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Hydrological effects of open ditch damming and controlled subsurface drainage in a Nordic agricultural field

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ABSTRACT

Controlled drainage (CRD) is an agricultural water management practice designed to adjust the capacity of a drainage system under varying hydrological conditions. This simulation study aimed to quantify the potential of combining a controlled subsurface drainage (CS) with open ditch damming (CD) to manage the water table depth (WTD) and field water balance in Nordic conditions. Simulations with and without controlled drainage were run using a hydrological model that had been set up for a flat loamy field in Northern Ostrobothnia, Finland, for the period 2010–2021. All CRD scenarios reduced the probability of deep WTDs during growing seasons (May–Sep). The impact of CS on WTDs was greater and more uniform than CD. The CRD effects on water balance were seen in water outflow pathways, as CS reduced drain discharge while CD had the opposite effect. When both methods were applied simultaneously, annual evapotranspiration increased 5–12% compared with the free drainage scenario. The effects of CRD on evapotranspiration were greatest during the dry years indicating that CRD has potential to reduce drought in food production areas. None of the CRD scenarios could maintain optimal WTDs during the entire growing season, highlighting the complexity of optimizing field water management using CRD alone.

Key words: macropores, modeling, water balance, water management, water table depth

HIGHLIGHTS

- Combining open ditch damming and controlled subsurface drainage provides flexibility for agricultural water management.
- Hydrological modeling provides a holistic view of field hydrology.
- Controlled drainage reduces the probability of deep water tables during the growing season.
- The impact of drainage design on field water balance was most clearly seen in runoff outflow pathways.

1. INTRODUCTION

Controlled drainage is proposed as an agricultural water management practice to manage water tables for more efficient food production (e.g., Castellano *et al.* 2019; Duffková *et al.* 2022; Youssef *et al.* 2023) as well as for environmental protection (e.g., Rozemeijer *et al.* 2010; Österholm *et al.* 2015). Traditionally, efficient artificial drainage has been the main water management practice in Nordic conditions due to the seasonal climate and the corresponding hydrological conditions (Castellano *et al.* 2019). Snow melt periods in spring and heavy rainfall in autumn require efficient removal of excess water from the fields to enable cultivation practices (e.g., Alakukku *et al.* 2003; Castellano *et al.* 2019). Controlled drainage can be implemented as controlled subsurface drainage (CS), by adjusting the drainage capacity of the subsurface drain network, or as open ditch damming (CD), by damming water in the main collector ditches. The possibilities and practical implications of CS are not fully understood despite multiple field experiments (e.g., Wesström *et al.* 2014; Österholm *et al.* 2015) and modeling studies (e.g., Youssef *et al.* 2018; Singh *et al.* 2020) on the topic. Additionally, recent studies have aimed to enhance water table management in agricultural areas by controlling the main collector ditches (e.g., Yli-Halla *et al.* 2020). However, there is limited evidence of the combined effects of the controlled drainage practices, such as CS and CD, on field hydrology. Possible increased yields and environmental benefits of controlled drainage are primarily gained though hydrological changes, which depend on field properties, meteorological conditions, and the operation of the controlled drainage system. This study contributes to the previous literature by quantifying the hydrological changes achieved in Nordic agricultural fields with three different CRD scenarios, including the isolated and combined effects of CS and CD.

In CS, the drain network outlet elevation can be temporarily elevated resulting in pressurized conditions in the network, which prevents drain discharge until the hydraulic head in the network exceeds the control level. In CD, the open ditch can be dammed with a weir that elevates water levels in the ditch, reducing its drainage capacity. Whereas a CS network is connected to individual fields, CD might be able to regulate the water table depths (WTDs) of several fields depending on the ditch properties (Paavonen *et al.* 2023, in preparation). In drainage systems where the subsurface drains discharge into a dammed ditch, these two methods interfere with each other under certain conditions; the drainage capacity of the subsurface pipe network is reduced if the ditch water level exceeds the network outlet elevation, and the discharge from the network can increase the amount of water stored in the ditch.

Controlled drainage has been studied as a method for environmental protection in terms of e.g. nutrient leaching (Tan & Zhang 2011; Wesström *et al.* 2014). High nitrogen loads in agricultural runoff enhance eutrophication in surface waters, which threatens aquatic ecosystems (Singh *et al.* 2020), and discharge from fields is one of the main environmental concerns in crop production. Studies examining the impacts of CS on field scale have primarily focused on drain discharge, and many have noted significant decrease in drain discharge when compared with free subsurface drainage, e.g., 60–95% by Wesström & Messing (2007), 40–60% by Wesström *et al.* (2014), 60% Sunohara *et al.* (2016), and 55–80% by Povilaitis *et al.* (2018). Often it is not clear how the reduced drain discharge is reflected in the field water balance, and Skaggs *et al.* (2012) noted that CS can be limited in reducing nitrogen losses if the water can exit the field through other outflow pathways. Rozemeijer *et al.* (2016) reported that increased overland flow and shallow groundwater flow compensated for the reduction of drain discharge when CS was applied. Studying the effects of controlled drainage on the entire field water balance, including evapotranspiration (ET) and all runoff outflow pathways, can provide a more comprehensive understanding of the total hydrological impacts and potential benefits of CRD. Additionally, the literature lacks evidence about how CD alters the field runoff dynamics.

The effect of controlled drainage on WTDs has been reported less compared with its effect on drain discharge. This induces uncertainty when evaluating the potential of CRD to manage field water tables for environmental benefits, such as reduction of sulfuric acid oxidation on acid sulfate soils (e.g. Åström *et al.* 2007; Nyman *et al.* 2023), or yield benefits (e.g. Youssef *et al.* 2023). Experimental studies have reported the impacts of CS on WTD, and according to Carstensen *et al.* (2019) and Wesström & Messing (2007), CS generally leads to higher wintertime WTDs with the impact ranging from negligible to circa 50 cm. Carstensen *et al.* (2016) reported on average a 5-cm higher water table during the drainage periods (September–April) with the control level being 70 cm above the drain depth. Growing season WTDs were reported in a simulation study by Salo *et al.* (2021), where CS was able to produce higher water tables during normal and wet growing seasons, but in dry growing seasons CS did not maintain higher levels compared with the free subsurface drainage. Due to varying site conditions, inconsistent effects of controlled drainage on WTD have been found and the results from different studies are not easily comparable. The above-mentioned studies considered the effects of CS alone but not the combined effects of both CS and CD. In addition, the spatial extent of the control effect on the field is not well known.

By maintaining the water table at optimal depths during growing seasons, CRD can contribute to higher crop yields because of the improved soil moisture conditions. In the literature, the effects of controlled drainage on crop yield vary, but CS studies suggest that controlled drainage increases the yield during dry periods but decreases the yield under higher soil moisture conditions, due to excessive wetness (Wesström & Messing 2007; Ramoska *et al.* 2011; Youssef *et al.* 2023). Both a too shallow and deep water table during the growing season can limit the plant photosynthesis because of the oxygen deficiency (oxygen stress) or insufficient water supply (water stress) in the root zone suggesting that, for each crop and soil type, an optimal WTD range could be designed (Zipper *et al.* 2015). Studying the impact of CRD on water tables under different hydrological conditions improves our understanding of yield benefits/penalties during the diverse growing seasons. Local conditions can even result in the simultaneous presence of oxygen and water stresses in different parts of the same field (Zipper *et al.* 2015), highlighting the need to consider the spatial extents of the different drainage methods.

Field scale studies provide insights into the local impacts of water management practices and are feasible to conduct. CRD on multiple fields with varying conditions has been investigated both in experimental (e.g., Wesström *et al.* 2014) and simulation studies (e.g., Youssef *et al.* 2018). Experimental field studies rely mostly on WTD and drain discharge measurements and they are limited in capturing all relevant hydrological processes, such as lateral seepage (see Turunen *et al.* 2015). Modeling tools, on the other hand, are a resource-efficient method for investigating the effects of different water management scenarios in the same system under varying hydrological conditions. Mathematical process models facilitate the analysis of the complete water balance and the role of different water management methods under identical input conditions, giving a clearer picture of the causality in the system. In simulations of agricultural hydrology, lumped models such as DRAINMOD (Skaggs 1978) have been commonly used. Alternatively, spatially distributed models account for the field spatial heterogeneity, facilitating the assessment of the spatial extent of local factors, such as an open ditch at the edge of the field (Haahti *et al.* 2016). The dual-permeability approach (Gerke & van Genuchten 1993) allows the description of preferential flow paths in macropores, which are shown to dominate water flow in structured soils (Turunen *et al.* 2013) as well as the efficiency of drainage management (Frey *et al.* 2016). As the demand for more flexible water management methods increases, so does the need for models that can describe different drainage methods and their interactions. Modeling as a tool will enhance the conceptual understanding of how a field responds to various drainage system designs.

This study aimed to simulate the effects of controlled drainage on the hydrology of a flat Nordic field using a process-based hydrological model FLUSH based on a setup that was previously tested against data (Salo *et al.* 2021). The model application was augmented to include theoretical descriptions of CS and CD following Salla *et al.* (2022). The first objective was to analyze the spatial effect of the main collector ditch damming on field WTDs, and the performance of CS with and without the main collector ditch control. The second objective was to quantify the role of different controlled drainage practices on growing season WTDs under the dry and wet hydrological conditions. The third objective was to investigate how controlled drainage changes the annual water balance under varying hydrological conditions. Finally, the study aimed to distinguish the role of soil macropores in the performance of controlled drainage practices.

2. MATERIALS AND METHODS

2.1. FLUSH model

FLUSH (Warsta *et al.* 2013) is a three-dimensional (3D) process-based model developed for simulating the hydrology of drained agricultural fields and it is tested at several experimental sites in the northern conditions (e.g., Turunen *et al.* 2013; Nousiainen *et al.* 2015). The model simulates the main hydrological processes in both two-dimensional (2D) surface and 3D subsurface domains. It applies a dual-permeability approach, meaning that in the subsurface domain the soil water can move through two parallel pore systems, soil matrix and macropores, which together represent the total soil porosity. Macropores facilitate fast water flow from the soil surface deeper into the soil through preferential flow paths. Soil matrix can be used to simulate slower water movement in the soil. Water enters the model through precipitation after which it accumulates on the surface depression storage. From the surface domain, water can either infiltrate into the pore systems or form surface runoff when the infiltration capacity of the soil and the surface depression storage capacity are exceeded. From the surface domain water can be lost to open ditches or as evaporation. The saturated hydraulic conductivity of both pore systems is used to determine the maximum infiltration capacity. In the subsurface domain, water can move through and between the soil matrix and macropores. From the subsurface domain the water can be lost via groundwater outflow, ET, topsoil layer runoff to open ditches, and discharge to subsurface drains.

FLUSH incorporates a diffuse wave approximation of the Saint-Venant equations for overland flow in the surface domain and the Richards equation (1931) for subsurface flow in both the soil matrix and macropores. The transfer of water between the two pore systems is governed by the Gerke & van Genuchten (1993) method, and soil water retention is modeled using the van Genuchten (1980) model. Darcy's law is used to describe the water flux into subsurface drains and the effect of controlled drainage is simulated with a threshold value for the drain cell pressure head:

$$q = K_s A_d \frac{H - (H_s + H_{cont})}{\lambda} \tag{1}$$

where q ($m^3\,h^{-1}$) is the water flux into the drain, K_s ($m\,h^{-1}$) is the soil hydraulic conductivity calculated as a mean of the horizontal and vertical saturated hydraulic conductivities, A_d (m^2) is the cylindric drain surface area in the cell, H (m) is the soil hydraulic head, H_s (m) is the drain hydraulic head, and λ (m) is the drain entrance resistance term. H_{cont} (m) is the term that describes the effect of control. If the hydraulic head in the drainpipe ($H_s + H_{cont}$) exceeds the soil hydraulic head, no drain discharge is formed.

Groundwater outflow can be removed from the boundaries of the computational domain (e.g., Warsta *et al.* 2013) or as seepage to open ditches (e.g., Häggblom *et al.* 2019). The snow accumulation and soil freezing in FLUSH are modeled with a process-based submodel (Koivusalo *et al.* 2001). Transpiration is removed from the soil layers based on vertical root mass distribution, and root depth time series are given to the model as an input. Transpiration is restrained if the conditions in the field are too dry according to Feddes (1982).

2.2. Site and data description

The Sievi experimental field is located in northern Ostrobothnia (Figure 1(a)). It has a mean slope of <0.2%, and the soil types range from loamy sand to loam. The loam soils are located along the edges of the field (blue and red soils in Figure 1(c)). The area is surrounded by similar agricultural fields. The field has been monitored since June 2015 when subsurface drainage was first installed with a drain spacing of 15 m. The drain depth varied between 0.98–1.18 m. The total area of the field is 2.3 ha with 1.07 ha covered by CS. Note that the Sievi site has only CS as the drainage method (Figure 1(b)), whereas CD was computationally included in the model setup of this study (Figure 1(c)).

The hourly hydro-meteorological data (precipitation, air temperature, relative humidity, and wind speed) were gathered for a 12-year period (2010–2021) from the closest weather stations of the Finnish Meteorological Institute (FMI): Ylivieska, Toholampi, and Pyhäjärvi located 24, 17, and 70 km, respectively, from the study site (Figure 1(a)). Missing temperature, relative humidity, and wind speed observations were linearly interpolated on an hourly basis. A 1-month period of missing hourly precipitation data at the beginning of the 2010s was estimated based on the daily precipitation and hourly cloudiness index by dividing the daily precipitation according to the cloudiness index. The measured rainfall observations were corrected according to Salo *et al.* (2021) using a standard factor of 1.1 for rainfall and 1.2 for snowfall. The wind speed was scaled to a measurement height of 2 m as per Allen *et al.* (1998).

During the study period (2010–2021), the average monthly temperatures in Sievi ranged from −8.8 °C in January to 16.5 °C in July (Figure 2(a)). The highest monthly rainfall (65–80 mm) occurred in late summer and early autumn. The average annual rainfall during the study period was 593 mm, with the driest year being 2018 (461 mm) and the year with highest rainfall being

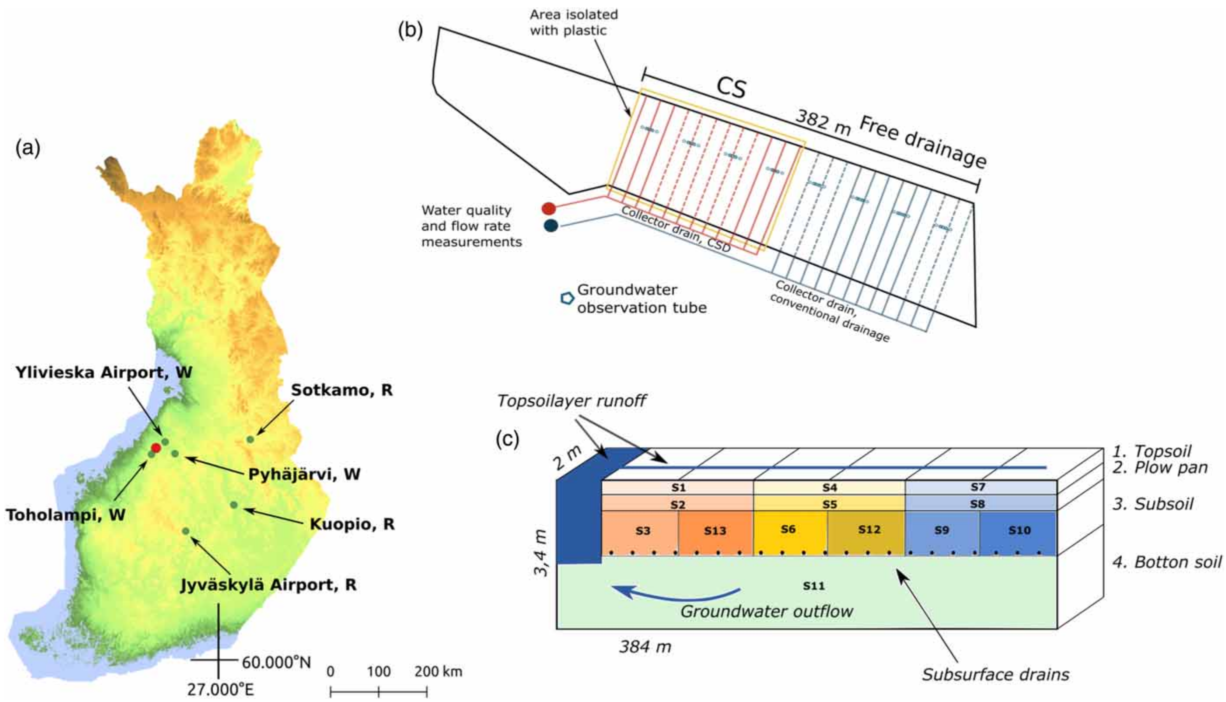

Figure 1 | (a) FMI weather stations. W stands for weather measurement and R for radiation. The red dot is the location of the Sievi experimental site. The colours of the background map illustrate the topography of Finland, and the highest elevation (∼1,300 m, dark brown) is in the top left corner. (b) Subsurface drainage and measurement devices of the Sievi experimental site. (c) Parameterization and computational grid of the field and its outflow pathways and soil types. Open ditch is the dark blue edge on the left and the rest of the colours represent different soil types. The parameters for each soil are given in Table S1 (Supplementary material). (b) and (c) are conceptual, and the scales of the figures are directive. Background map © NLS.

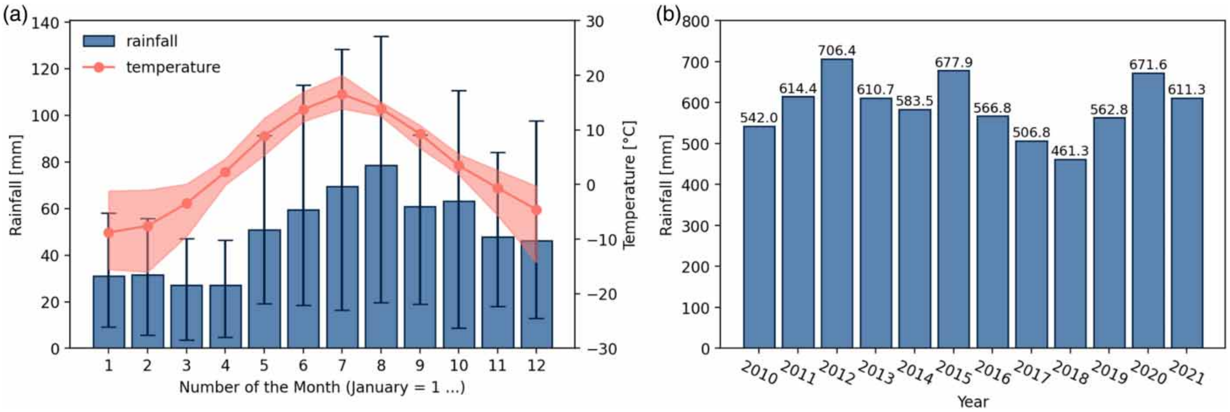

Figure 2 | Variability of weather conditions in the study site during the period 2010–2021. (a) The monthly average values of rainfall and temperature. Error bars and the shaded area represent the min and max monthly values during the study period. (b) Observed annual rainfall in the site.

2012 (706 mm) (Figure 2(b)). The median annual rainfall was 597 mm (average of the years 2013 and 2014). Observations of soil frost were not available on the site, but typically the soil frost lasts from November to April/May.

Global radiation was compiled from FMI weather stations located in Jyväskylä airport, Kuopio, and Sotkamo (Figure 1(a)). Upward and downward longwave radiations were calculated using the Stefan–Boltzmann law (Allen *et al.* 1998). Potential evapotranspiration (PET) was estimated using the Penman–Monteith equation (Allen *et al.* 1998).

2.3. Model setup

This study applied a 2D model setup that was based on previous FLUSH applications in the Sievi field (Salo *et al.* 2021; Salla *et al.* 2022). The simulated field domain was divided into six sections, each consisting of four soil layers based on the soil type (Figure 1(c)). The length of the 2D computational grid was 384 m (x), width 2 m (y), and depth 3.4 m (z). The cell size in the xy plane was 2×2 m^2. The cell depth ranged from 0.02–0.5 m and the cell depths were smallest in the upper layers. The total number of computational cells in the grid was $192 \times 1 \times 32$ (x–y–z). The depths and spacings of the subsurface drainpipes followed the actual drainage system of the Sievi field. To study the effects of CD, a hypothetical 1.5 m deep open ditch was added to the left edge of the grid (Figure 1(c)). The ditch served as the only path for lateral groundwater outflow. In addition, a 0.1 m deep open ditch was set as a sink for topsoil layer runoff and it covered all grid cells (Figure 1(c)). The bottom and side boundaries of the grid were impermeable. Water could exit the grid through ET, subsurface drainpipes, and the two open ditches. The same model setup was applied in Salla *et al.* (2022).

The soil parameters were adopted from Salo *et al.* (2021), who calibrated and validated their model of the Sievi field against groundwater table depth and drain discharge observations. Their model setup differed from that of this study with respect to the groundwater outflow path: instead of an open ditch, Salo *et al.* (2021) simulated groundwater outflow with two 3.0 m deep drainpipes located where the deepest groundwater tables were observed. The total porosities and water retention curves of the soil matrix in the three topmost soil layers were based on soil samples. The shares of macropores were determined by 0.1 m pressure in the water retention curves according to Jarvis (2007). The initial values of other soil parameters were based on the literature (Salo *et al.* 2021). The soil parameters are listed in Table S1, Supplementary material.

2.4. Controlled drainage scenarios

CS was simulated by adjusting the control depth of each drainpipe to a level of 0.6 m below the soil surface. The subsurface drain discharge was prevented if the WTD was at or deeper than 0.6 m (Equation (1)). CD was determined by the same control depth as CS, resulting in a water level of 0.9 m above the ditch bottom. The water level in the ditch and control level in the drainpipes were assumed to remain constant throughout the simulations. In the model, the ditch water level affects the groundwater outflow as groundwater outflow from the soil to the ditch occurs only when the groundwater level in the soil is above the ditch water level. The water level in the ditch additionally creates a hydraulic boundary condition for the subsurface drainage as the collector drain outlet is below the water level in the controlled ditch. When the ditch was controlled, the control depth of each drainpipe was configured using Equation (2).

$$\begin{cases} d = x, & x < N_s - N_v + a \\ d = N_s - N_v + a, & x \geq N_s - N_v + a \end{cases} \quad (2)$$

where d [m] is the control depth of a drainpipe, x [m] is the depth of the drainpipe, N_s [m] is the elevation at the drain location, N_v [m] is the elevation at the ditch location, and a [m] is the control depth of the ditch (0.6 m). When both control methods were in use, the ditch had no impact on the control depths of the drainpipes as due to the topography of the field N_s was always greater than N_v and the same control depth (0.6 m below the soil surface) was used for both drains and the ditch.

The annual growth of the root layer was described using a constant crop rotation to facilitate comparison between years. The crop cycle began with sowing on May 24 and ended with harvesting on September 16. Before sowing and immediately after harvest, the root depth was set to its minimum value of 0.05 m, which is used to describe the evaporation from the field surface in the model. The root depth increased linearly for 67 days after sowing and reached a maximum depth of 0.75 m. The root depth remained constant at 0.75 m until harvest.

The simulated WTDs and water balances of the three control scenarios were compared against the free drainage (Table 1). The free drainage scenario included the open ditch (OD) and uncontrolled subsurface drainage (OS). The comparison was based on the theoretical maximum effects that could be achieved through different control methods and therefore the control scenarios were maintained at a constant control depth throughout the year. The study comprised four simulations (Table 1) that were run for the 12-year period (2010–2021) using an hourly time step.

2.5. Output data processing

The FLUSH model outputs hourly time series of field hydrological variables, including WTD, total runoff, and ET. The total runoff encompasses drain discharge, topsoil layer runoff, and groundwater outflow as separate components. The model also accounts for water storage in the field. In this study, the modeled WTDs were extracted at 23 different locations (between drains) for both the soil matrix and macropores. WTD results are presented as probability distributions with a focus on the spatial variation within the field during growing seasons. Additionally, cumulative WTD probabilities are presented for the spatial average (average of 23 modeling locations) of the entire field as well as the average of the three closest and furthest WTD modeling locations from the ditch.

An optimal range for the growing season WTD was determined as follows: an upper limit at the depth of 0.6 m for optimal WTD was derived from the literature (Saadat *et al.* 2017; Häggblom *et al.* 2019; Jensen *et al.* 2021). The lower limit of the optimal range (maximum depth) is not well defined in the literature, as sufficient plant water availability is more typically described as soil water content between the local field capacity and the wilting point (e.g., Cousin *et al.* 2022). For this study, a maximum depth of 0.8 m (max rooting depth 0.75 m) was chosen as the lower limit.

To examine different water management scenarios under varying hydrological conditions, the driest, wettest, and median years in terms of total precipitation, and the corresponding growing seasons (May 25 to September 16) were determined. The driest year (precipitation 461 mm) and growing season (203 mm) was 2018, while the highest annual rainfall (706 mm) was recorded in 2012. The wettest growing season was in 2016 (341 mm). The median year was 2013 with 611 and 246 mm of annual and growing season precipitations, respectively.

Table 1 | Descriptions and abbreviations of simulated drainage scenarios (S1–S4)

Scenario	Description	Abbreviation
1	Reference scenario. Free subsurface drainage and open ditch	S1: OS + OD
2	Combined effects. Controlling both the ditch and subsurface drains	S2: CS + CD
3	Controlled subsurface drainage only. Ditch is open	S3: CS + OD
4	Open ditch damming only. Free subsurface drainage	S4: OS + CD

CRD scenarios include scenarios S2–S4, and S1 is the free drainage scenario used as a reference.

3. RESULTS

3.1. Effects of controlled drainage on daily average WTD

The daily average WTDs under each drainage scenario are shown in Figure 3. Daily average WTDs demonstrated that all CRD scenarios (S2–S4 in Figure 3) were able to maintain higher WTDs than the free drainage (S1). The impact of control was weaker during the growing season (25 May – 16 September) than during the rest of the year. The results clearly demonstrated that the highest impact on field average WTD was found in the CRD scenario 2 that combines the CS and CD (S2), whereas the smallest impact was achieved by controlling only the main ditch (S4). WTD was lifted by the CRD scenarios on average 0.48, 0.35, and 0.17 m in scenarios S2, S3, and S4, respectively.

3.2. Effects of controlled drainage on WTD during growing seasons

The probability distributions of growing season WTDs and their spatial variability across the field are illustrated in Figure 4. Controlled drainage (Figure 4(b)–4(d)) reduced the frequency of WTDs below 1 m compared with the free drainage (Figure 4(a)) Additionally, all CRD scenarios (S2–S4 in Figure 4) increased the occurrence of optimal WTDs (0.6–0.8 m), and also increased the probability of WTDs above the optimal range.

The WTD distributions in the soil matrix (green area in Figure 4) and macropores (blue area in Figure 4) were distinct in the simulated drainage scenarios. In general, WTDs in soil macropores were deeper than in the soil matrix. Half of the soil matrix WTDs and nearly all the WTDs in macropores were below the drainpipe depth (approximately. 1 m) when free drainage with no control was applied (Figure 4(a)). In contrast, the simultaneous control of the open ditch and subsurface drains (S2) resulted in the highest WTDs during the growing season in both pore systems (Figure 4(b)). In S2, the soil matrix WTDs were most likely to occur in the depth range of 0.3–0.6 m, while macropore WTDs remained deeper yet mostly above 0.8 m. The WTD distributions of the soil matrix and macropores became most similar in S2, compared with other drainage scenarios (Figure 4(b)).

The combination of CS and CD (S2) resulted in the most uniform water table across the simulated field, while the other two CRD scenarios (S3 and S4) resulted in larger spatial variability with respect to the distance from the open ditch (Figure 4). According to the simulations, the CD in S4 had a detectable impact on soil matrix and macropore WTDs further than 230 m from the ditch (Figure 4(d)). However, the effect in the soil matrix was considerably reduced already at a distance of approximately 150 m from the open ditch. The CD also reduced the occurrence of the deepest WTDs in the macropores and

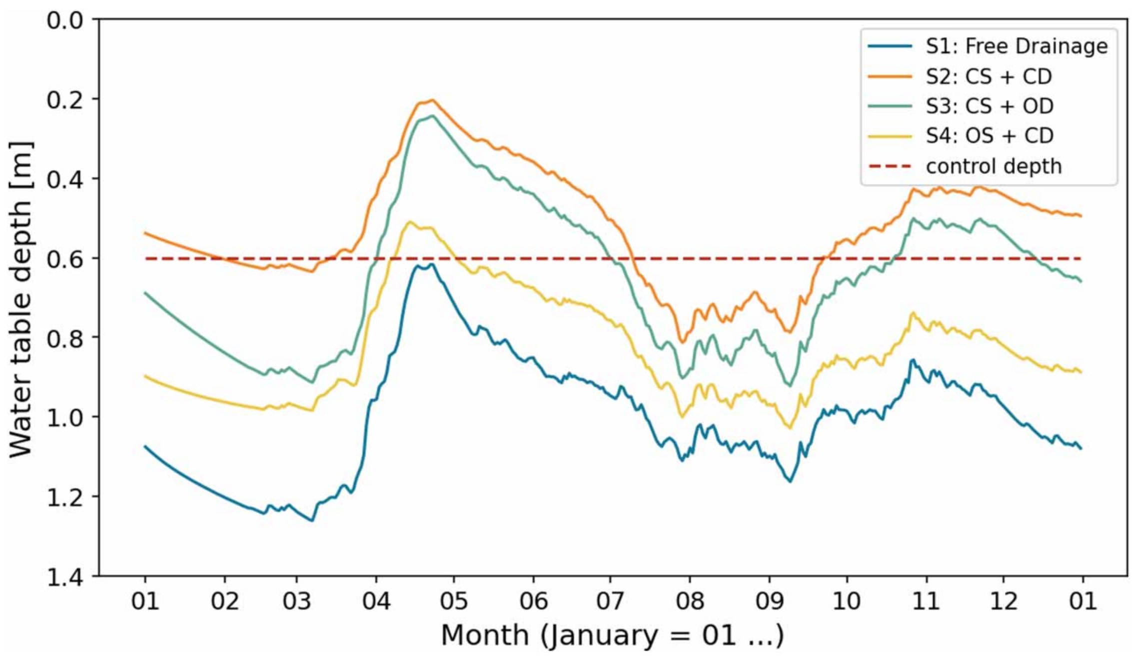

Figure 3 | Daily average WTD during the entire study period 2010–2021. The average WTD is calculated from the soil matrix.

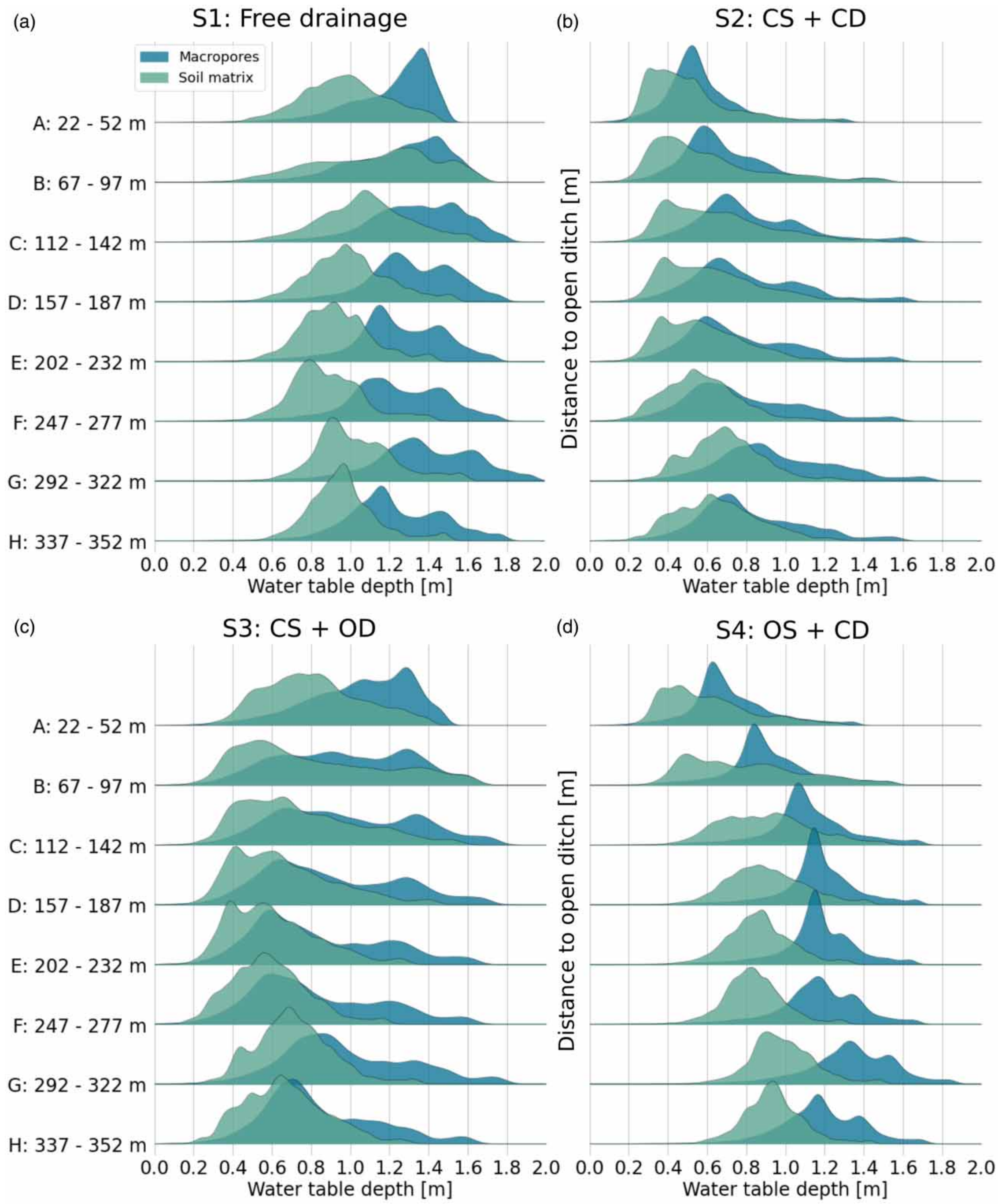

Figure 4 | Probability distribution of WTD during simulated growing seasons in soil matrix and macropores in relation to the distance of the open ditch. The length of the growing season is from May 25 to September 16 each year, and the figure includes the years 2010–2021. (a) S1: Free drainage, (b) S2: controlled subsurface and open ditch damming, (c) S3: controlled subsurface drainage, and (d) S4: open ditch damming.

increased the probability of the 0.6–1.15 m deep macropore WTDs along the entire field profile, but the impact was mostly observable within 230 m from the ditch (Figure 4(d)). By only controlling the subsurface drains, two effects were seen: first, the probability of WTDs below drain depth could be reduced across the simulated field (Figure 4(c)) compared with the free drainage, and second, deeper WTDs were observed close to the ditch (distance of 0–150 m) owing to the draining effect of the ditch.

During the dry growing season in 2018, about 50–59% of the simulated soil matrix WTDs were below the optimal WTD (lower limit 0.8 m) in all CRD scenarios (Figure 5(a)). In macropores, the WTDs were below the lower limit almost throughout the growing season. The average soil matrix WTD in the field was most likely within the optimum range with S4 (yellow line in Figure 5(a)) with a probability of 40%. CS caused the soil matrix WTD to remain above the optimum range in both S2 and S3 during the dry growing season with 40 and 16% probabilities, respectively, while WTDs lower than 0.8 m were almost as likely in all CRD scenarios. All CRD scenarios increased the occurrence of WTD in optimum range, because WTD in the free drainage scenario was below the optimum range (>0.8 m) during the entire dry growing season (Figure 5(a) and 5(b)).

In wet conditions, the average soil matrix WTD was most likely at or above the optimal range in all CRD scenarios (Figure 5(e)) with over 55% probability. During the wet growing season, 40–45% of the average soil matrix WTDs remained at the optimum range with S3 and S4. The corresponding probability for macropore WTDs was 10–20%. When combining CS and CD (S2 in Figure 5(e)), about 80% of the growing season WTDs occurred above and only 20% within the optimum range. Without any control (S1), the WTD was below optimal range also for most of the wet growing season, only 12% was at the optimum range.

The simulation results showed that CD (S4) increased the probability of optimal WTD only close to the ditch (at 22–67 m, Figures 5(c) and 5(g)), whereas far from the ditch (307–352 m, Figures 5(d) and 5(h)) the probability was similar to that of the free drainage scenario (S1) for both growing seasons. In comparison to the field average, WTDs in S4 were less likely to occur in the optimal range locally at the field.

3.3. Effects of controlled drainage on field water balance

All control scenarios increased annual ET during the examined years compared with the reference scenario. ET grew relatively the most (2.3–12%) during the driest year 2018 in all control scenarios (Table 2). In S2 and S3, ET increased the least in the wettest growing season (2016). In S4, the smallest increase in ET was in 2013, but the differences between the years were small. The increase of annual ET was reflected on the amount of total annual runoff that declined in all CRD scenarios (Table 2). The impact of controlled drainage on total runoff and ET was greatest when applying both control methods while CD alone resulted in the smallest change.

Hydrological conditions had a greater influence on the simulated total runoff and ET than the studied CRD methods (Figure 6). The simulations showed that as the annual precipitation decreased, the share of ET increased, and total runoff decreased in all scenarios (S1–S4). In the wettest year, ET accounted for 42.4–45.2% of the annual precipitation, while in

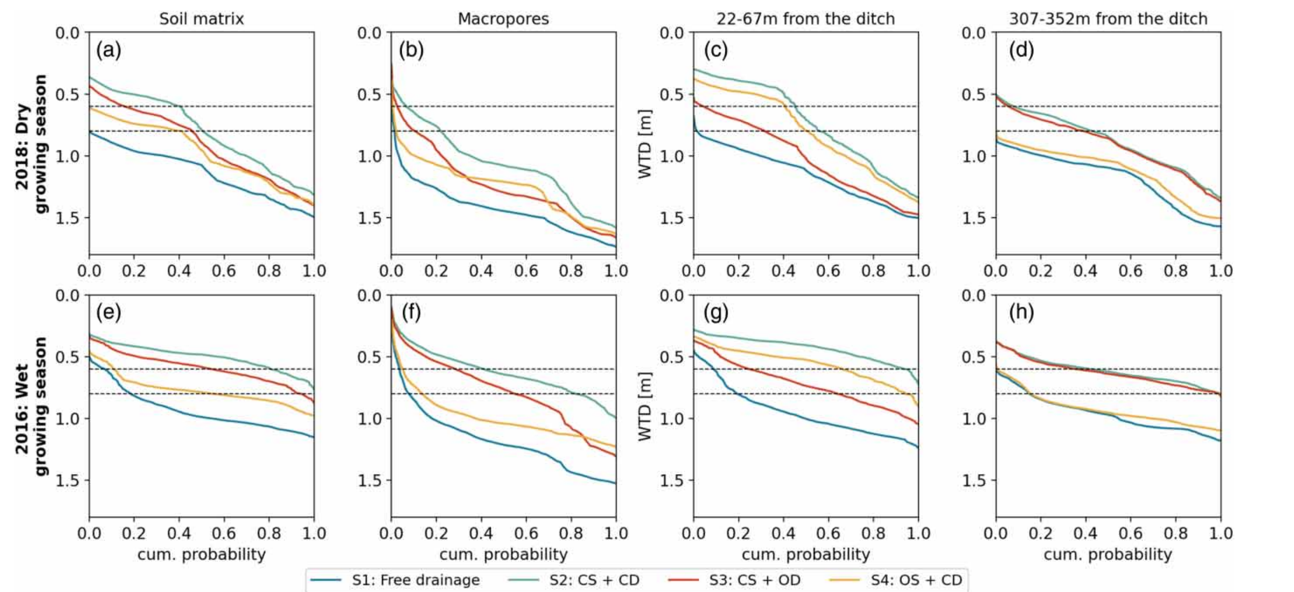

Figure 5 | Cumulative water table depth probabilities in soil matrix, macropores, and two location ranges during dry (a)–(d) and wet (e)–(h) growing seasons.

Table 2 | Relative change in the ET and total runoff in comparison with ET and total runoff of the reference scenario

Scenario	Year	Corrected Rainfall [mm]	ET [%]	Total runoff [%]
S2: CS + CD	2012	790.4	6.5	−3.9
S3: CS + OD			5.1	−3.2
S4: OS + CD			1.5	−1.1
S2: CS + CD	2013	688.4	10.9	−12.2
S3: CS + OD			8.4	−9.6
S4: OS + CD			0.7	−0.5
S2: CS + CD	2016	637.2	5.4	−9.4
S3: CS + OD			4.6	−6.6
S4: OS + CD			1.3	−3
S2: CS + CD	2018	518.8	12	−13.8
S3: CS + OD			8.8	−10.6
S4: OS + CD			2.3	−1.9

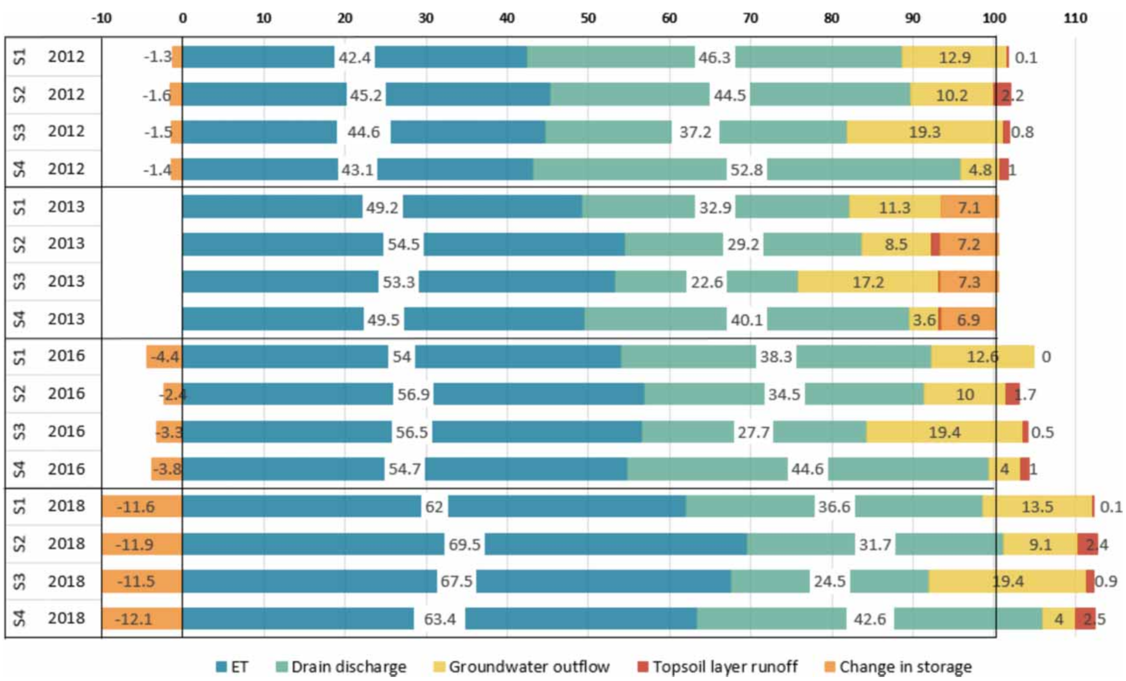

Figure 6 | Water balance components as shares of annual precipitation [%] during extreme and median weather conditions. 2012 had the highest annual precipitation, 2013 was the precipitation median year, 2016 had the highest precipitation during the growing season, and 2018 was the driest year. Years correspond to calendar years covering the periods between 1 January to 31 December. S1: Free drainage, S2: controlled subsurface drainage and open ditch damming, S3: Controlled subsurface drainage, S4: Open ditch damming.

the driest year the corresponding share was 62–69.5% (Figure 6). In the driest year (2018), ET as a share of precipitation increased by 1.4, 5.5 and 7.5 percentage points. The corresponding values were 0.7, 2.2, 2.8 percentage points, respectively.

The field outflow pathways were clearly influenced by the CRD methods during the examined four years (Figure 6). The share of drain discharge of annual water balance was smallest when only CS (S3) was applied resulting in 20–33% less drain discharge than S1. In addition, the share of groundwater outflow was highest in S3 (about 50% more than in S1). In contrast to CS, CD (S4) increased drain discharge (14–20%) and decreased groundwater outflow (63–70%) compared with the free drainage scenario under all hydrological conditions. Combining CD and CS (S2) decreased both drain discharge (maximum 13%) and groundwater outflow (max. 33%) compared with S1. All CRD methods increased topsoil layer runoff (max 2.4% units) compared with S1.

4. DISCUSSION

4.1. Water table management

All controlled drainage scenarios resulted in higher probability of WTDs within the optimal range of 0.6–0.8 meters, but also above the optimal range in comparison with the free drainage scenario. If WTD is shallower than optimum, excess soil moisture causes yield losses, whereas if it is deeper than optimal, WTD decreases yield because the water stress makes the crop more sensitive to weather variability (Zipper *et al.* 2015). This implies that the potential benefits or detriments of an elevated water table on the field are relative to optimum depth. Above the optimal range, CRD intensifies oxygen stress causing yield penalties, but below the optimal range, CRD improves water availability by enhancing the capillary rise of water from the root zone. According to Zampieri *et al.* (2017), crops such as wheat are more sensitive to excess soil moisture than droughts. In wet conditions, the simulated control scenarios caused the field average soil matrix WTD to remain above the optimal range in S2, S3, and S4. Excessive soil moisture was less probable during the dry growing season, but both scenarios including CS (S2 and S3) still resulted in higher than optimal water tables. These findings suggest that CRD has the potential to positively influence the growing conditions in the field. However, the continuous control scheme resulted in too wet conditions both during the dry and wet growing seasons.

The literature has reported positive impacts of CRD on crop yield during dry conditions, but adverse effects during wet growing seasons (e.g., Ramoska *et al.* 2011; Youssef *et al.* 2023). Adverse effects have been caused by excessive water in the root zone, and variability in growing season precipitation has been suggested as the key factor influencing yield responses to CRD (Youssef *et al.* 2023). Our simulation results further demonstrated that excessive soil moisture can also occur during the dry growing seasons when drainage is continuously controlled. Saadat *et al.* (2017) and Youssef *et al.* (2023) concluded that the duration of wet conditions can be reduced by managing the drainage system according to the meteorological conditions. According to Saadat *et al.* (2017) opening the control structures before a heavy rainfall event accelerated the recession of the water table from surface to optimal depth. The proactive management of control structures was not tested in our scenarios, but it can increase the probability of WTDs in the optimal range both in the dry and wet conditions, especially under CS. In rainfed agriculture, the WTDs below the optimal range could only be avoided if irrigation was used.

The simulation results showed that not only did changes in hydrological conditions affect the WTDs in the field, but also that the open ditch management caused differences in soil moisture conditions across the field. In both dry and wet growing seasons, S3 (CS) and S4 (CD) resulted in the highest probability of field average WTDs in the optimal range. However, the location of the open ditch in the field led to notable spatial variability in the effects of the controlled drainage in S4, and thus, CD improved growing conditions only in limited sections of the field. WTDs above the optimal range were common in the vicinity of the ditch, but far from the ditch, the majority of WTDs were below the optimal range in S4. The most uniform and largest effect on WTDs across the field was achieved when CS and CD were combined, indicating that the combined control could provide the most flexible water table management option. However, for the combined CS and CD, an appropriate control schedule would be necessary to avoid excessive moisture. According to Youssef *et al.* (2023), the current practice of manual outlet management (e.g., Salo *et al.* 2021) is not able to maximize the yield, and data-driven water management systems should be developed. This is also supported by our findings of spatial variability, which makes WTD management even more challenging, highlighting the importance of developing advanced management strategies.

All CRD scenarios decreased the occurrence of deep (>1 m) WTDs, which is important for minimizing deep oxidation in sulfide soils and subsequently reducing the acid load (Österholm *et al.* 2015). It has been reported that having control on during snowmelt influenced WTDs and the effectiveness of CRD during the growing season (Virtanen *et al.* 2016; Salo *et al.*, 2021; Salla *et al.* 2022). Therefore, it is presumed that in this study having the control on during snowmelt reduced the occurrence of the deepest growing season WTDs.

The simulated soil matrix and macropore WTDs showed deeper WTDs in the macropore domain than in soil matrix in all the drainage scenarios. Controlling the macropore WTDs can have important environmental impacts as macropores have been reported to increase leaching of nutrients applied to soil surface as fertilizers (Lehmann & Schroth 2002). Yu *et al.* (2023) noted that macropore surfaces were strongly enriched in compounds resulting in acid formation in acid sulfate soils, which points out the importance of high WTDs in macropores when aiming to reduce oxidation and acid formation.

The role of macropores in plant water uptake and crop production is not clear and it differs between crops (Carter & Johnston 1989; Emerman & Dawson 1995). Consideration of water flow in soil matrix and macropores is important to understand the role of structured soil and its effects on the potential of CRD (Frey *et al.* 2016). The presence of macropores can be detected in field scale studies (e.g., Alakukku *et al.* 2010), but their hydrological function is not easily captured in field experiments. The simulation results in this study showed that CRD had a stronger impact on WTDs in macropores than in the matrix, resulting in smaller differences between the matrix and macropore WTDs in CRD than the reference scenarios, the difference being the smallest in S2 combining CS and CD.

4.2. Water balance

FLUSH enabled studying the complete water balance including groundwater outflow and topsoil layer runoff, which may be challenging to quantify by field measurements (Rozemeijer *et al.* 2010; Äijö *et al.* 2014). The results showed that all CRD scenarios reduced the total amount of runoff, but the water balance was still dominated by weather conditions. The reductions in total runoff were considerably smaller than reported in studies considering only one outflow pathway, typically drain discharge (Wesström & Messing 2007; Wesström *et al.* 2014; Sunohara *et al.* 2016; Povilaitis *et al.* 2018), which emphasizes the need to consider the overall water balance instead of only drain discharge.

Using only CS in S3 decreased drain discharge, but this led to increased groundwater outflow into the ditch. During the examined years, the drain discharge reductions in S3 varied between 20 and 33%, which is on the lower side in comparison with the empirical values reported in the literature (Wesström & Messing 2007; Wesström *et al.* 2014; Sunohara *et al.* 2016; Povilaitis *et al.* 2018). This can be due to factors such as the timing of the experiment (specific seasons vs. the whole year) and drainage settings in the fields, but another possible explanation is lateral seepage into the surrounding areas, as the lateral boundaries in this study were impermeable except for the open ditch. The increase in groundwater outflow varied between 49 and 70% of the reduced drain discharge, which is considerably less than the 96% of drain discharge turning into lateral seepage in the DRAINMOD study by Youssef *et al.* (2021), highlighting the importance of the surrounding areas in field water management. Skaggs *et al.* (2012) noted that CS has limited effectiveness in preventing nitrogen losses when the water that was not removed through subsurface pipes exits via other pathways. Conversely, water flowing into the open ditch likely spends more time filtrating through the soil in comparison with subsurface pipes. This can result in cleaner discharge, which is supported by Palko & Yli-Halla (1993) and Rozemeijer *et al.* (2010), who compared the water qualities when discharged through subsurface pipes and open ditches. When CS and CD were combined, groundwater outflow and drain discharge were both reduced compared with the reference scenario S1, but this led to increased topsoil layer runoff, which has reported to increase erosion and phosphorus leaching (Ekholm *et al.* 2005).

The reductions in total runoff were accompanied by an increase in ET. The increase was largest during the driest year, which is in line with Sojka *et al.* (2020). This supports the idea that controlled drainage can be used to mitigate drought risks. The limiting effect of too much soil moisture on transpiration was not included in our model.

4.3. The model setup and uncertainties

FLUSH was chosen as the model because of its previous applications in high-latitude conditions and its spatially distributed description of field hydrology. While this exact model setup has not been validated against field observations, Salo *et al.* (2021) calibrated and validated the soil parameters using a similar model setup with observations made under conventional subsurface drainage. Their performance metrics can be found in Tables S2 and S3 of the supplementary material. Salo *et al.* (2021) concluded the model performance to be moderate but acceptable for running hypothetical drainage scenarios. In this study, the model was modified by changing the groundwater outflow path from deep subsurface drainpipes to an open ditch. Simulation models are not complete descriptions of physical reality, and thus, any selected soil parameters should not be considered as 'true' independently of the model setup that was used to calibrate and validate them. However, we consider the soil parameterization by Salo *et al.* (2021) to be a plausible description of the Sievi field and our model setup to be suitable for running hypothetical drainage scenarios and increasing the understanding of water management in the Nordic agricultural fields.

The selection of lateral flow boundary conditions at the edges of the simulated area can have a strong impact on the field water balance. Liu & Gupta (2007) listed system boundaries as one of the main sources of uncertainty in hydrological modeling. In this study, an impermeable condition was selected, which assumes that the hydraulic head is equal on both sides of the boundary. If the model generated lateral groundwater outflow through the boundaries during drainage control, this would likely lead to decreased effects on groundwater levels and increased effects on discharge through drainpipes and the ditch.

Similar impermeable boundary conditions at the bottom and sides of a 2D model were earlier used by Häggblom *et al.* (2019). Another way to compute groundwater outflow through the boundaries is to use soil surface gradient as a proxy for hydraulic gradient (Turunen *et al.* 2013). However, in flat areas, such as the Sievi field, this would closely resemble an impermeable boundary condition.

In this study, CS and CD were implemented to describe their theoretical maximum effect by assuming similar control of all drainpipes, a constant water level in the ditch, and the continuous control for the simulation period. In reality, field slope decreases the effect of control in drainpipes further from the control well, water level in a ditch is often lowered by evaporation and seepage, and control is typically scheduled according to the crop cycle and hydrological conditions, which would likely lead to lower effects of controlled drainage on WTDs and runoff.

5. CONCLUSIONS

The current simulation study examined the computational effects of two different controlled drainage methods on WTDs, annual water balance, and runoff outflow pathways of a flat loamy field in Nordic conditions. The simulations showed that the collector ditch affected WTDs in a flat field up to 200 m away from the ditch. The open collector ditch drained efficiently the part of the field closest to the ditch. The performance of the CS in the field is affected by the open collector ditch: the groundwater table depth within the field was spatially more uniform when water level in the collector ditch was also controlled with damming.

All controlled drainage methods maintained WTDs closer to the soil surface compared with the free drainage scenario. However, none of the controlled drainage options were able to maintain WTD at the optimal range across the field during the growing seasons, because the weather conditions dominated the field hydrology. During wet conditions, controlled drainage elevates the water table too much, while during dry periods, controlled drainage cannot be the only solution to replace missing water demand.

Controlled drainage options altered the water outflow volumes through discharge pathways. Controlling subsurface drainage decreased drain discharge and increased groundwater outflow, while the damming of open ditches alone had an opposite effect. All control methods increased ET and the relative increase was the highest during a dry year. The soil macropores domain showed a fast response to controlled drainage, and the response in terms of WTD changes was more extreme than in the soil matrix.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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