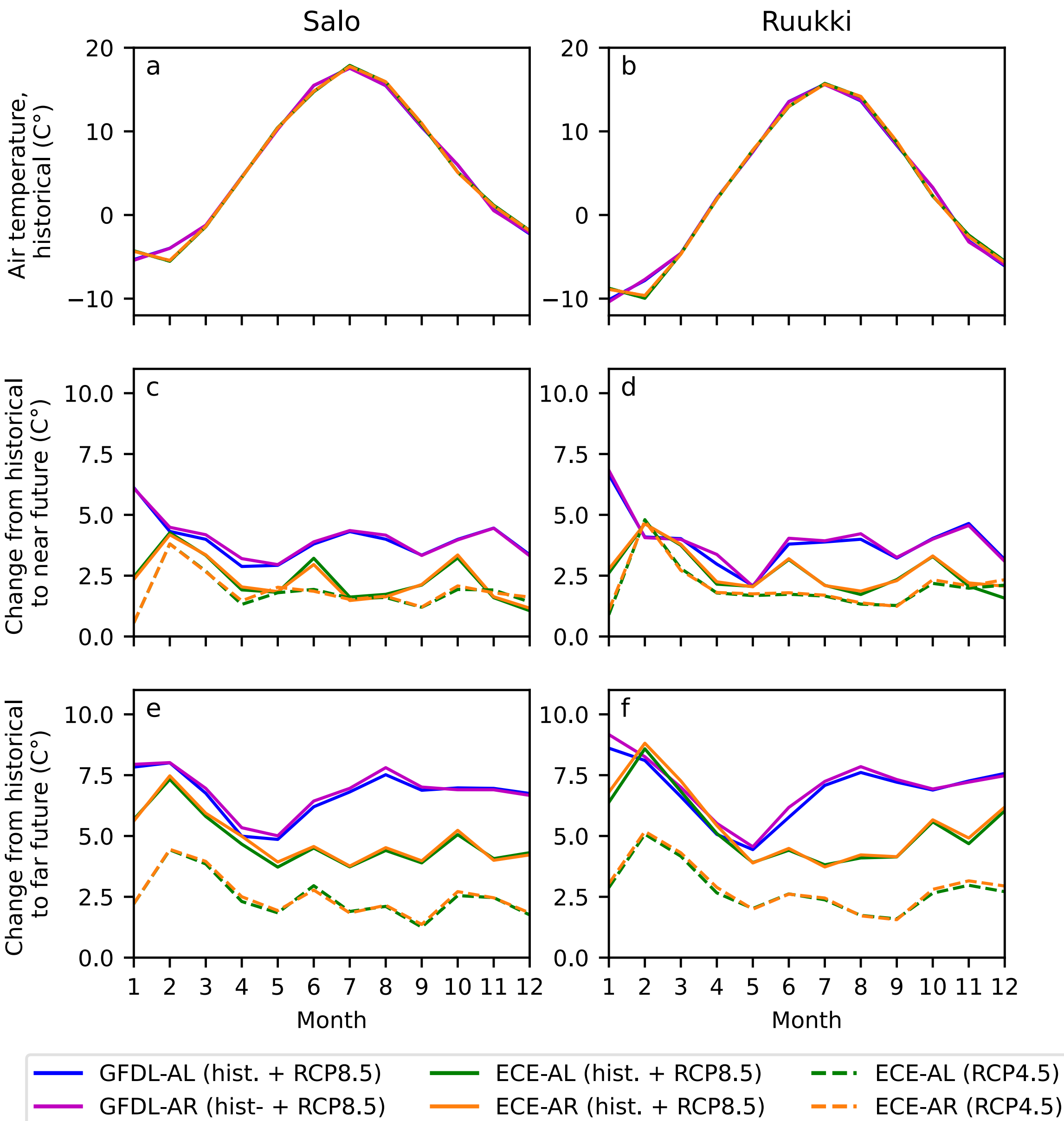

Fig. 5. Average monthly air temperature in Salo (a) and Ruukki (b) during the historical period and its changes in the future periods: near future in Salo (c) and Ruukki (d); far future in Salo (e) and Ruukki (f).

RCP8.5 produced the most extreme changes, predominantly during autumn and winter. In the near future (Fig. 8c-d, Table 2), most of the RCP8.5 scenarios projected decreased average GWT depths (i.e., average GWTs closer to the soil surface) in comparison to the historical period, and the decreases tended to be slightly larger in Salo. The RCP4.5 scenarios projected increased average GWT depths, and the changes were larger in Ruukki. The largest changes in average summer GWT depths were projected by ECE-AR RCP8.5 in Salo (0.07 m decrease) and ECE-AR RCP4.5 in Ruukki (0.07 m increase).

In the far future (Fig. 8e-f, Table 2), the GFDL-AL/AR models with RCP8.5 resulted in further decrease in the average GWT depths, while the changes in ECE-AL/AR RCP8.5 remained small. Unlike in the near future, the ECE-AL/AR models with RCP4.5 projected small decreases in the far future average GWT depths in comparison to the historical period (<0.05 m). Notable changes in the average summer GWT depths were projected by ECE-AR RCP8.5 in Ruukki (0.10 m increase) and ECE-AR RCP4.5 in Salo (0.09 m decrease).

The future changes in the fractions of deep GWTs (deeper than the drainage depth of 1.1 m) in comparison to the historical period are illustrated in Table 2 (see also Fig. 14 in Section 3.4). The deep GWT depths took place mainly during summer and autumn. In Ruukki, the fractions increased in most of the climate scenarios in both future periods, regardless of the changes in average GWT depths, and the largest increases were projected in the near future by ECE-AL/AR RCP4.5. In Salo, the magnitudes of the changes were comparable to those in Ruukki, but the directions (increase or decrease) exhibited more variation.

Average annual drain discharges were projected to increase in most scenarios, the magnitudes being similar between Salo and Ruukki (Fig. 9, Table 2). Only the ECE-AL/AR RCP4.5 scenarios in the near future showed decreases, particularly in Ruukki. Still, these scenarios projected increased winter drain discharges. By far, the greatest increases in drain discharge were projected by the GFDL-AL/AR RCP8.5 scenarios in both future periods, predominantly in autumn and winter. In Ruukki, also ECE-AL/AR models showed large increases in winter drain discharges, especially with RCP8.5.

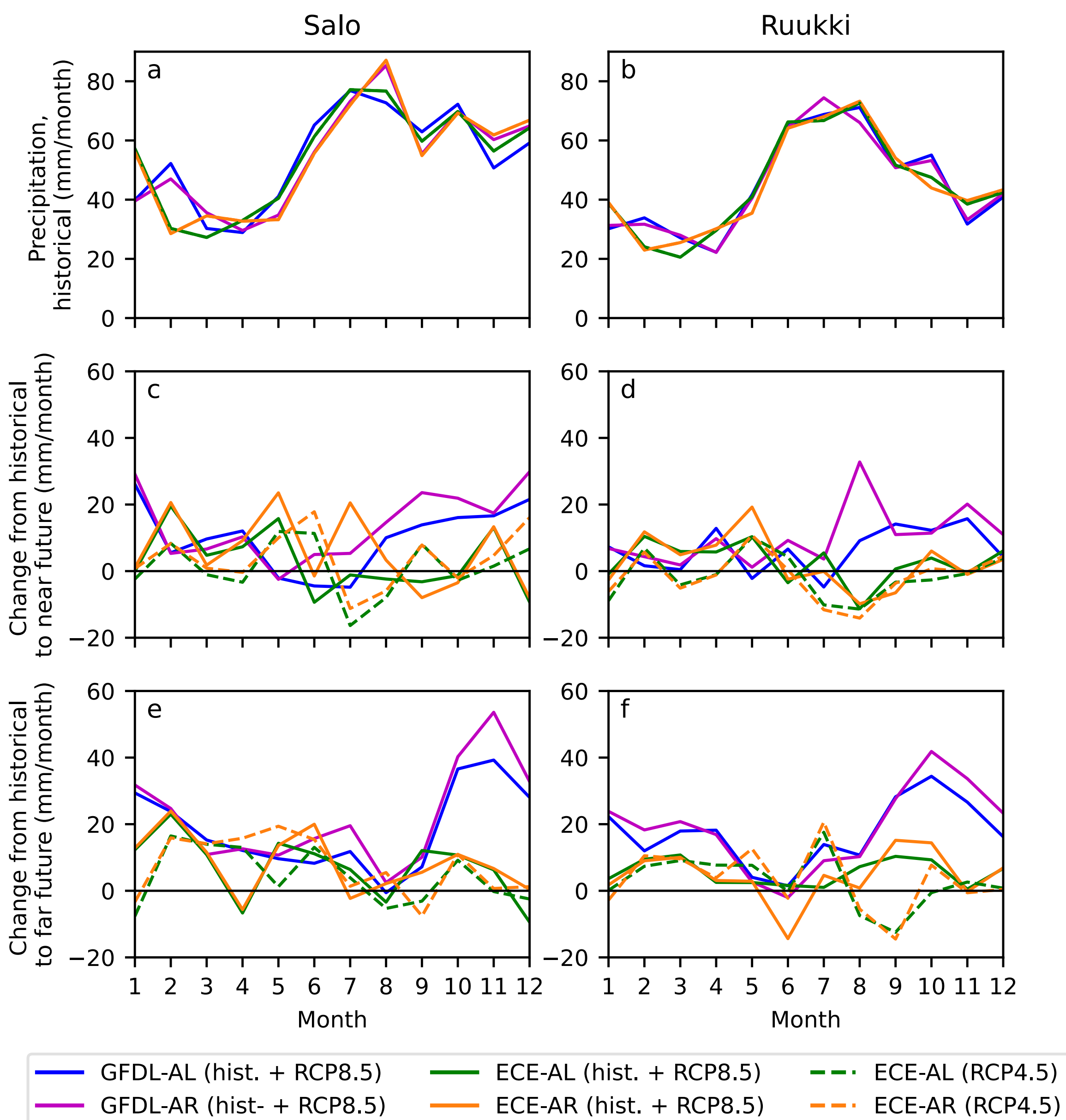

Fig. 6. Average monthly precipitation in Salo (a) and Ruukki (b) during the historical period and its changes in the future periods: near future in Salo (c) and Ruukki (d); far future in Salo (e) and Ruukki (f).

3.3. *Control effects*

Controlled drainage (CD) raised average GWTs during the historical period by 0.10–0.11 m in Salo and by 0.12–0.13 m in Ruukki, depending on the climate model (Fig. 10a-b). Summer average GWTs were raised by 0.06–0.07 m and 0.07–0.09 m, respectively. CD prevented 19–23 % of the deep (>1.1 m) GWTs in Salo, and 17–50 % in Ruukki (see Fig. 14 in Section 3.4). Drain discharge was reduced by 32–37 mm/a (11–14 % reduction) and 14–19 mm/a (7–9 % reduction), respectively (Fig. 11a-b). In Salo, the reductions in drain discharge were larger during autumn and winter than during summer, while in Ruukki it was the opposite. The CD scheme resulted in drain discharge higher than with conventional drainage (ND) when the control was turned off in the end of March and in the middle of August (see Fig. 4). This is why spring drain discharge was higher with CD in comparison to ND. Reducing drain discharge increased evapotranspiration, discharge into the open ditch, and surface layer runoff (Fig. 12a–b). Particularly in Salo, the increase in surface layer runoff was large in comparison to the increases in evapotranspiration and ditch discharge. The responses of these other components to CD (relative to reduced drain discharge) remained similar in the future periods (Fig. 12c–f).

In the near future (Fig. 10c-d), the CD effects on long-term average GWTs experienced a statistically significant change in comparison to the historical period only in GFDL-AL and GFDL-AR (RCP8.5) in Salo, where the average effect decreased by 0.02 m and 0.01 m, respectively, the decrease taking place mainly during winter (Fig. 10c). The changes during summer were small in every climate change scenario in both locations, and the only one considered as statistically significant was an increase of 0.01 m projected by ECE-AR RCP8.5 in Salo. During winter, the CD effects in Salo were projected to decrease by the GFDL-AL/AR RCP8.5 scenarios (0.04 m) and ECE-AR RCP4.5 (0.02 m), and in Ruukki, decreases of 0.02–0.03 m were projected by the ECE-AL/AR RCP4.5 scenarios. In Salo, there was some variability within models in the ability of CD to prevent deep GWTs, but the range of reductions between models (15–24 % less deep GWTs) was similar to the historical period (see Fig. 14. in Section 3.4). In Ruukki, the range was 14–34 %,

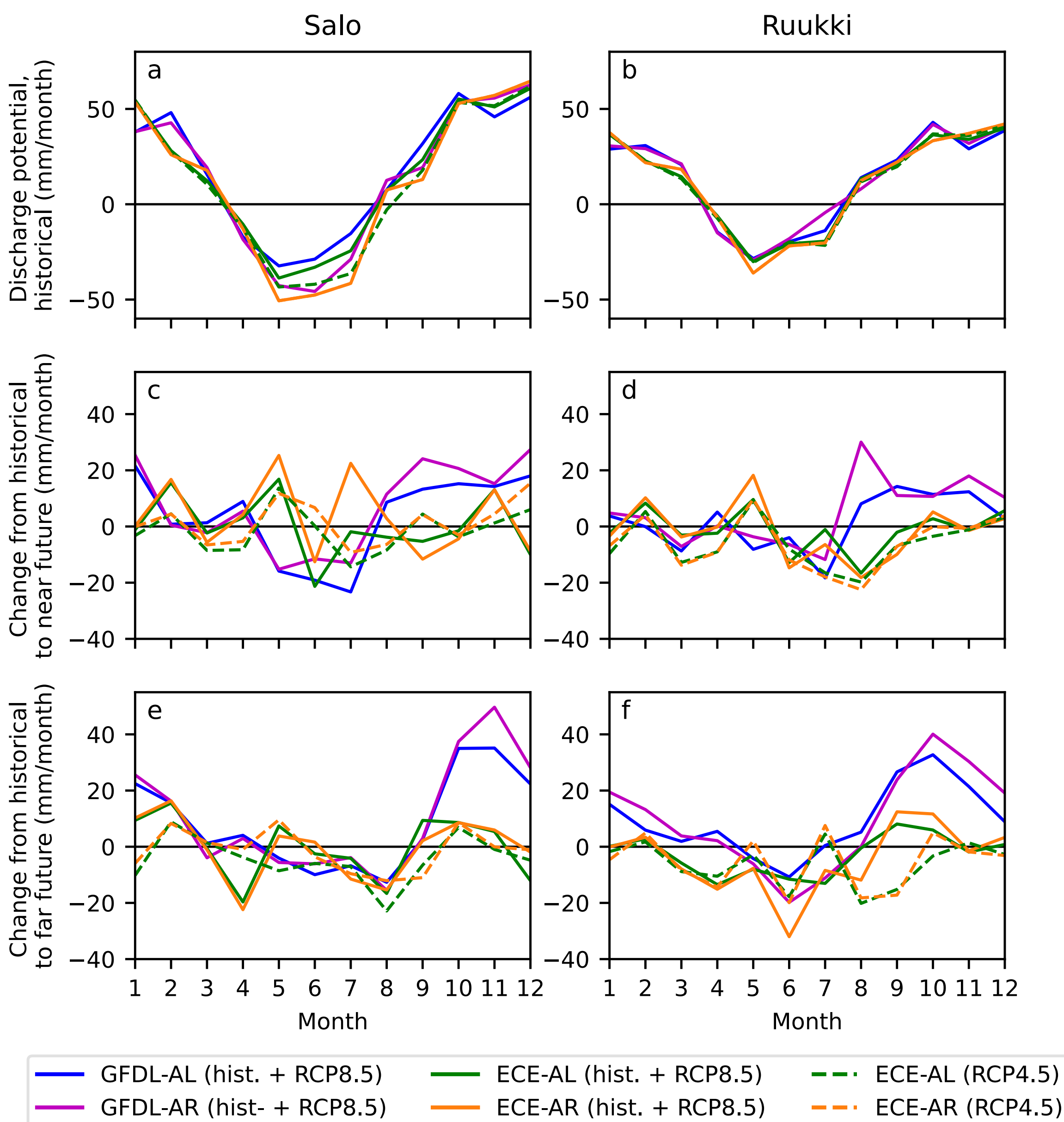

Fig. 7. Average monthly discharge potential (precipitation - PET) in Salo (a) and Ruukki (b) during the historical period and its changes in the future periods: near future in Salo (c) and Ruukki (d); far future Salo (e) and Ruukki (f).

which is smaller in comparison to the historical period, mainly due to decrease in CD effect in GFDL-AL/AR RCP8.5 and ECE-AL RCP4.5 scenarios.

In the far future (Fig. 10e-f), the only statistically significant changes in the CD effects on average GWT depths in comparison to the historical period were projected by the GFDL-AL/AR RCP8.5 scenarios, with decreases of 0.02 m in Salo (in both GFDL-AL/AR) and decreases of 0.01 m and 0.02 m in Ruukki (in GFDL-AL and GFDL-AR, respectively). In Salo, the decreases were stronger in winter whereas in Ruukki they were more spread out over the year apart from spring. In Salo, the largest change in summer was projected by ECE-AR RCP4.5 with an increase of 0.01 m, the changes in other climate scenarios being statistically insignificant. In Ruukki, the GFDL-AL/AR models with RCP8.5 projected decreases of 0.02 m in the CD effects during summer. During winter, the GFDL-AL/AR RCP8.5 scenarios decreased the effect by 0.05–0.06 m in Salo and 0.01–0.02 m in Ruukki. In Salo, the ability of CD to prevent deep GWTs dropped to the range of 13–20 % with a decrease in all climate scenarios in comparison to the historical period (see Fig. 14 in Section 3.4). In Ruukki, the range was 19–36 %, with increase in comparison to the historical period in all scenarios except the GFDL-AL/AR scenarios, which projected high reductions of 50 % in the historical period.

Regarding CD effect on average drain discharge, mostly increases (i.e., larger reductions of drain discharge) were projected for the future periods in comparison to the historical period (Fig. 11). In the near future (Fig. 11c-d), larger than 1 mm/month average changes were projected only in Salo by GFDL-AL and GFDL-AR (RCP8.5) with increases of 2.0 mm/month and 2.3 mm/month, respectively. These changes took place mainly in winter, when the average increases were 5.5 mm/month and 6.6 mm/month, respectively. On annual level, the changes in other climate scenarios were not statistically significant. During winter in Ruukki, statistically significant changes were projected by ECE-AL RCP8.5 (1.7 mm/month increase) and by ECE-AL RCP4.5 (1.1 mm/month increase). While relatively large increases in the average effect during autumn were projected by the GFDL-AL/AR RCP8.5 scenarios, these were not considered to be statistically significant.

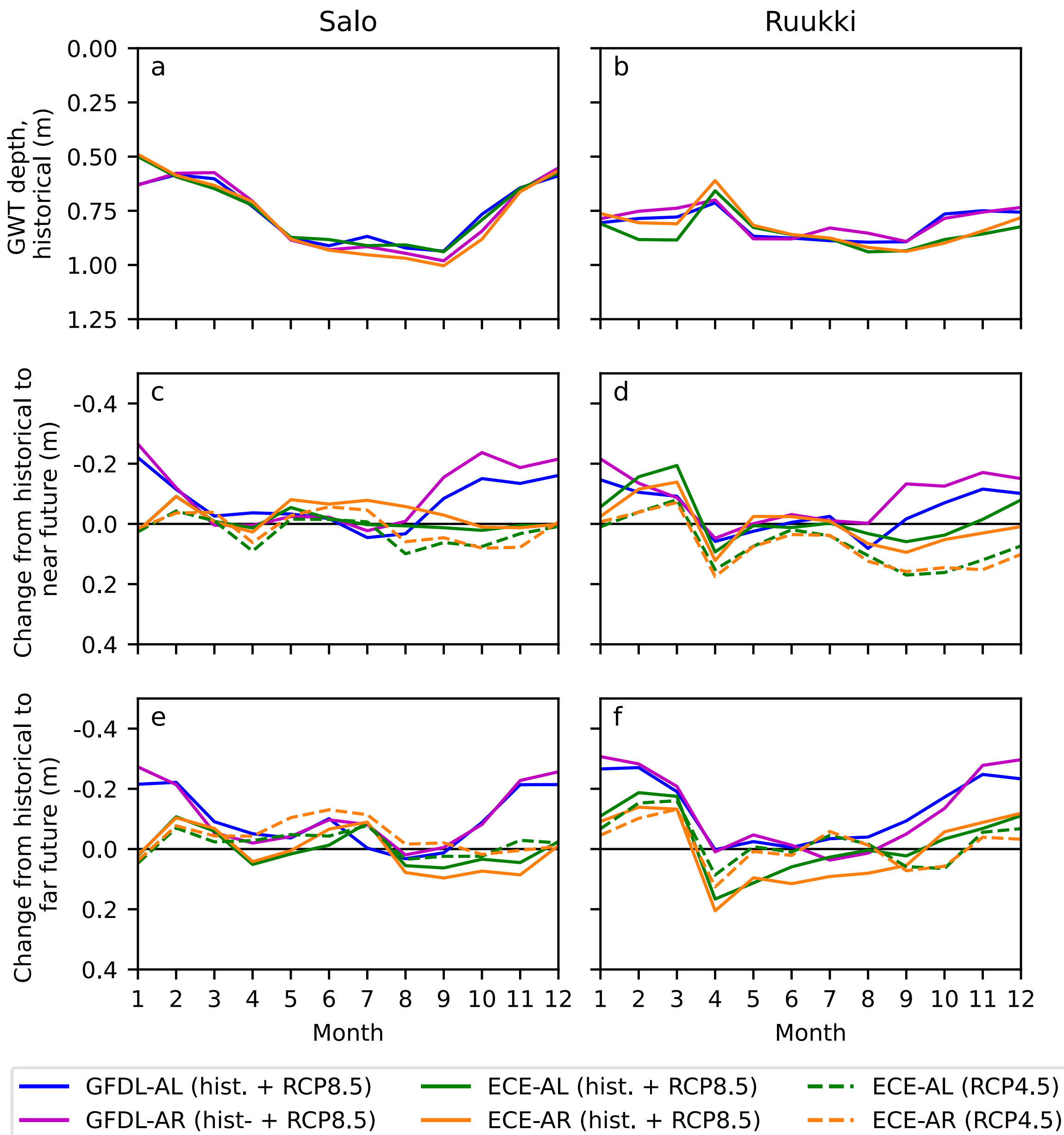

Fig. 8. Average monthly GWT depths Salo (a) and Ruukki (b) during the historical period and the changes in the future periods in comparison to the historical period: near future in Salo (c) and Ruukki (d); far future in Salo (e) and Ruukki (f). Positive change refers to future groundwater level being closer to soil surface (decreased GWT depth) and negative change deeper from the soil surface (increased GWT depth) than the historical reference.

The largest far future changes in the CD effect on average drain discharge were again projected by the GFDL-AL and GFDL-AR (RCP8.5) scenarios, with increases (i.e., larger reductions of drain discharge) of 3.0 mm/month and 3.6 mm/month in Salo, respectively, and increases of 1.9 mm/month and 2.8 mm/month in Ruukki, respectively. These changes took place mainly during autumn and winter. The changes in other climate scenarios or during other seasons were not statistically significant.

3.4. Peat subsidence

Peat subsidence and its effects on field hydrology during the 20-year near future period were simulated under GFDL-AR RCP8.5 and ECE-AL RCP4.5 climate scenarios. The amounts of peat subsidence under different climate and drainage scenarios in Salo and Ruukki are listed in Table 3. In both climate scenarios, more subsidence took place in Ruukki. Under GFDL-AR, the amounts of subsidence were similar in Salo and Ruukki, and CD reduced subsidence by 0.034 m (19 %) and 0.043 m (22 %), respectively. In comparison to GFDL-AR, the amounts of subsidence were larger under ECE-AL, and there was also a greater difference between Salo and Ruukki. In ECE-AL, CD reduced subsidence by 0.039 m (17 %) and 0.041 m (14 %) in Salo and Ruukki, respectively.

The near future period of 20 years was simulated again with the reduced peat cover thicknesses. Fig. 13 and Table 4 show the impact of peat subsidence on GWT depths, drain discharges and CD effects. Peat subsidence resulted in decreased average GWT depth and drain discharge in both drainage scenarios. Even though peat subsidence was greater in ECE-AL in both locations, GFDL-AR showed slightly larger impacts of peat subsidence on average GWT depths in Ruukki and on drain discharge in both locations. Peat subsidence decreased the CD effect on average GWT depths, and the impact correlated with the impact on average GWT depths. The CD effect on drain discharge increased due to peat subsidence, but this impact did not correlate with the impact subsidence had on the amount of drain discharge.

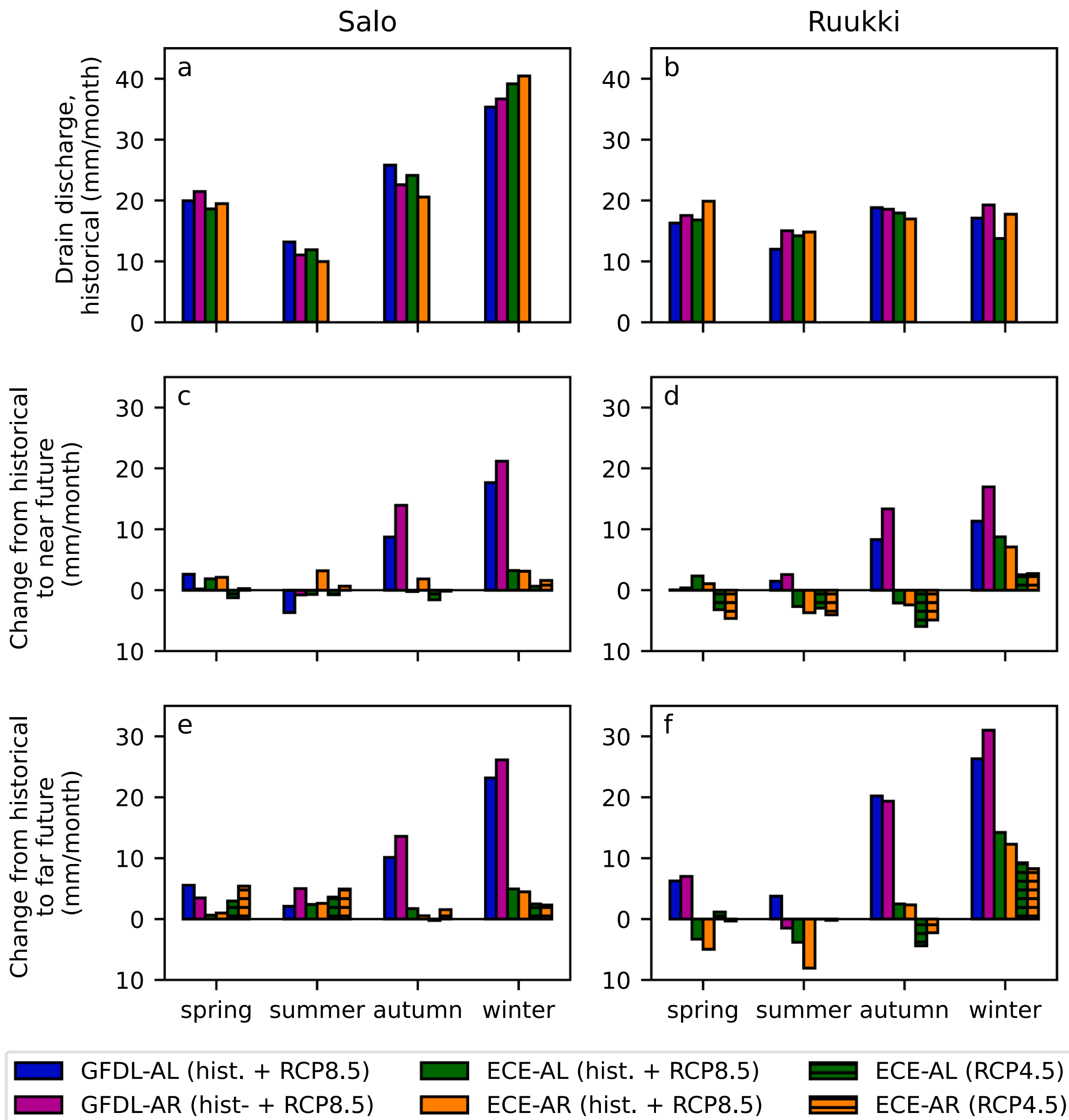

Fig. 9. Average seasonal drain discharges in Salo (a) and Ruukki (b) during the historical period and the changes in the future periods in comparison to the historical period: near future in Salo (c) and Ruukki (d); far future in Salo (e) and Ruukki (f).

During most of the year, peat subsidence caused decreased GWT depths, but this was reversed during summer and early autumn, as GWTs reached deeper with subsided peat, and this effect was slightly stronger in the ECE-AL scenario (Fig. 13). Subsidence also increased the annual frequency of deep (>1.1 m) GWTs. The effect of CD on this frequency remained similar with subsidence (Fig. 14). Subsided peat occasionally resulted in higher drain discharge only in Ruukki under normal drainage scenario. In GFDL-AR, this occurred in February, and in ECE-AL during February and March.

4. Discussion

4.1. Climate change and hydrological impacts

The hydrological simulations were produced with six climate projections consisting of two GCMs, two RCMs, and two RCPs. The climate projections of the HCLIM project consisted of hourly meteorological time series, corresponding to the input data time resolution in the FLUSH calibration process by Salla et al. (2024). Considerable differences were present in the projections between the climate models even with the same RCPs, which lead to varying hydrological impacts, particularly outside summer months (June–August). The differences point out the need to include several models and RCPs to reveal uncertainties in future results and to allow reflection between meteorological input differences and simulated hydrological impacts.

All projections showed the strongest future warming taking place in winter with the warming being stronger in Ruukki (north) than in Salo (south). This is similar to the multi-GCM comparison in Finland by Ruosteenoja and Jylhä (2022), where November–December warmed more in the northern Finland than in the south. Milder winters may lead to higher N_2O and to some extent CO_2 emissions in cultivated peatlands (Gerin et al., 2023). All projections also agreed that future increase in precipitation is larger in Salo than in Ruukki, but they were not consistent on seasonal developments. Increased precipitation can be helpful in maintaining higher soil moisture to reduce peat decomposition, but it can also lead to increased drain discharge, surface layer runoff, and nutrient load, especially during times of low evapotranspiration.

Table 2
Changes in average GWT depth and drain discharge in comparison to the historical period.

	Changes in average GWT depth (m)		Changes in average drain discharge (mm/month)		Changes in fractions of deep (>1.1 m) GWTs (percentage point)	
Near future	Salo	Ruukki	Salo	Ruukki	Salo	Ruukki
GFDL-AL RCP8.5	-0.08	-0.04	6.33	5.29	-3.47	3.43
GFDL-AR RCP8.5	-0.10	-0.08	8.63	8.32	-5.17	0.42
ECE-AL RCP8.5	-0.01	-0.02	1.05	1.58	0.15	-0.10
ECE-AR RCP8.5	-0.03	0.00	2.56	0.51	-0.72	3.35
ECE-AL RCP4.5	0.03	0.07	-0.72	-2.39	4.36	9.96
ECE-AR RCP4.5	0.01	0.07	0.58	-2.71	4.58	9.67
Far future	Salo	Ruukki	Salo	Ruukki	Salo	Ruukki
GFDL-AL RCP8.5	-0.10	-0.13	10.22	14.12	-1.00	1.10
GFDL-AR RCP8.5	-0.11	-0.13	12.04	13.97	-0.41	1.20
ECE-AL RCP8.5	0.00	-0.02	2.42	2.40	4.14	1.34
ECE-AR RCP8.5	0.01	0.00	2.14	0.39	5.25	2.77
ECE-AL RCP4.5	-0.02	-0.03	2.20	1.50	-0.41	-3.44
ECE-AR RCP4.5	-0.04	-0.01	3.54	1.36	-2.41	0.58

Under conventional subsurface drainage, the magnitude and direction of future changes in average GWT depths varied between climate scenarios. The most notable (> 0.05 m) changes were the decreases projected by the GFDL-AL/AR RCP8.5 scenarios in both locations and future periods and the near future increases projected by the ECE-AL/AR RCP4.5 scenarios in Ruukki. Otherwise, the changes in GWT depths were less than 0.05 m. Future changes of similar magnitude were reported by Sojka et al., (2020) in Poland, although their simulations excluded winter. Similarly, future changes in GWT depths during summer months, when the peat decomposition rates are likely higher (Bader et al., 2018; Heikkinen et al., 2024), varied between climate models, the largest changes reaching up to 0.1 m. The summertime changes tended more towards decreases in depth (higher GWTs) in Salo and towards increases (lower GWTs) in Ruukki. The results suggest some climate scenarios might lead to changes in peat decomposition rates, but the uncertainty is high. Salimi et al. (2021) concluded that climate change alone without water level management could not cause significant changes in peatland carbon dynamics in Sweden. In the current study, future changes in drain discharge were small except according to the GFDL-AL/AR RCP8.5 scenarios, which increased drain discharge during autumn and winter, possibly triggering increased nutrient leaching to surface waters (Christianson and Harmel, 2015; Grenon et al., 2023).

4.2. Controlled drainage effects

The effects of controlled drainage were studied with climate change scenarios in two locations using a constant annual schedule for the CD management (Fig. 4). In reality, CD management should take into account varying meteorological conditions. After all, one of the benefits of CD is that it can be adjusted to wet and dry conditions. However, our goal was to quantify the effects of CD under different climate conditions, and we wanted to avoid introducing additional variables, such as differences in CD management. The CD schedule used in this study is one where control is applied in all times except during spring and autumn, when drainage is typically needed for field operations in high-latitude agriculture.

Wils et al. (2025) concluded that raising annual mean GWTs is essential to reduce greenhouse gas emissions and subsidence in cultivated peatlands, and a meta-analysis by Hall et al. (2025) noted CD to be a valid tool in mitigating climate change. In our results for the historical period, CD raised the average GWTs by 0.10–0.11 m in Salo and by 0.12–0.13 m in Ruukki, which is within the ranges measured and simulated by Tähtikarhu et al. (2025) on a cultivated peatland field with thin and thick peat soils. The effects were lower than in a mineral soil simulation by Salla et al. (2022), who applied a similar CD management as in this study, but they may still help to reduce CO_2-emissions (Aben et al., 2024; Evans et al., 2021; Jeewani et al., 2025; van der Poel et al., 2025). On annual basis, the future projections showed only small changes in the efficacy of CD to raise GWTs in both locations, the largest changes being decreases of 0.01–0.02 m (projected by the GFDL-AL/AR RCP8.5 scenarios), which is contrary to Salla et al. (2022), where the average effects increased in the future. The changes in CD effects on GWTs did not clearly correlate with changes in GWT depths.

Peat decomposition is temperature dependent, and consequently, Boonman et al. (2022) recommended using summer average GWT depths over annual average GWT depths in modeling peat decomposition. Accordingly, Heikkinen et al. (2024) pointed out that the optimal time to raise GWTs to reduce the climate impacts is mid-growing season, but this can be challenging due to evapotranspiration losses. Tähtikarhu et al. (2025) found only small effects of CD on GWTs during growing season on a cultivated peatland field. Conversely, in this study CD caused a clear rise in average GWTs (0.06–0.09 m) during summer months (June–August) in the historical reference period, albeit this effect was weaker compared to other seasons. This suggest that CD still has benefit in reducing peat decomposition even if majority of the decomposition takes place during summer (Evans et al., 2021; Heikkinen et al., 2024). In the future scenarios, the changes in CD effects on GWT depths during summer were mostly small and statistically insignificant. A few climate scenarios projected changes of 0.01–0.02 m and these were increases in Salo and mostly decreases in Ruukki. The largest changes in the CD effects on GWT depths were projected in Salo during winter by the GFDL-AL/AR RCP8.5 scenarios (~0.05 m decreases). The simulation of CD in the historical and future periods suggests that the projected changes in climate likely will not have a major impact on the functioning of CD when it comes to altering GWT depths in Nordic regions.

In the historical reference period, CD reduced drain discharge on average by 32–37 mm/a in Salo and by 14–19 mm/a in Ruukki, which corresponds to relative reductions of 11–14 % and 7–9 %, respectively. These reductions are small in comparison to previous controlled drainage studies including both peat and mineral soils (Salo et al., 2021; Tähtikarhu et al., 2025; Wesström and Messing, 2007). This difference may be linked to lateral groundwater outflow, which has been reported to increase in response to CD (Salo et al., 2021; Sunohara et al., 2014). In our model application, lateral groundwater flow exits only through the 1.5 m deep open ditch in one end of the model grid, the side boundaries being otherwise impermeable. This corresponds to a situation where the water levels are managed the same way in the surrounding areas, and thus, CD does not create hydraulic gradient driving lateral groundwater outflow through the field boundaries. Consequently, more water is stored in soil during control and turns into drain discharge when control is taken off. The drain discharge reductions in this study were close to Salla et al. (2022), where similar model application was used in mineral soil. Allowing more lateral groundwater outflow in the model would likely lead to larger CD effect on drain discharge but lower effect on GWT depths. In the future periods, the CD effect on drain discharge remained stable at an annual level, and significant changes took place mainly during winter, when also discharge potential increased.

The ability of controlled drainage to reduce substance load depends on how it changes the total water balance and on the dynamics of the compounds in the soil profile (Skaggs et al., 2012). Reducing drain discharge with CD increased evapotranspiration, discharge into the open ditch, and surface layer runoff. Exchanging drain discharge to open ditch discharge may be beneficial due to more extensive filtration in the soil, which can lead to cleaner discharge (Rozemeijer et al., 2010). On the other hand, increasing surface layer runoff may be harmful especially in terms of phosphorus losses (Pham et al., 2023). In Salo, surface layer runoff increased substantially more than evapotranspiration or discharge into the open ditch.

4.3. Subsidence

The peat subsidence simulations were included in the study as the

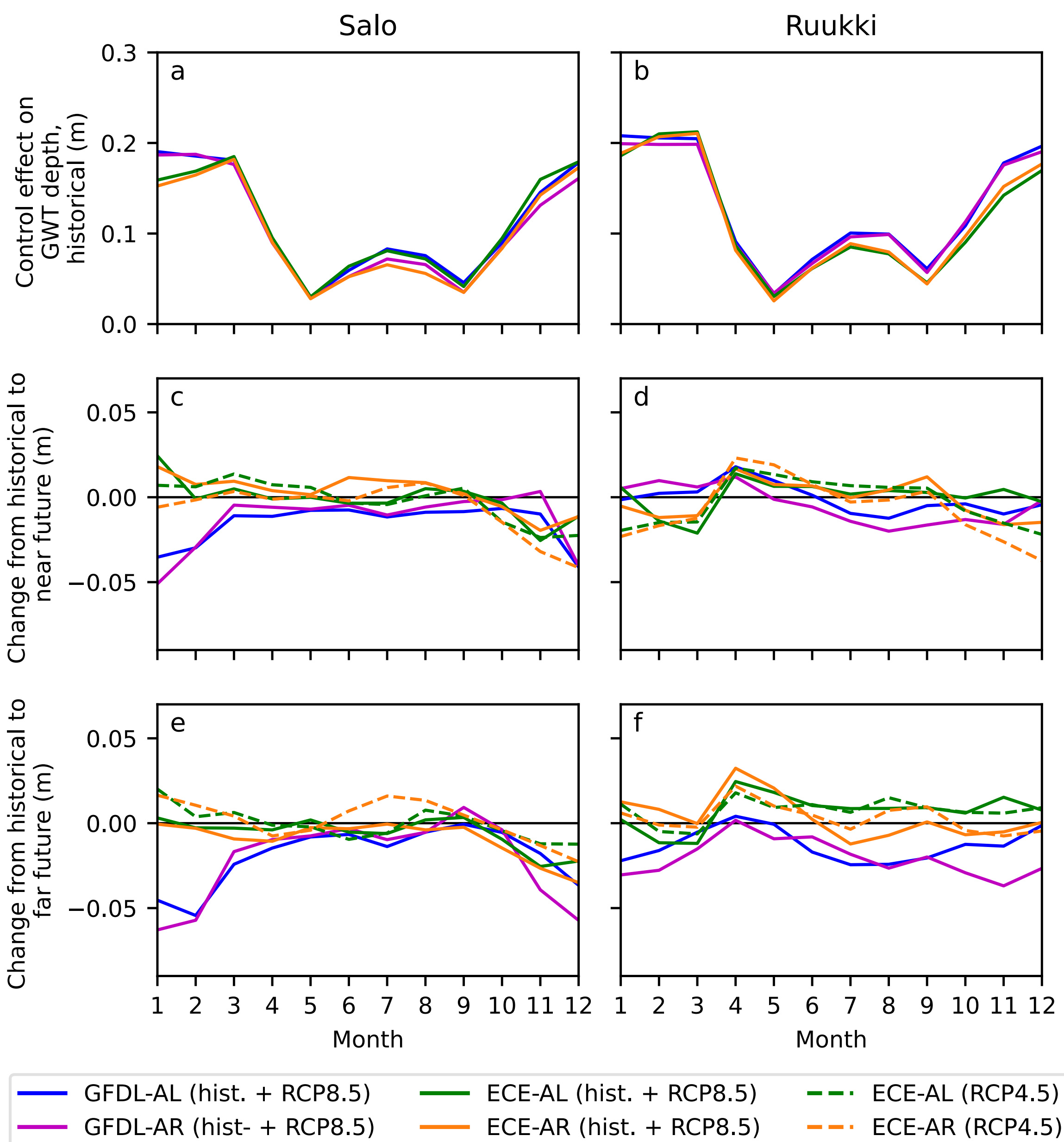

Fig. 10. Average monthly effects of CD on GWT depths in Salo (a) and Ruukki (b) during the historical period and the changes in the future periods in comparison to the historical period: near future in Salo (c) and Ruukki (d); far future in Salo (e) and Ruukki (f). In a and b, positive values refer to decreased GWT depth. In c–f, positive values refer to larger reduction of GWT depth.

peat surface is known to experience topographic changes in the long term due to compaction and oxidation (Berglund, 1989; Yli-Halla et al., 2022). To simulate peat subsidence during the near future, a simple relationship between average GWT depth and subsidence was adopted from Evans et al. (2019). This enabled the estimation of peat subsidence without calibration against subsidence observations, which were not available for the study.

In our simulations, the difference in subsidence between Salo and Ruukki was small in GFDL-AR RCP8.5, whereas in ECE-AL RCP4.5, where subsidence rates were higher, more subsidence took place in Ruukki. Despite the possible overestimation discussed above, the simulated subsidence rates fit to the range of 0.5–2.5 cm/a in Nordic cultivated peatlands reported by Berglund (1989) and to 1.2 cm/a (standard deviation = 0.6 cm/a) reported by Räsänen et al., (2023)) in Finland. Subsidence resulted in decreased GWT depths and reduced drain discharge due to decreased drainage depth, except during summer and autumn, when it caused deeper GWTs. In the model, the peat layer had higher porosity and water retention capacity than the underlying mineral soil, making it an important water source for evapotranspiration during growing season. Thus, a thicker peat layer enabled evapotranspiration with lower impact on the GWT depths, and as a result, larger increases in growing season GWT depths took place and deep (>1.1 m) GWTs became more frequent with the reduced peat cover thickness. While subsidence weakened the CD effect on GWT depths, it increased the CD effect on drain discharge. This was due to a larger proportion of the prevented drain discharge turning into surface layer runoff.

During the 20-year period, CD reduced the amount of subsidence by approximately 3–4 cm (14–22 %). Considering the role of temperature (Bader et al., 2018; Heikkinen et al., 2024), the stronger CD effects outside summer months, and the fact that much of the CD effects on GWT depths during summer took place below the peat cover, these amounts may be overestimations. Peat subsidence was simulated only for the near future period but based on the small differences in CD effects on GWT depths between the time periods, the results would likely have

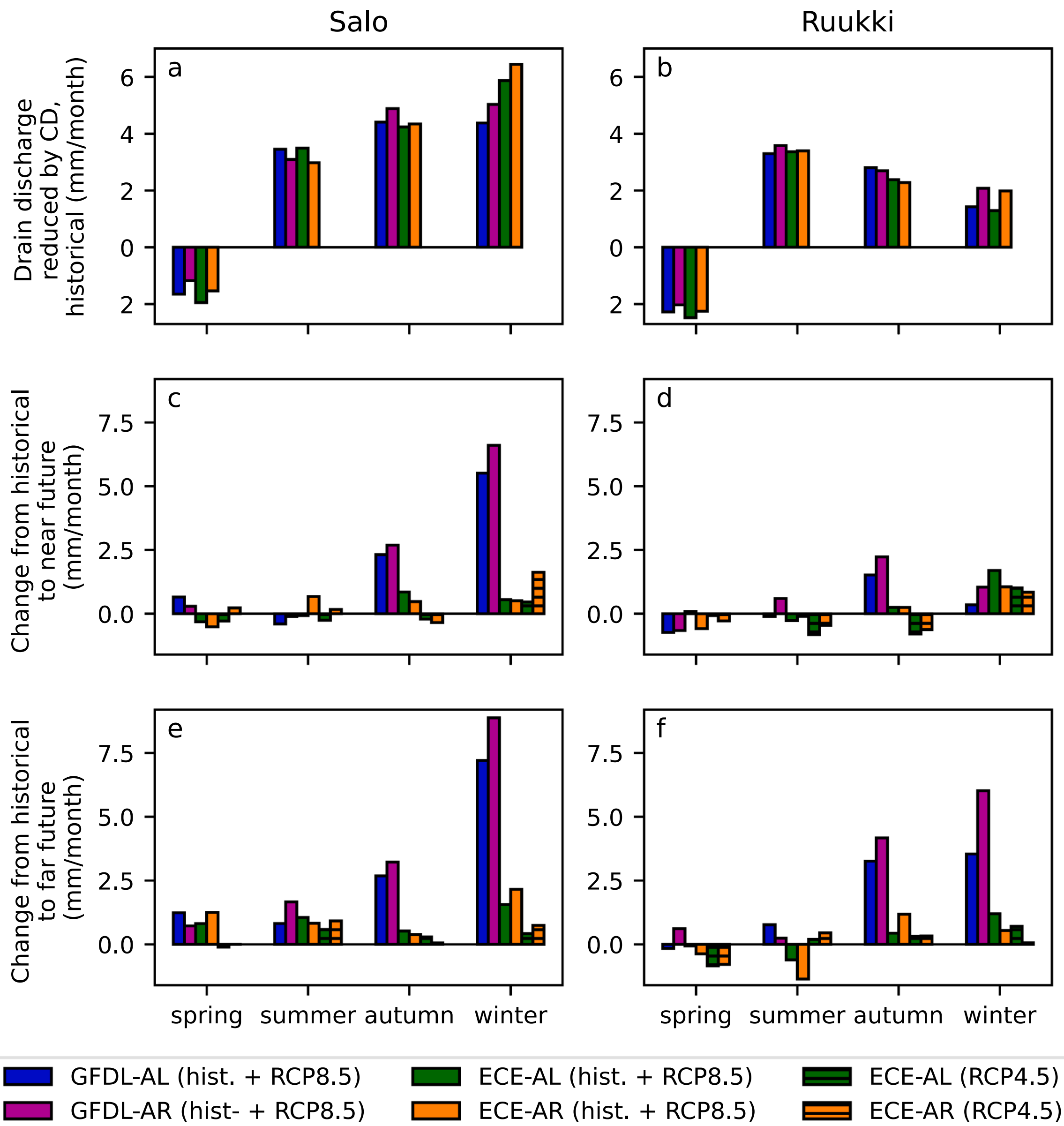

Fig. 11. Average seasonal effects of CD on drain discharge in Salo (a) and Ruukki (b) during the historical period and the changes in the future periods in comparison to the historical period: near future in Salo (c) and Ruukki (d); far future in Salo (e) and Ruukki (f). In a and b, positive values refer to reduced drain discharge. In c–f, positive values refer to larger reduction of drain discharge.

been similar in the historical and far future periods. These results beg the question whether controlled drainage alone is a worthwhile investment regarding peat conservation and emission reduction in Nordic conditions, where most of the decomposition likely takes place during times when raising the water levels is the most difficult (Heikkinen et al., 2024). Effective reduction of peat decomposition might require irrigation (Boonman et al., 2022), and controlled drainage systems provide means for subsurface irrigation (Österholm et al., 2015).

4.4. Uncertainties

Model performance against observations is one source of uncertainty in the analysis. The capability of the model to reproduce measured GWT depths was modest (Appendix A), but comparable to several previous peatland studies (e.g., Laurén et al., 2021; Tähtikarhu et al., 2025; Urzainki et al., 2023). One possible cause for the limited model performance was challenges in the field measurements, which exhibited some inconsistencies between measured GWT depths and drain discharge (Salla et al., 2024). Furthermore, hydrological modeling of peatlands is known to be challenging due to the complexity and heterogeneity of the peat medium (Rezanezhad et al., 2016), hydrological connections between the site and its surroundings (Salla et al., 2024), and peat volume changes resulting in transient hydraulic properties (Kennedy and Price, 2005). In high-latitude sites, seasonal freezing and melting of the surface peat layers adds to the difficulty. Thus, point-scale observations are very difficult to accurately reproduce with a model. Still, we believe our model is a plausible description of a cultivated field with a shallow peat cover and adequate for assessing CD effects under high-latitude climate change.

The peat subsidence simulations were a subject to following uncertainties. First, the GWTs were much of the time deep in the soil below the peat cover, and it is uncertain how this affects the applicability of the linear equation (e.g., Tiemeyer et al., 2020). The studies used by Evans et al. (2019) had thicker peat covers, but the data was not always clear on the GWT depths in comparison to the peat cover. One can assume that changes in GWT depths below the peat cover have a lower impact on

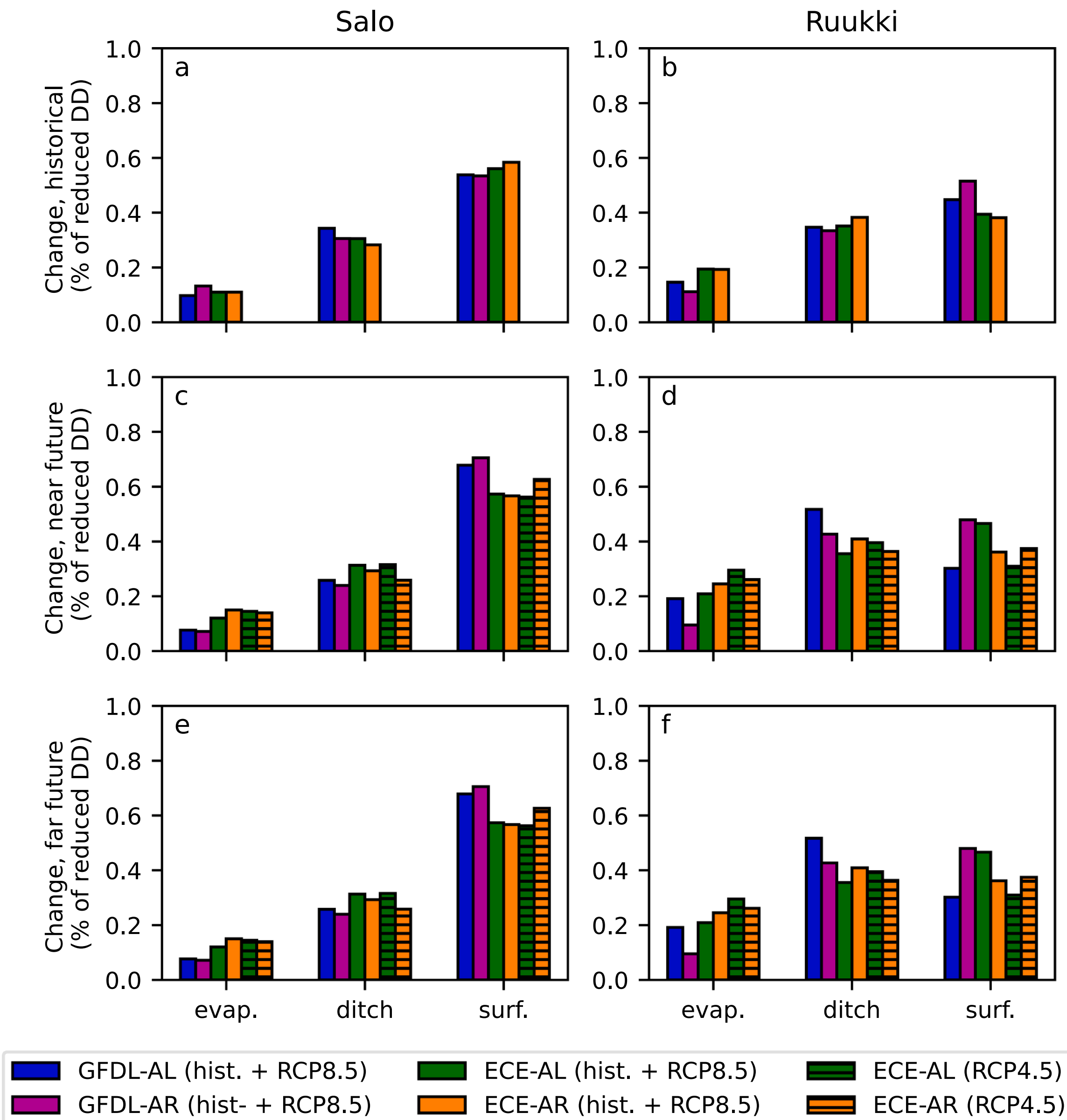

Fig. 12. The changes in evapotranspiration (evap.), discharge into the open ditch (ditch), and surface layer runoff (surf.) caused by controlled drainage as proportions of reduced drain discharge (DD) in the historical (a, b), near future (b, c), and far future (e, f) periods in Salo and Ruukki.

Table 3
Peat subsidence during the simulated 20 years of the near future period under CD and ND.

	GFDL-AR RCP8.5		ECE-AL RCP4.5	
Location	CD	ND	CD	ND
Salo	0.149 m	0.183 m	0.185 m	0.224 m
Ruukki	0.152 m	0.195 m	0.242 m	0.283 m

peat subsidence compared to changes within it, but they likely still have some effect on peat moisture deficit (Pham et al., 2026), and consequently, on subsidence. Hence, it is possible that the equation overestimated subsidence and the effect of CD on subsidence to some extent in our case.

Second, the equation does not consider the impact of temperature on peat subsidence. Process based approaches including temperature could be used, but without calibration against field data, this is not necessarily better than using the empirical equation by Evans et al. (2019) combining several studies. The differences in average air temperature between the two locations in both climate change scenarios were ~3 °C, which likely does not cause a large difference in peat subsidence.

Third, the relationship between peat decomposition and environmental factors is complicated and not completely understood (Laiho, 2006), and low moisture conditions have been reported to limit peat decomposition (Moyano et al., 2013; Säurich et al., 2019). Furthermore, this study did not consider the changes in soil hydraulic properties related to peat decomposition due to lack of relevant soil data (Rezanezhad et al., 2016). Regardless, conserving agricultural peatlands and reducing their climate impacts with water management is an important topic and needs attention. In this study, we outlined a transparent method based on model parameterization from previous research to demonstrate the potential of controlled drainage for managing peatland hydrology and peat subsidence.

5. Conclusions

The climate change scenarios applied in this study resulted in a

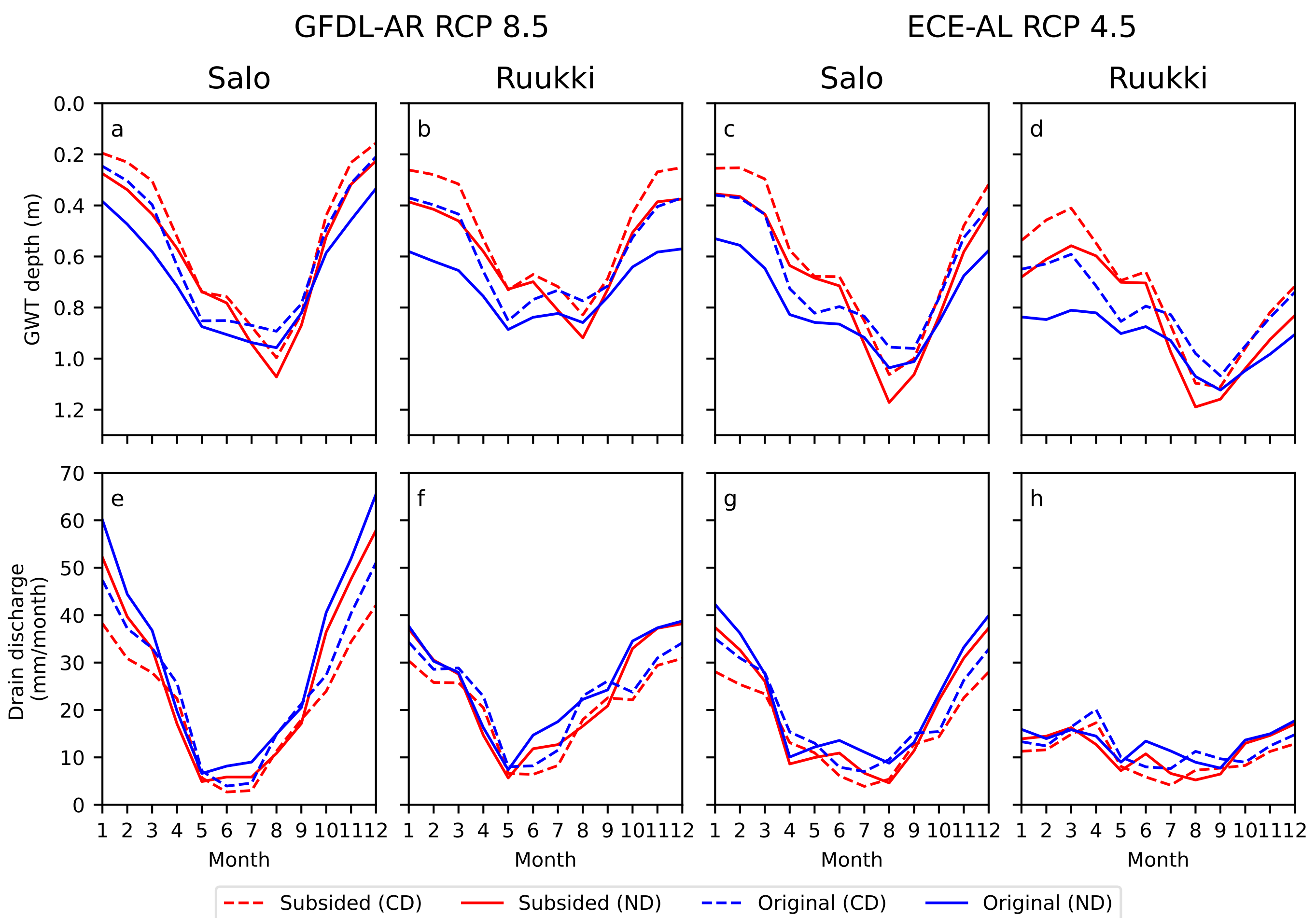

Fig. 13. Impacts of peat subsidence on GWT depths and drain discharge during the near future period in GFDL-AR RCP8.5 (a, b, e, f) and ECE-AL RCP4.5 (c, d, g, h). Original results refer to simulations without subsidence for conventional drainage (ND) and controlled drainage (CD).

Table 4
GWT depths, drain discharges and effects of CD in comparison to normal drainage (ND) with and without peat subsidence during the near future period.

	GFDL-AR RCP8.5			ECE-AL RCP4.5		
Mean GWT depth (m)	CD	ND	ND-CD	CD	ND	ND-CD
Salo (subsided)	0.52	0.59	0.07	0.60	0.68	0.08
Salo (original)	0.57	0.67	0.10	0.66	0.78	0.12
Ruukki (subsided)	0.50	0.58	0.08	0.74	0.83	0.09
Ruukki (original)	0.58	0.71	0.13	0.80	0.93	0.13
Mean drain discharge (mm/a)	CD	ND	ND-CD	CD	ND	ND-CD
Salo (subsided)	260	328	68	194	239	45
Salo (original)	314	378	64	236	271	35
Ruukki (subsided)	246	286	40	121	138	17
Ruukki (original)	280	309	29	145	157	12

variety of hydrological impacts in terms of groundwater table (GWT) depths and drain discharge. This variety was to large extent rooted to differences between the GCMs, and less to differences between the RCPs. The changes in the field hydrology in the future periods were most visible outside of the growing season, while the differences between the study locations of Salo (southern region) and Ruukki (northern region) were less distinct. In the historical reference period, controlled drainage (CD) resulted in decreased average GWT depths, although the effect was always considerably smaller than the applied control level. Despite the highest seasonal evapotranspiration losses, CD reduced groundwater table depths during summer too. The CD effects on GWT depts were similar between Salo and Ruukki and did not go through large changes in the future periods. CD reduced drain discharge by 7–14 % during the historical period, and it mostly turned into surface layer runoff and open ditch discharge and to a less extent into lateral groundwater outflow and evapotranspiration. The largest future changes in drain discharge reductions were driven by increases in drain discharge potential, particularly in autumn and winter. The simulation results suggest that controlled drainage has relevance in managing GWTs and consequently reducing peat decomposition in current and future climate in Finland. The subsidence simulations showed controlled drainage to have a reducing effect of 14–22 % on peat subsidence. Overall, CD is the most efficient outside of the growing season when there is excess water to be controlled, while during the growing season, when the subsidence rates are likely the highest, irrigation may be required for more efficient conservation of Nordic cultivated peatlands.

CRediT authorship contribution statement

Mika Tähtikarhu: Writing – review & editing, Conceptualization. **Harri Koivusalo:** Writing – review & editing, Supervision, Conceptualization. **Heidi Salo:** Writing – review & editing, Methodology, Conceptualization. **Aleksi Salla:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare the following financial interests/personal

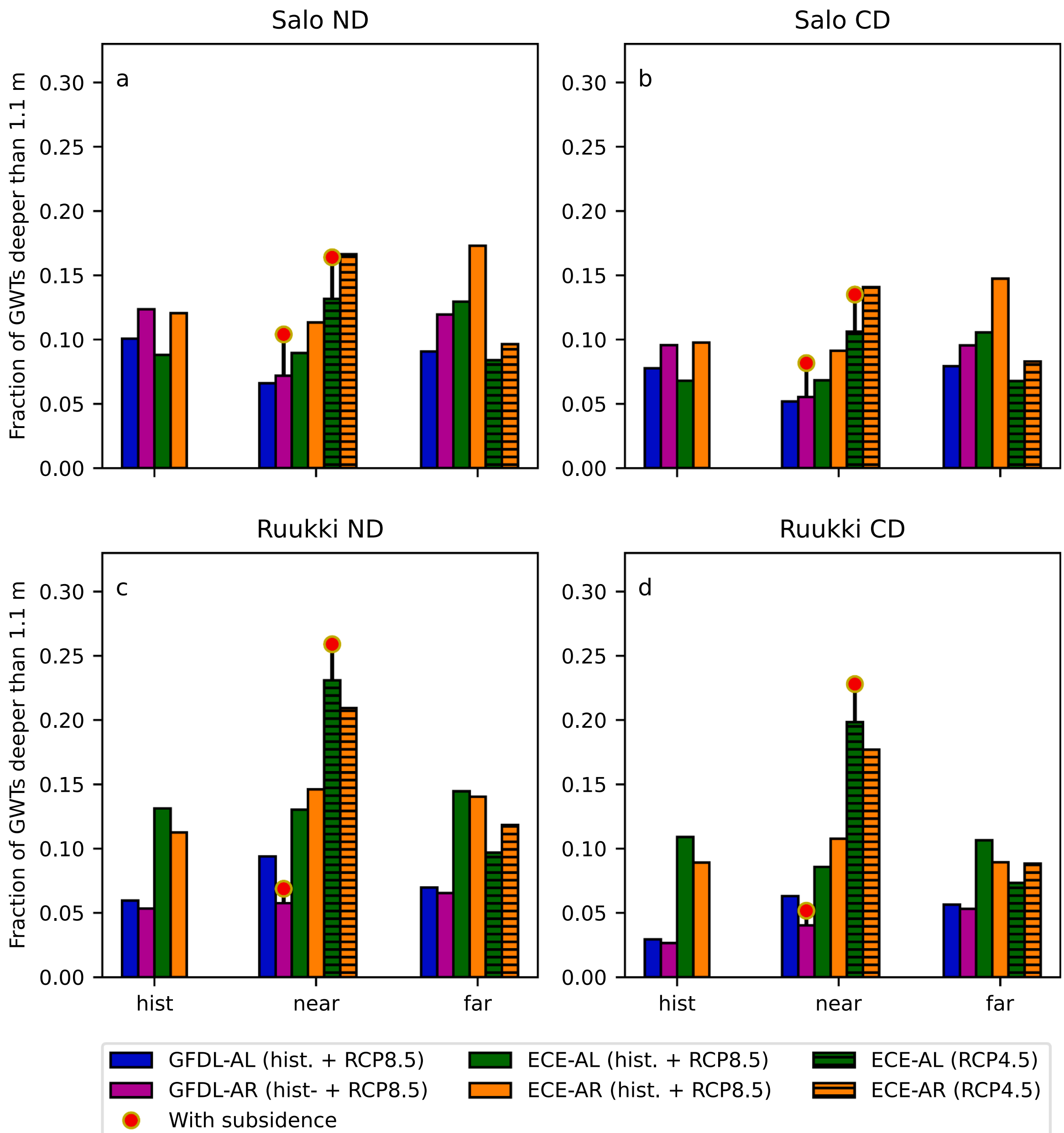

Fig. 14. The fractions of GWTs deeper than the original drainpipe depth (1.1 m) in Salo (a) and Ruukki (c) with conventional drainage (ND), and in Salo (b) and Ruukki (d) with controlled drainage (CD). The effect of peat subsidence is shown for GFDL-AR RCP8.5 and ECE-AL RCP4.5.

relationships which may be considered as potential competing interests: Aleksi Salla reports financial support was provided by Land and Water Technology Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2025.110010.

Data availability

Data will be made available on request.

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