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Analysing hydrological impacts of controlled drainage, peat thickness and groundwater fluxes in cultivated peat soils

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ABSTRACT
This study analysed the effects of controlled drainage, peat layer thickness and hydrological connections on the hydrology of agricultural peatlands. A hydrological model was combined with a comprehensive field-scale dataset, consisting of several field plots with controlled and regular subsurface drainage, and with varying peat thickness. Controlled drainage markedly reduced the amount of drain discharge (up to 862 mm) during the 1.5-year simulation period, while the consequent increase in groundwater levels was modest (mean difference 0.01–0.17 and 0.10–0.21 m in thin and thick peat, respectively). Thus, controlled drainage can change flow routes, and the impact on the groundwater table can depend on the related groundwater out- and influxes. Controlled subsurface drainage had a higher potential to increase groundwater levels in areas with thick peat soils and steep upslope than in areas with a shallow peat layer and steep downslope areas. If the soils are drained efficiently during the spring, controlled drainage cannot increase groundwater levels during the following growing season if the amount of evapotranspiration exceeds the amount of precipitation and influxes. The model application complemented the knowledge gained from the empirical data. Furthermore, our analysis shows knowledge gaps regarding the hydrology of agricultural peatlands.

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Subsurface drainage; peatland; agricultural water management; lateral flow

Introduction

Dynamics and distribution of soil moisture and groundwater table levels within agricultural peat soils have implications for greenhouse gas fluxes, environmental loads, crop productivity and farming operations (e.g. Kløve et al. 2017; Evans et al. 2021). Knowledge of sustainable peat soil management and related water management procedures still has important knowledge gaps (Thorsøe et al. 2023). Soil moisture variability is controlled by environmental and anthropogenic factors, including hydrometeorological conditions, catchment characteristics and soil properties, as previously demonstrated in organic and mineral soils (Turunen et al. 2015; Jaros et al. 2019; Mahmood et al. 2023; Salla et al. 2024). Removing excess water from the fields with proper drainage practices is necessary for conventional crop cultivation in peatlands in high-latitude conditions. Conventionally, drainage is conducted with subsurface drain pipes or open ditches with a constant drainage depth (hereby regular drainage). Compared to regular free drainage practices, controlled drainage provides a more flexible water management method. With controlled subsurface drainage, the moisture and groundwater level dynamics can be actively affected by temporally adjusting the drainage depth (outlet elevation) in control wells. The method is recognised as a potentially efficient practice for controlling the water table, soil moisture and water balance components in agricultural fields with different soils (Wesström et al. 2014; Sunohara et al. 2016; Salo et al. 2021; Salla et al. 2024). However, knowledge of the applicability of controlled drainage to different environmental conditions is still limited. Particularly studies in peat soils with different thicknesses are rare. Regarding peat soils, the thickness of the peat layer can be of particular interest among the controlling variables when the reduction of environmental loads is of interest (Yli-Halla et al. 2022).

The impacts of controlled drainage can also be affected by factors such as the availability of water, hydrological connections and soil hydraulic properties (e.g. Salo et al. 2021; Youssef et al. 2021; Salla et al. 2022; Salla et al. 2024). This means that the field-scale impacts can be spatially variable and dependent on the hydrological processes of the catchment area and characteristics of the surrounding areas (e.g. Turunen et al. 2015; Rozemeijer et al. 2016; Ahmad et al. 2021;

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Mahmood et al. 2023; Salla et al. 2024). However, the hydrological impacts of controlled drainage in peat soils have been clearly less studied than in mineral soils.

While there can be hydrological differences between agricultural fields, there can also be significant hydrological variability within individual experimental fields or plots. This variability can affect and complicate the interpretation of the impacts of controlled drainage. Due to the spatial variability of soil properties (e.g. Hare et al. 2017; Lambert et al. 2022) and other controlling factors, individual point measurements describing soil hydrological processes (e.g. moisture and groundwater level) can be challenging to interpret. For example, even closely located sensors may yield varying values regarding the studied hydrological variables due to the small-scale variability in the location and properties of macropore networks in different soils (e.g. Bouma et al. 1980; Dekker and Ritsema 1996; Weiler 2005; Doležal et al. 2015; Hare et al. 2017). Other factors, such as hysteresis and hydrophobicity, can also induce similar spatiotemporal effects within experimental sites (e.g. Dekker and Ritsema 1996; Naasz et al. 2008; Hewelke et al. 2016). When field-scale hydrological processes and the hydrological impacts of water management procedures (e.g. drainage impacts) are of interest, systemic field-scale analyses can add to the knowledge gained from individual measurements, especially regarding the hydrology of cultivated peat soils, which has been less studied than mineral soils.

Hydrological models provide a method to improve the systemic understanding of hydrological processes, and they complement the knowledge gained from empirical data. Particularly, process-based models, which describe the key hydrological processes and their connections, have the capability to combine different types of data into a single computational framework. Thereby, they can improve the comprehensive understanding of the studied system and disentangle the impacts of different factors on the hydrological processes of the studied site. Previously, such models have been applied in various conditions, including peat soils (e.g. Haahti et al. 2016; Jaros et al. 2019; Mahmood et al. 2023; Salla et al. 2024), but applications in cultivated peat soils with different peat thicknesses and controlled drainage are rare. The models often apply effective parameter values to simplify or average the small-scale variability within the simulated domain, which has often resulted in a reasonable description of the studied variables (e.g. Hansen et al. 2007). However, in peat soils, which have been relatively rarely modelled, it could be beneficial to study the applicability and implications of the simplifications with comprehensive data.

To increase understanding of the controls and drivers affecting the hydrology of drained agricultural peat soils, we combine a process-based 3D hydrological model with a new comprehensive empirical dataset from an experimental site. The aim was to improve systemic understanding of the hydrology of cultivated peatlands by quantifying the hydrological impacts of controlled drainage, peat layer thickness and hydrological connections via groundwater fluxes. The dataset consists of hydrological time series and soil property measurements from several field plots with controlled and regular subsurface drainage installations and varying peat thickness.

Materials and methods

Simulation scenarios were conducted to assess the hydrological impacts of (1) controlled drainage, (2) peat thickness and (3) terrain topography, as summarised in Figure 1 and explained in more detail below.

Experimental site and hydrological time series

The experimental site is located in south-western Finland (WGS84: 60°47′19″, 23°32′41″). The long-term mean annual temperature at the site is about 5.5°C and mean precipitation 620 mm. The landscape around the experimental site is undulating, but the elevation differences in the region are typically modest. The monitored site is surrounded (directly outside the field borders, Figure 2) by coniferous forest (mainly spruce), which is typical in the area. While the site consists of 12 monitored field plots, the current study focused on eight plots that had regular and controlled subsurface drainage installations (Figure 2). The areas of each of these plots were approximately 0.5 ha (Figure 2). The monitored plots had a flat topography (slope <1%), and the soil surface in the adjacent forested areas typically had higher elevation than the monitored plots. In Finnish conditions, the thickness of drained agricultural peatlands reduces annually by an average 0.012 m (Räsänen et al. 2023), which likely explains part of the elevation difference. The forest areas were drained with sparsely located shallow open ditches. The experimental site is surrounded by open ditches that connect to the open ditch network of the catchment.

At the monitored site, the peat thickness gradually increases from approximately 0.4 m on the western side of the site to ≥1.2 m in the eastern parts of the site. The average peat thickness was 0.4–0.6 m at plots 1, 2, 5 and 6 while the plots 3, 4, 7 and 8 had a mean peat thickness of 1.2 m (Figure 2). The peat layers (fen peat) were underlain by clayey soils, which are typical in the region (Yli-Halla and Mokma 2001). The clayey

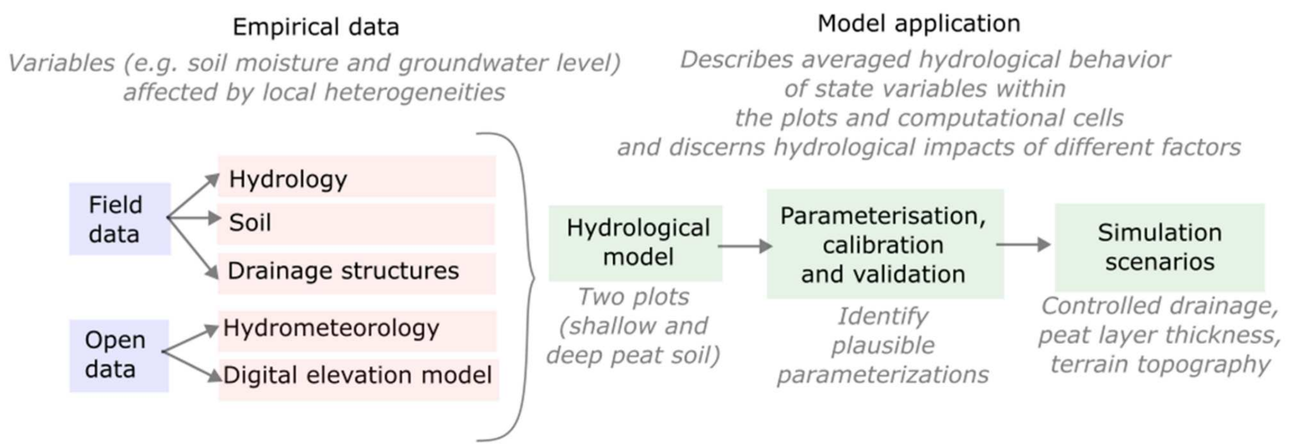

Figure 1. Schematic overview of the study approach and key materials and methods.

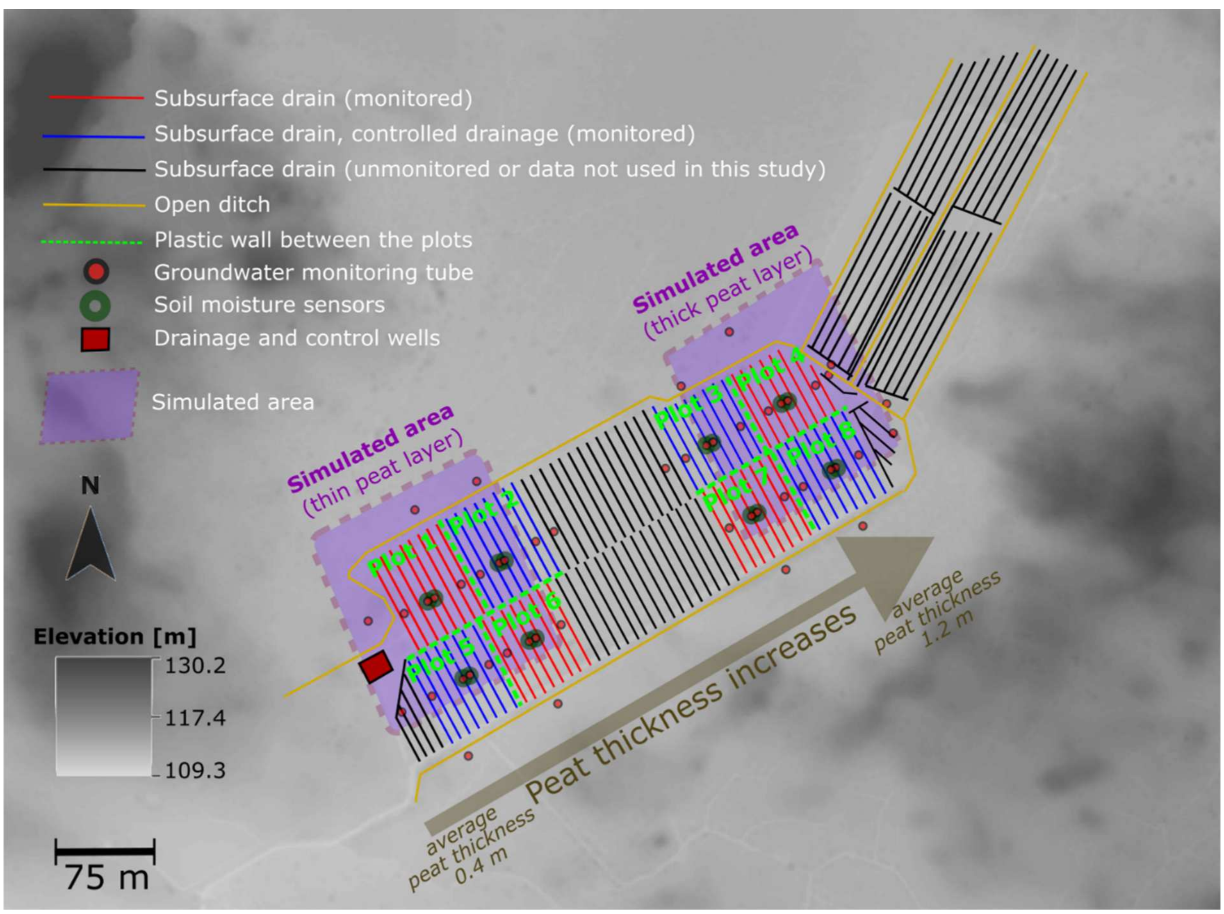

Figure 2. Layout of the experimental site, drainage structures, hydrological measurement devices and the topography.

soils had an average clay content of 30% at the topmost layers and gradually reached 85% after a depth of 0.9 m. Based on the thickness of the organic layers, the soils fit well within many definitions of peat and organic soils (e.g. Hammond 1979; De Bakker and Schelling 1989; Soil Classification Working Group 1998; Soil Survey Staff 1999; IUSS Working Group WRB 2022). While the field has been in agricultural use for decades, the monitoring campaign was initiated in 2021. The aim of the campaign was to produce information on the hydrology of agricultural fields with thin and thick peat soils, with and without controlled subsurface drainage. During the time of the study (Aug 2021–Feb 2023), grass (timothy and meadow fescue) with a small amount of barley was cultivated at the plots (sowing 23–30 June and harvest 18–22 September).

Before the measurement campaign, the field plots had shallow and poorly functioning subsurface drains at a depth of 0.6–0.7 m with a drain spacing of 22 m. New plastic subdrains were installed in summer (July–August) 2020 at a depth of 1.1–1.2 m and a drain spacing of 8 m (Figure 2). That is, the drainpipes were situated either in the peat soil (plots 3, 4, 7 and 8) or the underlying clay soil (plots 1, 2, 5 and 6), depending on the peat thickness at the location of the pipe. Four field plots (plots 2, 3, 5 and 8) had controlled drainage while plots 1, 4, 6 and 7 were under regular subsurface drainage (free gravitational drainage with a constant drainage depth). The drains had an inner diameter of 0.05 m. About 0.2 m of gravel was used as the drain envelope material. The old shallow drains were broken during the installation of the new drains. During the installation of the new drains, it was noted that there was seepage of water from the soil to the new installation trenches in spatially variable locations.

Subsurface collector pipes (watertight) conveyed the water from the drains to the wells (Figure 2), where the subsurface drain discharge was monitored (separately from each field plot). That is, the flow direction from the subsurface drains is towards the drainage and control wells (Figure 2). The flow direction of the open ditches is from northeast to southwest (Figure 2). In the wells, the drain discharges were monitored with v-notch weirs, based on water level readings from data loggers (temporal resolution 15 min). Water pumps ensured that the free gravitational discharge occurred through the weir also during periods with high discharge. Regarding the water level readings, we used an uncertainty interval of ±5 mm (based on the estimate from the supplier) to estimate the propagation of uncertainties (e.g. possible occasional staining of the sensors) in the discharges.

Impermeable plastic walls from a depth of 0.5 to 1.5–2.0 m were installed (using a tractor excavator) between the plots (Figure 2) to reduce hydrological connectivity and consequently facilitate a more reliable comparison of the hydrological impacts of controlled and regular drainage. The depth of the plastic walls (1.5–2.0 m) was greater than the depth of the surface of the underlying clayey soils (0.4–1.2 m). Therefore, they were considered efficient in reducing the hydrological connectivity between the experimental plots. The walls were located between the collector pipes and the drains.

From each plot, soil moisture and groundwater levels were monitored from 2 and 4 different horizontal locations, respectively (Figure 2) (from August 2021 onwards) with a temporal resolution of 3 h. Soil moisture was measured from 3 different depths (0.1, 0.3 and 0.5 m) in the two locations (Figure 2) within each plot using frequency domain reflectometry (FDR) sensors (Masinotek Ltd, Vihti, Finland). Groundwater levels were observed with pressure sensors from observation tubes located within the plots, and pipes were also installed outside the plots (Figure 2) to provide information related to the possible impacts of the surrounding areas on the hydrology of the monitored plots. Hydrometeorological variables were measured at an adjacent observatory of the Finnish Meteorological Institute.

Hydraulic property measurements in peat and clay

Water retention curves were measured from four different locations (plots 1, 4, 6 and 7). The samples (height 48 mm and diameter 72 mm) were collected from six different depths (0.15, 0.3, 0.45, 0.65, 0.95 and 1.25 m) at each location, and four replicates were taken from each depth. Thus, depending on the peat thickness and sampling depth, the samples were taken from the peat or the underlying clay soil. The water retention curves were measured as drying curves (suctions 0.01, 0.1, 0.3, 1.0, 3.0, 10.0, 30.0 and 150 m) with the sandbox apparatus (suction of 0.01–0.1 m; Eijkelkamp, the Netherlands), ceramic plates in a pressure extractor (0.3–30 m; Soilmoisture Equipment Corp., USA), and vapour pressure equilibrium with saturated ammonium oxalate (150 m).

Sample collection for determining soil vertical saturated hydraulic conductivity (K_{sat}) was conducted in June 2015 from one location (plot 4). Undisturbed sample rings (height 60 mm and diameter 72 mm) were collected from the depths of 0.13–0.25, 0.25–0.47, 0.47–0.7 and 0.7–1.0 m. Six replicates were taken from each depth. Thus, the measurements describe local peat soil properties and variability, even though they may not entirely describe variability within the whole experimental site, as the measurements were conducted only in one location. K_{sat} was determined in the laboratory by evaporation experiments and subsequent inverse modelling according to Dettmann et al. (2019). All samples were collected from pits, which were excavated manually or with a tractor excavator.

Following the evaporation experiments, samples were dried at 105°C and weighed in order to determine bulk density, which was found to be 0.32 g cm^{-3} at the topsoil (depth 0.13–0.25 m) and 0.14–0.18 g cm^{-3} at the deeper soil layers (0.25–1.0 m). Simultaneously, multiple disturbed samples were collected from each of the depths to determine the degree of decomposition (von Post) and total soil organic carbon content (TOC). Following the von Post classification (Ad-Hoc-AG Boden 2005), horizons were identified as H10, H4, H6 and H7 at the different depths, respectively. TOC contents were measured by dry combustion at 400°C (RC 612, LECO Corporation, St. Joseph, USA), ranging from 0.46 to 0.51 g/g. Loss of ignition (plot 4, depth 0–1 m) was on average 0.87 g/g, ranging from 0.72 to 0.94. The high TOC contents and LOI also confirm that the soil of the experimental field consists of organic or peat soil material according to international and Finnish soil classification systems (Haavisto 1983; Soil Survey Staff 1999; IUSS Working Group WRB 2022).

Hydrological model

A dynamic process-based 3D hydrological model, written in the C++ programming language, was used to integrate the empirical data and to describe the field hydrology. The numerical solution is described in Tähtikarhu and Okkonen (2023), and the model is largely based on previous modelling studies (e.g. Šimůnek et al. 2008; Warsta et al. 2013; Laine-Kaulio et al. 2014). The model takes hydrometeorological time series (precipitation, potential evapotranspiration and air temperature) as input and describes the key hydrological processes of the modelled area. The purpose of the model is to describe the temporal variation of key hydrological variables, including soil moisture, groundwater level and outflow components. Soil water flow in 3D and overland water flow in 2D were computed with Richards' and Saint-Venant equations, respectively. Thus, the water flow is controlled by soil hydraulic properties (water retention parameters and K_{sat}) as well as differences in the hydraulic pressure heads and elevation differences. Water retention and unsaturated hydraulic conductivity are described with the van Genuchten (1980) model (hereafter VG model). Overland flow can occur in the model when the infiltration capacity is exceeded, and the flow is controlled by the water level on the soil surface, soil surface elevation differences and roughness parameters (Manning's *n*). Snow accumulation and melt are described with a degree-day approach (see Tähtikarhu and Okkonen 2023). Conceptually, the model is described in Figure 3.

While the same numerical approach has been previously used for modelling groundwater hydrology (Tähtikarhu and Okkonen 2023), in the current study we also included descriptions for subsurface drainage and drainage by open ditches. These drainage structures were described as sink terms in the numerical solution. The location of the sinks in the computational grid was set according to the location of the drainage lines in the experimental site (horizontal location and depth from the soil surface). The fluxes to the drainage structures (e.g. subsurface drain pipes) were computed with Darcy's law when the simulated groundwater level was above the given drainage depth in a computational cell containing a sink term. This means that the water flux to subsurface drain pipes and open ditches is controlled by a drainage resistance parameter and hydraulic head in the cell containing a segment of the drain or ditch lines (e.g. Warsta et al. 2013). A similar solution has been previously used in the FLUSH model (e.g. Warsta et al. 2013).

Regarding the drainage-related sink terms, controlled drainage (regarding the subsurface drain pipes) was also considered in the current study. Controlled drainage was simulated by setting the drainage depth in the simulations according to a given (input) drainage control time series. That is, without controlled drainage, the subsurface pipe drainage depth was set according to the depth of the pipes. When controlled drainage was used in the field, the drainage depth was set according to the outlet elevation in the control well (e.g. Salo et al. 2021; Salla et al. 2022).

Since the drainage depth of open ditches can be affected by temporally varying water levels in the ditches, their drainage depth was set according to the ditch depth and thereafter temporally adjusted during each time step by subtracting the water level in the ditch from the ditch depth. The water level in the ditch was set according to the measured groundwater level at the adjacent monitoring pipe. Note that the open ditches were not under any controlled drainage measures as such (i.e. the water level was not actively adjusted at the experimental site, but the water level emerged due to seepage processes). The computational scheme is a simplification that was considered reasonable since, according to our preliminary simulations, the impacts of the open ditch scheme on the hydrology of the monitored areas were minor.

Regarding boundary conditions, the bottom of the computational domain was set to have no flow. The top of the domain was set to have a system-dependent boundary controlled by infiltration into the domain, as shown in Figure 3. The infiltration into the soil was controlled by the water level on the soil surface, as well as the pressure head and hydraulic conductivity at the topmost grid cell (see Tähtikarhu and Okkonen 2023). The hydraulic heads at the horizontal grid boundaries were set to the values given by measured time series (groundwater level observations in the vicinity of the boundaries).

At the location of the impermeable plastic walls (which prevented horizontal flow of water between

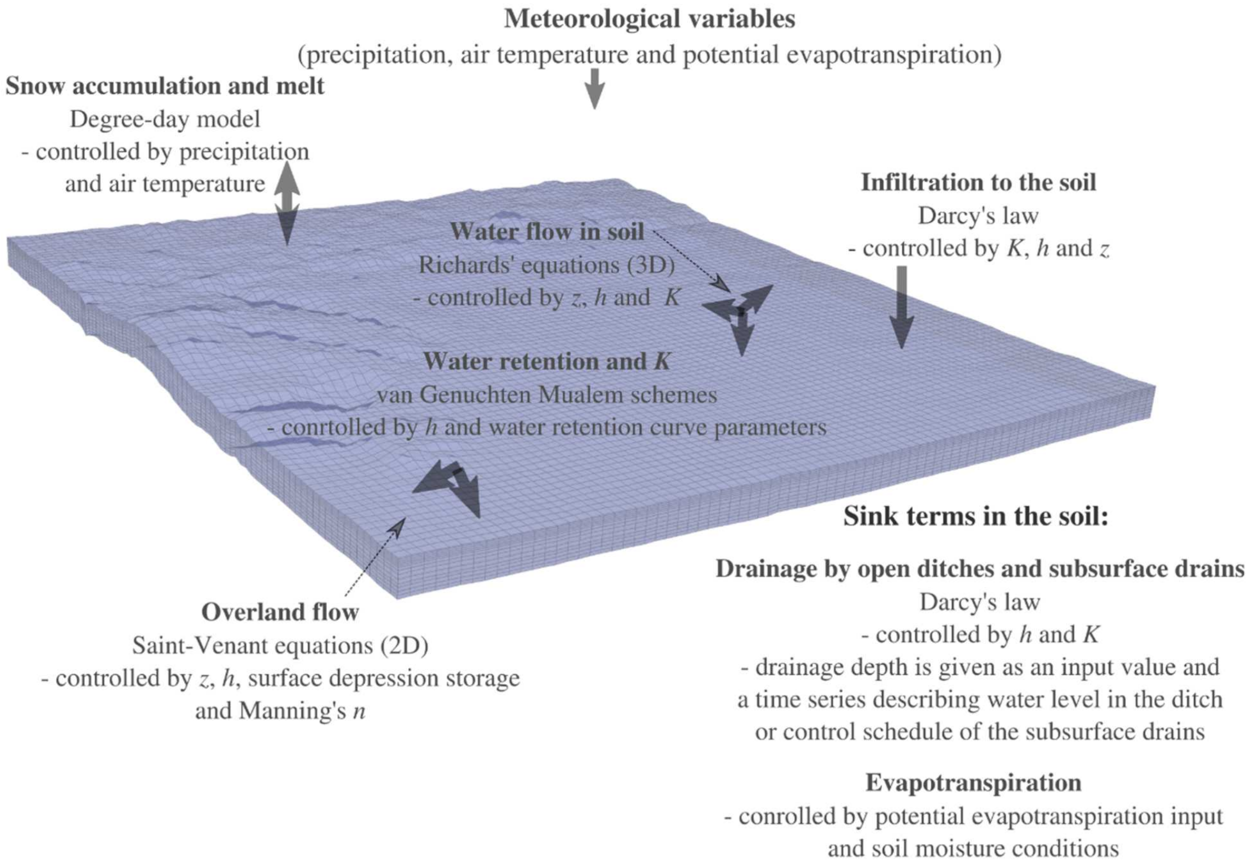

Figure 3. Dominant variables, processes and governing equations in the applied model. K = hydraulic conductivity, h = hydraulic pressure head and z = elevation.

adjacent plots, Figure 2), a no-flow condition (hydraulic conductivity zero) was set between those horizontally adjacent computational cells where the walls were located.

Computational grid, soil parameterisation and model calibration and validation

We delineated two areas from the experimental site to describe the hydrology of two field plots with (1) a thin (peat layer thickness 0.4 m) and (2) a thick (thickness 1.25 m) peat soil. The delineation is presented in Figure 2 and was considered reasonable since the water levels at the domain borders were set according to the measured groundwater levels in the adjacent locations.

Elevation differences within the simulated domain were described with the digital elevation model (DEM) of the National Land Survey of Finland (2020), which is based on aerial laser scanning and has a resolution of 2×2 m^2. The horizontal resolution was also 2×2 m^2 in the model application. Vertical soil layers were set to gradually increase from 0.05 m (at the top of the grid) to 0.2 m (at the bottom, Figure 3). Thicker layers at the bottom reduced the computational times. Moreover, the larger layers at the bottom were considered appropriate as the layers were mostly saturated during the study period, and for example more detailed information regarding the moisture of the deepest soil layers was not considered interesting. The locations of the subsurface drains and shallow open ditches were set according to their locations at the site (Figure 2).

Water retention parameters were derived by fitting the VG model (van Genuchten 1980) to the measured water retention curve measurements. However, due to the shape of the curves (Figure 4), the model did not reasonably fit the observations, which also consequently induced non-convergence of our preliminary simulations. Note that typically the shape of water retention curves in drained agricultural peat soils differs from those of pristine peatlands (Menberu et al. 2021), and the water retention properties are rarely measured up to the wilting point (suction of 150 m). The VG model is designed particularly for S-shaped curves, which explains the non-commensurability. It was also noted that our water retention curves differed from measured drainage-induced moisture reductions (the soil moisture reductions caused by drainage were identified by analysing moisture reductions during frost-free time

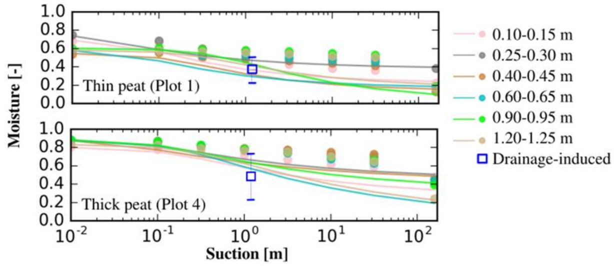

Figure 4. Measured (circles) and modelled (lines) water retention curves (6 different depths) and plot-scale drainage-induced moisture reductions (observed moisture reductions during frost-free seasons when evapotranspiration was minimal) in plots 1 and 4 of the experimental site. The whiskers show the standard deviation and the squares show the means.

Table 1. The water retention parameters (van Genuchten 1980 model) at the different depths from the soil surface in the two simulated domains. Peat parameters are denoted in bold font.

	Thin peat				Thick peat			
Depth [m]	θ_r [–]	θ_s [–]	α [m^{-1}]	n	θ_r [–]	θ_s [–]	α [m^{-1}]	n
0–0.15	**0.22**	**0.71**	**19.4**	**1.4**	**0.21**	**0.80**	**6.9**	**1.2**
0.15–0.35	**0.38**	**0.78**	**60.4**	**1.3**	**0.44**	**0.89**	**12.4**	**1.3**
0.35–0.55	0.13	0.55	6.6	1.4	**0.41**	**0.89**	**31.1**	**1.2**
0.55–0.75	0.17	0.59	18.3	1.4	**0.00**	**0.88**	**5.5**	**1.2**
0.75–1.25	0.01	0.60	1.8	1.3	**0.34**	**0.89**	**8.0**	**1.3**
1.25–2.20	0.14	0.58	3.5	1.4	**0**	**0.83**	**3.4**	**1.2**

θ_s = saturated water content.
θ_r = residual water content.
α = parameter of the van Genuchten (1980) model, estimated on the basis of water retention characteristics.
n = parameter of the van Genuchten (1980) model, estimated on the basis of water retention characteristics.

periods when evapotranspiration was minimal) found in the field-scale soil moisture time series. Therefore, we fit the VG model using the observations in the suctions ≤30 m and thereafter adjusted the curves with three goals: (1) to reflect the measured drainage-induced moisture reductions, (2) to reflect the observed water retention curves and (3) to enhance model convergence. The adjustment was conducted by gradually increasing the *n* parameter of the VG model, which resulted in a 15% (peat soils) and 30% (clay) increase in their values in the adjustment (compared to the original non-adjusted curves). The resulting water retention curves are shown in Figure 4 and listed in Table 1. It was assumed that the adjustment reflects hydrophobicity and hysteresis in the water retention properties (e.g. Rasa et al. 2007; Naasz et al. 2008) and, on the other hand, provided a technical solution to use the benchmark VG model. It is also recognised that the adjustment is a rough simplification, and the plausibility of the model was assessed by comparing the simulated values with the field-scale time series (model calibration and validation).

The model was thereafter calibrated with a multi-objective optimisation approach against the groundwater level, soil moisture and drain discharge time series. The main interest was in groundwater levels and soil moisture values, while the drain discharge accumulations were used to inform the model about the water balance. The calibrated variables were K_{sat} for four different soil layers, drainage resistance and an anisotropy coefficient (ratio of horizontal to vertical K_{sat}). The calibration period was 2 August 2021–22 November 2021. The validation period was 23 November 2021–20 February 2023. The calibration was conducted with the Latin Hypercube Monte Carlo (LHMC) approach (e.g. Yu et al. 2001) using the prior parameter ranges shown in Table 2. The prior ranges for the K_{sat} values for the peat and underlying mineral soil layers were derived from the measurements (median ± standard deviation) and literature (Warsta et al. 2013), respectively. Regarding K_{sat} of the topmost soil layers, the K_{sat} was given a relatively large range based on previous simulation studies in peat soil (Haahti et al. 2016; Laurén et al. 2021). The lowermost soil layers were given low K_{sat} ranges (e.g. Turunen et al. 2013; Warsta et al. 2013). For the drainage resistance parameter, the range was set based on previous drainage simulation studies (Turunen et al. 2013; Warsta et al. 2013) to 2.0–10.0 m. For the coefficient of anisotropy, we sampled a relatively wide range (0.05–2.0) since there was no clear knowledge about the degree of anisotropy. All parameters were given uniform distributions in the LHMC sampling. The plausibility of the assumptions was assessed with the comparison of the simulation results with the observed time series.

The model performance indicator *I* (describing the degree of correspondence with the simulations and the data) was set following the limits of acceptability approach (e.g. Beven 2006; Liu et al. 2009) and a simple binary weighing function:

$$I(\Theta,\ X,\ t) = \begin{cases} 1, & M_{\min}(X,\ t) < S(\Theta,\ X,\ t) < M_{\max}(X,\ t) \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

Table 2. The prior ranges (based on the measurements in peat and literature regarding clay, topsoil and bottommost soil) of the saturated vertical soil hydraulic conductivities (K_{sat}) at the different depths from the soil surface.

Depth [m]	Thin peat K_{sat} [m h^{-1}]	Thick peat K_{sat} [m h^{-1}]
0–0.45	**0.05–6.00 (3.4–4.3)**	**0.05–6.00 (0.5–4.5)**
0.45–0.75	0.001–0.1 (0.04–0.08)	**0.01–0.32 (0.06–0.19)**
0.75–1.25	0.001–0.1 (0.06–0.10)	**0.02–0.48 (0.05–0.07)**
1.25–2.2	0.001–0.02 (0.007–0.018)	**0.001–0.02 (0.001–0.019)**

The posterior ranges (based on the inverse modelling approach) are given in parentheses. Peat parameters are denoted in bold font.

where $M(X, t)$ is a measured variable of measurement X (e.g. soil moisture or groundwater level) and time t. $S(\Theta, X, t)$ is the corresponding simulated variable with parameter set Θ. M_{min} and M_{max} were set according to the minimum and maximum values of the measurement. That is, the binary performance indicator described whether the simulated values reside within the acceptability limits. The soil moisture measurements from the two locations and three depths within both simulated field plots were pooled for the computation of the performance indicator. That is, the indicator describes whether the simulated values from the depths 0.1–0.5 m are within the measured range from the depths 0.1–0.5 m (instead of comparing the simulated and observed values separately for each soil depth). The indicator was considered to reasonably consider subgrid variability in point measurements (groundwater levels and soil moistures) and uncertainty interval in the drain discharge measurements.

Based on Equation (1), the performance indicator values I_x for each measurement were calculated as:

$$I_X(\Theta, X) = \frac{1}{n}\sum_{i=1}^{n}(W_X\, I(\Theta, X, t_i)) \quad (2)$$

where n is the number of time steps and W is a dimensionless weighing coefficient. Aggregated performance indicator (I_a) was thereafter computed as the average of the three I_x values. Each W was set based on the number of simulated time series. That is, W values were $\frac{1}{6}$, $\frac{1}{4}$ and 1 for soil moisture (two locations and three depths), groundwater level (four locations) and drain discharge, respectively. Thus, the W values balance the weight of the different optimisation targets, and I_a can range between 0 and 1.0. The performance indicator describes the weighted share of simulation results that are within the acceptability limits.

Behavioural (acceptable) simulations were thereafter chosen based on their performance rank. That is, we (1) ran 105 simulations with the LHMC approach, (2) computed I_a values for each parameterisation and finally (3) chose the three best-performing simulations based on their I_a rank. 105 was considered a reasonable number of runs to sample the parameter space and to produce plausible parameterizations (e.g. Christiaens and Feyen 2002; Haahti et al. 2016). The calibration scheme follows the GLUE framework (e.g. Beven 2006) but model predictions are equally weighted (e.g. Steffens et al. 2013).

Simulation scenarios

Three different simulation scenarios were conducted with the behavioural model realizations (3 parameterizations for both thin and thick peat soil). The scenarios were conducted to assess the hydrological impacts of (1) controlled drainage, (2) peat thickness and (3) terrain topography.

In the controlled drainage scenario, the drainage depth was changed dynamically according to the drainage control schedule at the site. The plausibility of the simulations was estimated by comparing the simulated change in groundwater depth, soil moisture and drain discharge with the corresponding observed difference between the plots with controlled drainage and regular drainage. Regarding the thin peat soils, the observations from plots 1 and 6 were compared with those of 2 and 5 (Figure 2). Regarding the thick peat soil, the observations from plot 4 were compared with those of plot 3 (Figure 2), since there was a systematic difference between groundwater levels of plots 3–4 and 7–8, which would have complicated the straightforward comparisons (even though qualitatively the differences were minor). The parameterisation and simulated area were the same as in model calibration and validation, and only the drainage control schedule was changed in the model in this scenario.

Hydrological impacts of peat thickness were assessed by swapping the soil parameters between the two simulated domains. That is, the simulations in plot 1 (peat layer thickness 0.4 m) were run using the soil hydraulic parameters from plot 4 (peat layer thickness 1.25 m), and vice versa.

The hydrological impacts of the topography surrounding the monitored plots were analysed with two different scenarios related to the DEM (terrain topography scenarios). In the first scenario, the terrain slope of the areas sloping towards the experimental site (north side of the plots) was increased to 0.05 (hereby upslope scenario). In the second scenario, the terrain slope of the areas sloping outwards from the experimental site (west side or east side of plots 1 and 4, respectively) was changed to 0.05 (hereby downslope scenario). It was presumed that the upslope and downslope scenarios can increase or decrease, respectively, the net influx of groundwater to the experimental site.

Results

Model calibration and validation

The multiobjective calibration in the thin and thick peat domain resulted in I_a values of 0.75–0.76 and 0.77–0.80, respectively, for the three behavioural model parameterizations (Table 2), which demonstrates that the simulated values were mostly within the measured ranges (Figure 5). The mean simulated and measured groundwater level (Pearson $r = 0.63–0.73$, $p < 0.01$) and soil moisture ($r = 0.26–0.57$, $p < 0.01$) values also correlated, which demonstrates the correspondence between the timing of the simulated and measured values. However, there were also differences between the measured and simulated values. In the thin peat soil, the simulated groundwater table was often deeper than the observed values (Figure 5a). Note also that there was clearly more variability in the measured soil moisture values than in the simulation results (Figure 5c,d).

The model validation resulted in I_a values of 0.38–0.53. That is, the performance was comparable but weaker than during calibration. Note also that during the frost period, the measured liquid share of soil moisture dropped, and the process was not described by the model (Figure 5c–d). After the frost period, the simulated and measured mean soil moisture values clearly differed in the thick peat soil (Figure 5c–d). This demonstrated how soil frost can affect the distribution of soil moisture during winter periods. Note also that in the thin peat soil, the simulated amount of drain discharge during snowmelt was lower than the measured amount (Figure 5e). Overall, the amount of drain discharge (simulated and measured) was clearly higher in the thin than in the thick peat soil (Figure 5e–f). For reference, the amount of precipitation was 1031 mm during the calibration-validation period.

Hydrological impacts of controlled drainage

The simulated controlled drainage impact on groundwater depth (mean decrease of 0.17–0.21 m compared to regular drainage) was of the same order of magnitude but higher than the measured impact (mean decrease of 0.01–0.10 m) in the studied plots (Figure 6a–d). The simulations generally overestimated the impact between November 2021 and April 2022 (Figure 6a–d). The simulated controlled drainage impact on soil moisture (mean increase of 4.7–5.8 percentage points) was of the same order of magnitude as the measured impact (mean increase of 2.2–8.5) (Figure 7a–d). Both the measured and simulated groundwater depth and soil moisture impacts were higher in the thick than in the thin peat soil (Figures 6 and 7). During the growing season (May-Sep), the mean moisture and groundwater depth values were practically similar in the plots with regular and controlled drainage (Figures 6 and 7). Both the simulated and measured impacts of controlled drainage were lower during the summer season (June–August) than during the other seasons. Regarding the measurements in the thin peat soil, the differences in groundwater depths were higher between different groundwater tubes within the plots with regular drainage than between the controlled and regular drainage plots (Figure 6b). The measured soil moisture values were clearly more variable than the simulated values (Figure 7).

According to both simulations and measurements, controlled drainage can overall increase the probability of lower groundwater depth and higher soil moisture values compared to regular drainage (Figures 6e–j and 7e–j). The mean simulated impacts (the difference between the controlled drainage scenario and the regular drainage scenario) mostly shared a positive correlation with the corresponding measured impacts ($r = 0.56–0.63$, $p < 0.01$, Figures 6j and Figure 7i–j), with the exception of groundwater depths in the thin peat soil, where the mean measured impact was very small (see Figure 6b and i).

The simulated impact of controlled drainage on the drain discharge accumulations also corresponded with the measured impact (Figure 8a,b). According to the mean of measurements and simulations, controlled drainage reduced the amount of drain discharge by 862 and 457 mm in the thin and thick peat soil, respectively (Figure 8a,b).

Hydrological impacts of peat thickness and terrain topography

In the peat thickness simulation scenarios with regular drainage, the mean groundwater depth was on average 0.02–0.06 m smaller in the thin peat soil compared to the thick peat soil (Figure 9a and c). Drain discharge was 0.31–0.35 m smaller with the thick peat than with the thin peat. Under controlled drainage, the mean groundwater depth was 0.01–0.05 smaller in the thick peat than in the thin peat soils (Figure 9b and d). Overall, the increase in peat thickness decreased groundwater depths quite systematically throughout the simulation period with controlled drainage, with the exception of the early autumns (September-October), when groundwater depths decreased more rapidly in the thin than in the thick peat soils (Figure 9b and d).

The terrain topography scenarios showed how the simulation results were affected by changes in the terrain slope (Figure 9e–h). In the upslope scenario (where the upslope terrain slope was increased to 0.05), the groundwater depth decreased on average by 0.20 m, and drain discharge increased by 0.72 m in the thin peat soil (compared to the simulations with the

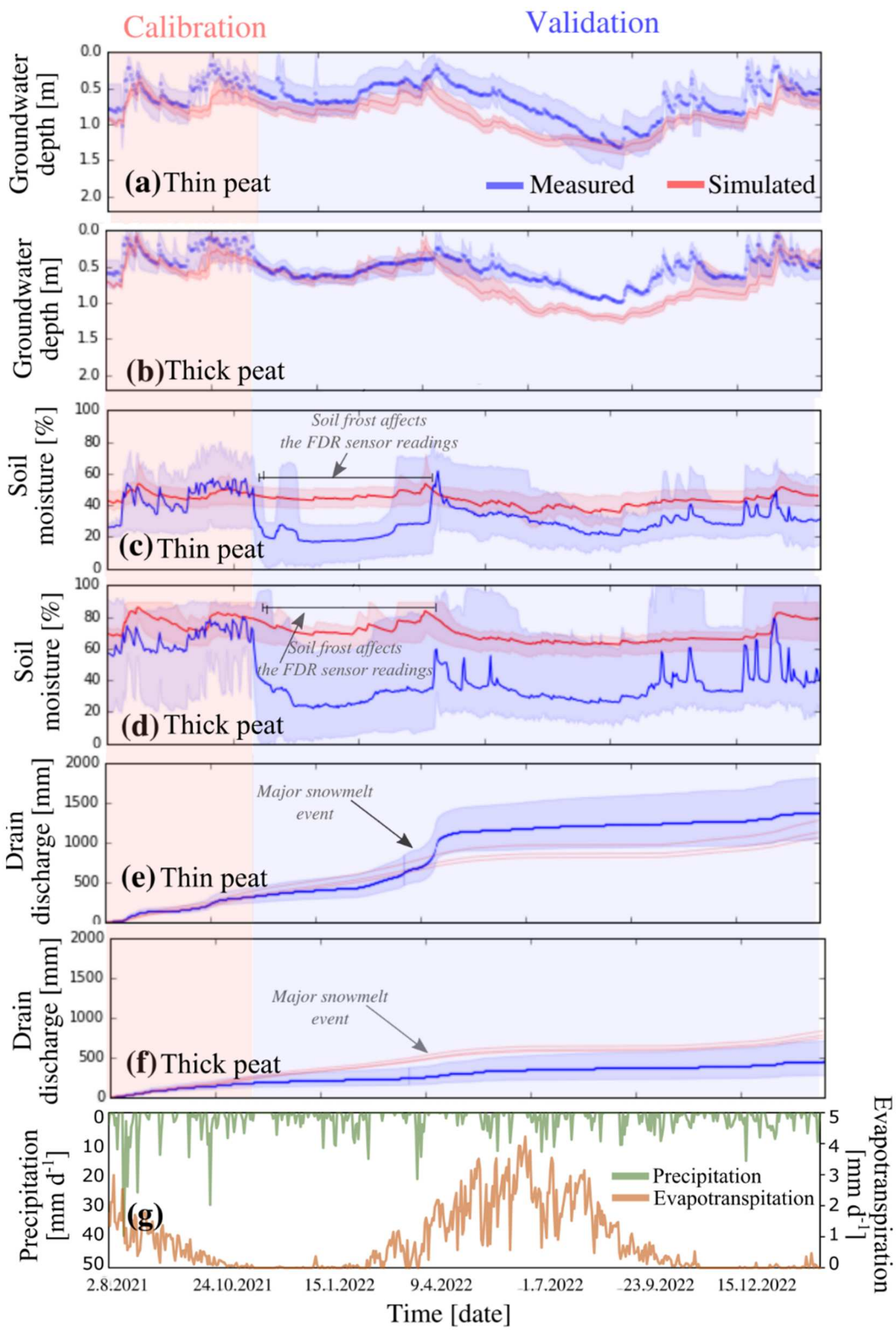

Figure 5. The measured and simulated (a–b) groundwater depths, (c–d) soil moistures (0.1–0.5 m) and (e–f) drain discharges during the calibration and validation periods in the monitored field plot with thin (left) and thick (right) peat soil layers. Precipitation and potential evapotranspiration are shown in g. The lines show the mean, and the envelopes denote the minimum and the maximum.

measured DEM, Figure 9e). In the thick peat soil, the upslope scenario decreased groundwater depth by 0.05 m and increased drain discharge by 0.11 m (Figure 9g). The downslope scenario increased the groundwater depth by 0.15 m and decreased drain discharge by 0.39 m in the thin peat soil. In the thick peat soil, the

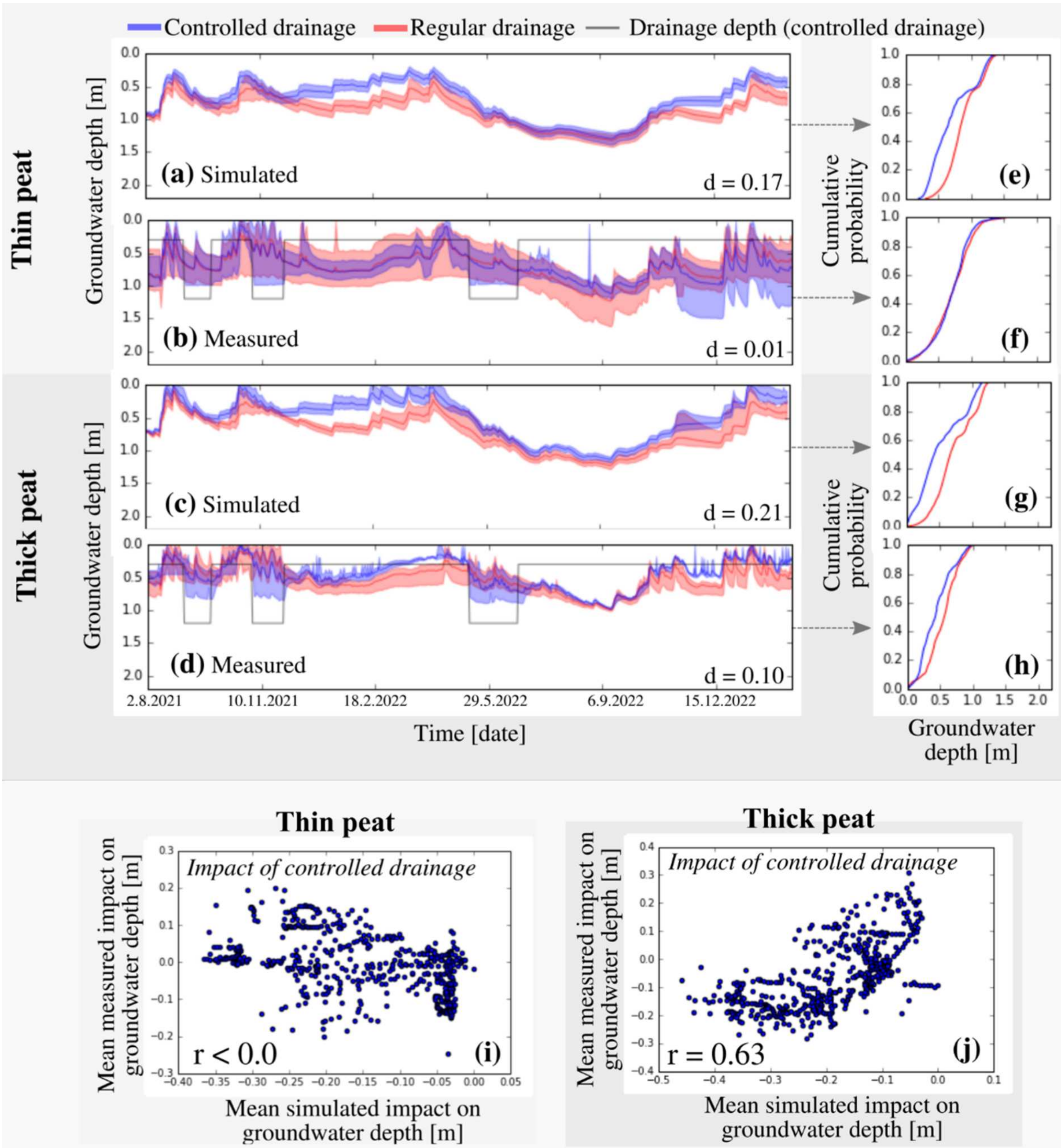

Figure 6. The simulated and measured groundwater depth with controlled and regular drainage in (a–b) thin and (c–d) thick peat soil, the related cumulative probability distributions in (e–f) thin and (g–h) thick peat soils, and (i–j) the relationship between the measured and simulated mean impact of controlled drainage. In a–d, the lines show the mean, and the envelopes denote the minimum and the maximum. The d values denote the mean difference between the groundwater levels in the controlled drainage and regular drainage simulations or measurements. The drainage control time series (corresponding to drainage outlet elevation at the control well) is shown in b and d. Comparison between the control time series and measured groundwater levels demonstrates how close to the control depth (depth of drainage outlet from the soil surface) the groundwater levels were during the study period.

downslope scenario increased groundwater depth by 0.05 m and decreased drain discharge by 0.09 m.

Controlled drainage impacted the groundwater levels in the terrain topography scenarios as follows. In the thin peat soil, groundwater depth was smallest with the steep upslope (mean depth 0.46 m), while the mean depths were 0.70 and 0.89 m with the measured DEM and with the steep downslope terrain, respectively (Figure 9f). Controlled drainage affected groundwater depth more in the upslope (mean decrease 0.22 m) than in the downslope (mean decrease 0.13 m) scenarios (Figure 9f). Regarding thick peat soil, the results were similar but with smaller differences (mean decrease 0.22 and 0.20 m in the up- and downslope scenarios),

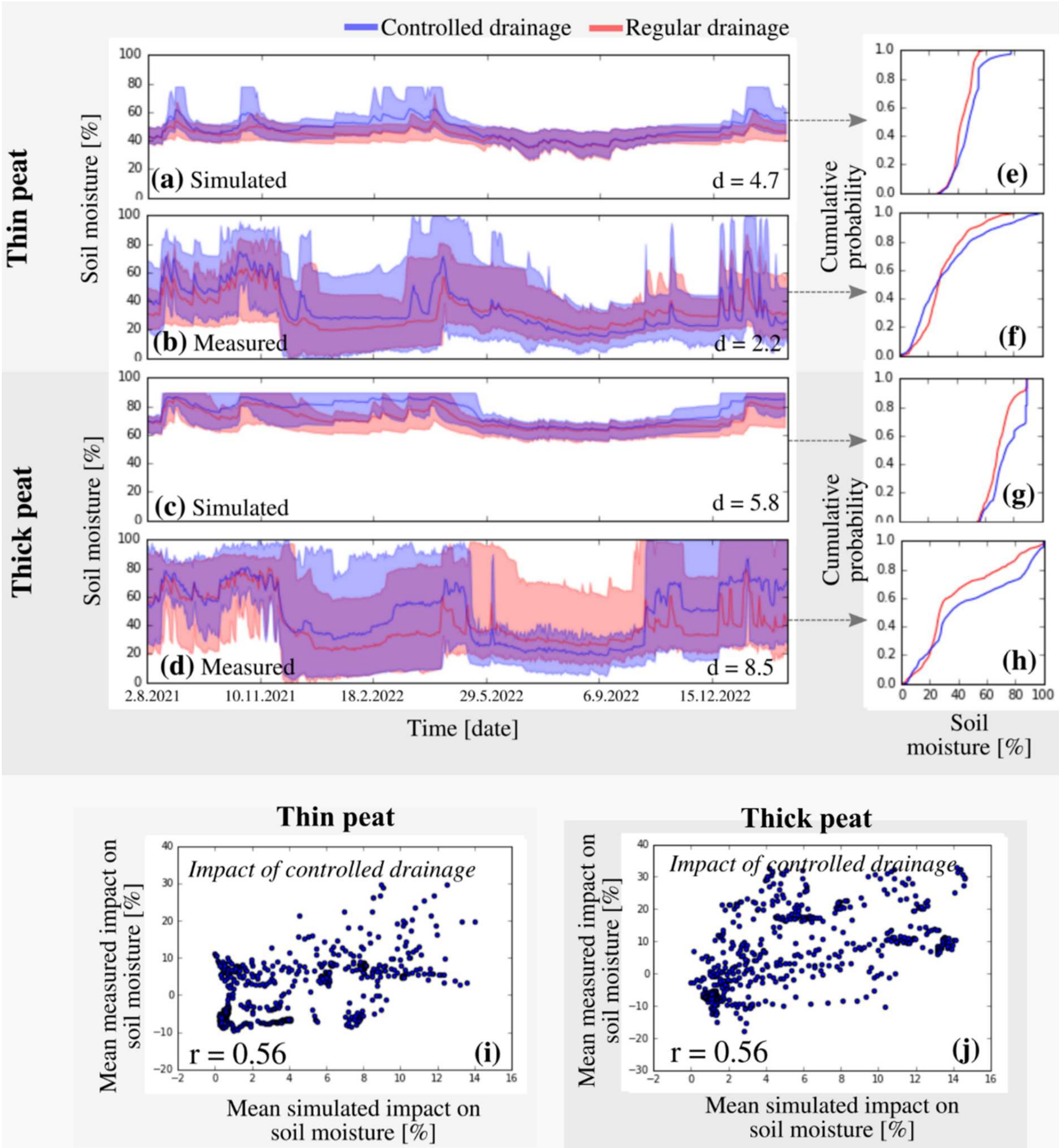

Figure 7. The simulated and measured soil moisture time series (0.1–0.5 m) with controlled and regular drainage in (a–b) thin and (c–d) thick peat soil, the related cumulative probability distributions in (e–f) thin and (g–h) thick peat soils, and (i–j) the relationship between the measured and simulated impact of controlled drainage. In a–d, the lines show the mean, and the envelopes denote the minimum and the maximum. The d values denote the mean difference between the soil moistures in the controlled drainage and regular drainage simulations and measurements.

and the groundwater depth resided closer to the soil surface (mean depth 0.46–0.56 m) than in the thin peat soil (Figure 9h).

Discussion

The results showed how controlled drainage had an impact on groundwater levels, but the measured and simulated impact on groundwater levels (≤0.21 m) was low compared to the adjustment of the drainage depth (0.8 m above the drainage depth of the regular subsurface drainage). The magnitude of the impact is comparable to previously reported results in peat soil (Salla et al. 2024) and silty soil (e.g Salo et al. 2021; Salla et al. 2022). On the other hand, the impact of controlled drainage on the amount of drain discharge can

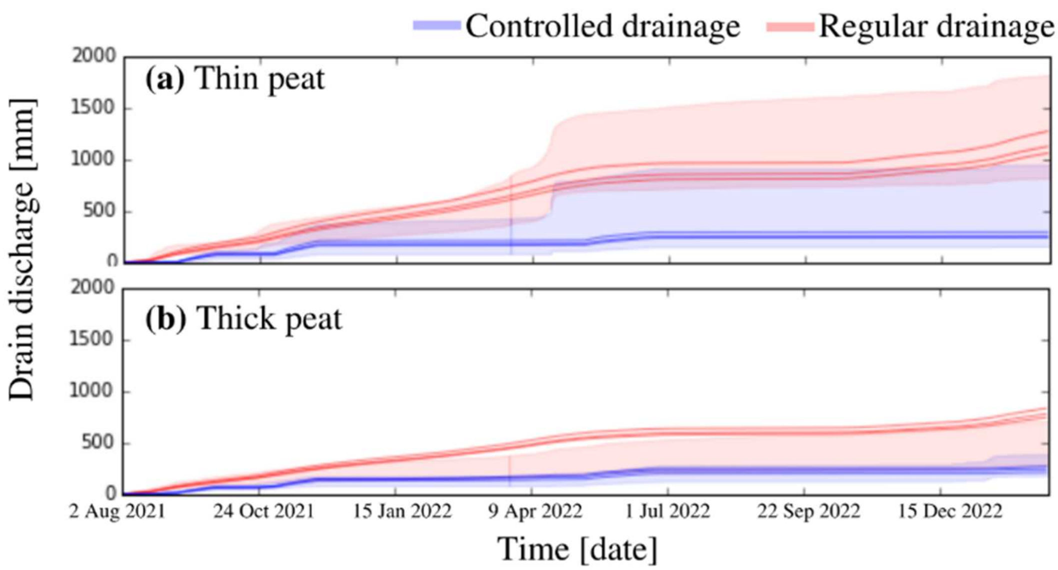

Figure 8. Simulated (lines) and measured (ranges) drain discharge accumulations in the areas with (a) thin and (b) thick peat soil.

be high (Figure 8), which raises the question of why the impact on groundwater tables remains modest. Previous studies have also reported a high impact of controlled drainage on drain discharge (e.g. Salo et al. 2021; Salla et al. 2024). The high impact on drain discharge and relatively low impact on groundwater levels in the current study demonstrate that controlled drainage can change the water flow routes more than the field-scale soil water storages (soil moisture and groundwater levels). That is, when drain discharge decreases due to controlled drainage, it does not necessarily increase groundwater levels but can increase lateral groundwater seepage from the fields. Similar results have also been found in mineral (Liu et al. 2019; Youssef et al. 2021) and peat soils (Salla et al. 2024). Changes in evapotranspiration would not explain the difference, since most of the discharge occurs during the dormant seasons when evapotranspiration is minimal (e.g. Jin and Sands 2003; Turunen et al. 2015). Also, the simulated amount of surface runoff was negligible.

Practically, the impact of controlled drainage on groundwater levels can be counteracted by evapotranspiration during the growing seasons and net groundwater fluxes throughout the years. While evapotranspiration is minimal outside the growing seasons (e.g. Turunen et al. 2015), groundwater fluxes and other flow routes can affect or counteract the drainage control measures also during the dormant seasons. Topography and lateral fluxes are strong drivers of hydrological processes (e.g. McGuire et al. 2005; Maxwell and Condon 2016). Previously, also Youssef et al. (2021) showed how lateral seepage can affect the hydrological implications of controlled drainage in a mineral soil. Recently, also Mahmood et al. (2023) and Turunen et al. (2015) demonstrated how lateral fluxes can affect field-scale drain discharge. Additionally, Quillet et al. (2017) and Bourgault et al. (2019) showed how peatlands can be connected to surrounding hydrological systems. Our study shows the implications of field-scale water management in peat soils with a spatially distributed approach. The benefit of the approach, compared to 1D models or field-scale data, is that it can more comprehensively consider spatially varying features, such as terrain slope variations and locations of drainage lines. The approach is useful, for example, for scenario analyses or disentangling hydrological impacts of different spatial features. Practically, topography and hydraulic gradients can generate groundwater influx, which increases drain discharge and groundwater levels. On the other hand, groundwater seepage from a field can decrease the groundwater levels even during those time periods when evapotranspiration is minimal and the drainage control level is close to the soil surface. In other words, when assessing the hydrological impacts of controlled drainage, the location of a field within a landscape (within the spatial variations of topography, drainage lines, hydrogeological structures and soil characteristics) can be important. In addition to water flow, groundwater fluxes can transport substances. Therefore, environmental load assessments that consider only loads via drain discharge may not comprehensively describe the loads. Regarding the targeting of controlled drainage measures, in our simulations, controlled drainage affected the groundwater depth the most when the groundwater influx to the monitored area was high

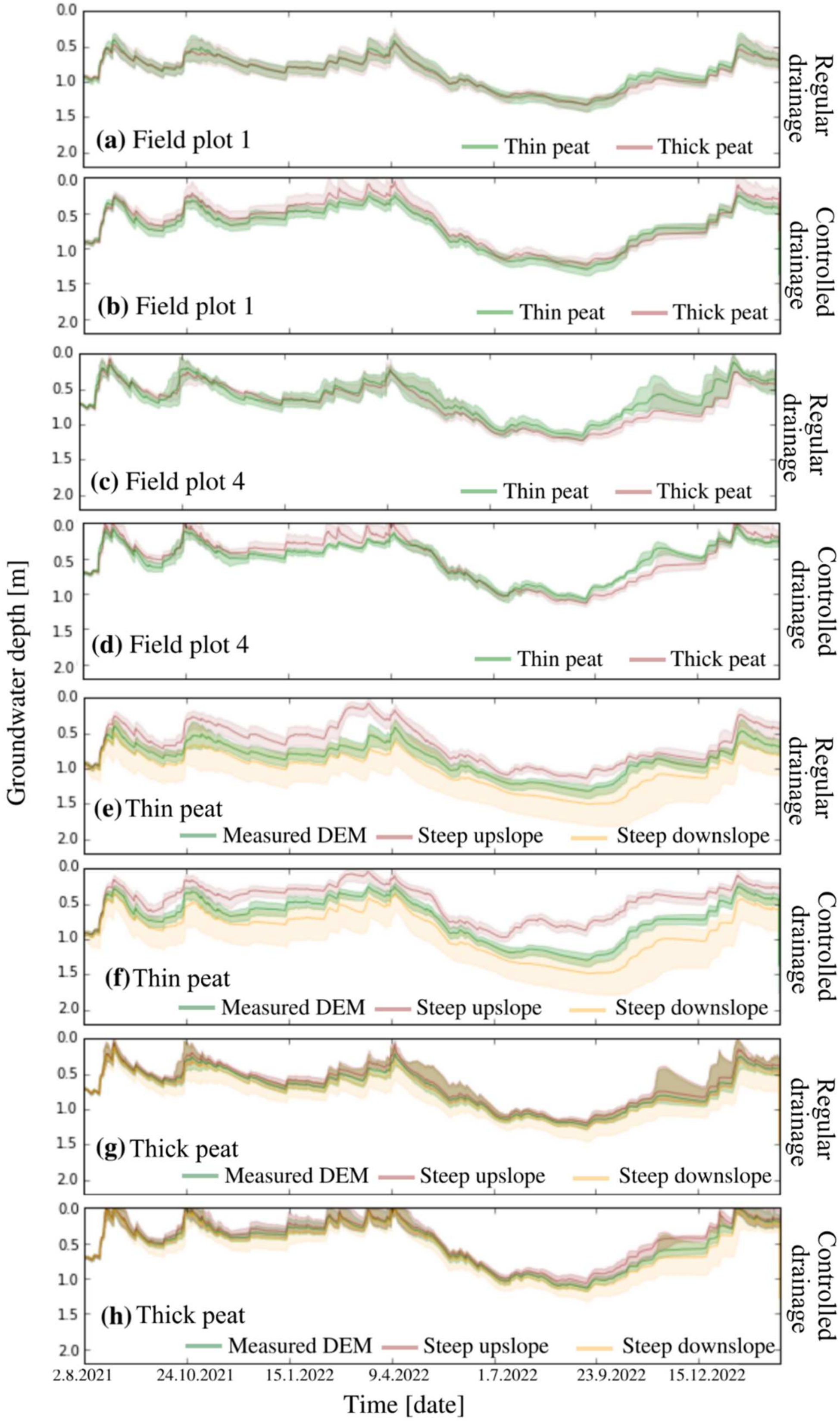

Figure 9. The simulated groundwater levels in the simulation scenarios with varying (a–d) peat thickness (thin or thick peat parameterisation) and (e–h) terrain topography (steep upslope or steep downslope), with regular and controlled drainage. The scenarios were conducted with the parameterizations from plots 1 and 4. The lines show the mean, and the envelopes denote the minimum and the maximum.

(Figure 9). However, influx does not necessarily increase the impact of controlled drainage on groundwater levels (Salla et al. 2024), but the effect depends on the relation between incoming and outgoing outflow routes.

During the growing seasons, the amount of evapotranspiration exceeds the amount of precipitation in high latitude conditions and thus decreases soil water storage and groundwater levels (e.g. Jin and Sands 2003: Turunen et al. 2015; Salo et al. 2021). Controlled drainage is practically unable to increase groundwater levels and soil moisture values during the growing seasons (Figures 6–7) if the amount of evapotranspiration exceeds the amount of precipitation and groundwater influxes. However, depending on the control schedule, controlled drainage could be used to maintain relatively high groundwater levels before the growing season, to keep soil water contents higher than with regular drainage during the early growing season (e.g. Salo et al. 2021). The challenge is that increased groundwater levels can affect trafficability and farming operations, and therefore the drainage control schedule must be set carefully when considering both emissions and productivity. Moreover, if the groundwater influxes are high, controlled drainage may increase groundwater levels also during the growing season (Figure 9e–f). The largest share of greenhouse gas emissions in cultivated peatlands occurs during growing seasons (Heikkinen et al. 2024; Honkanen et al. 2024), which means that mitigation of the emissions would need groundwater levels increases particularly during the growing seasons. Each 0.1 m rise in groundwater level can considerably reduce emissions (Evans et al. 2021; Lång et al. 2024). Our analysis shows the challenge of achieving such increases during growing seasons while keeping soil conditions simultaneously favourable for agricultural operations and productivity. The most effective way to increase groundwater levels would be to block drains and open ditches, but it would negatively impact farming operations and the trafficability of the soils.

The data and the simulations also showed how controlled drainage affected groundwater levels more in the thick than in thin peat. Moreover, peat can retain a large amount of water even under the suction pressures corresponding to the drain depth (Figure 4) and thick peat layers can retain large volumes of water. Therefore, under a similar amount of evapotranspiration, the groundwater table in thick peat soil can remain higher than in thin peat soil underlain by mineral soil layers (Figure 9). Note also that the hydrological implications of peat thickness are also dependent on the hydraulic properties of the underlying mineral soil. In the current study, the peat layers were underlain by clayey soil. Clayey soils can typically retain a relatively large share of water and have lower hydraulic conductivity compared to coarser soil types (e.g. Schaap et al. 2001). Peatlands can be underlain by different types of mineral soils (e.g. Quillet et al. 2017). Thus, the difference between plots with thick or thin peat layers is likely more pronounced when the peat is underlain by coarser mineral soil material.

The benefit of our model application was to disentangle the different factors affecting hydrological variables at the experimental site. Practically, such analysis would be challenging without computational tools, even though groundwater fluxes could be monitored with comprehensive field campaigns (Rozemeijer et al. 2016). Our results show that the net in- or outflux of groundwater can affect groundwater levels as much or more than controlled drainage measures (Figure 9). Moreover, the impact of controlled drainage was higher in the upslope scenarios than with the measured DEM. Knowledge of the hydrological impacts of different factors (e.g. peat thickness and topography) can be beneficial regarding the targeting of controlled drainage measures within catchments. Such knowledge could be combined, for example, with catchment-scale topographic wetness index computations (e.g. Sørensen et al. 2006; Grabs et al. 2009) when targeting of the measures within landscapes is of interest. Process understanding related to the flow routes within landscapes can also be relevant regarding drought assessment. Under similar precipitation deficiency conditions (meteorological drought), areas which receive a constant influx of water can be less prone to hydrological drought (e.g. Van Loon 2015) than areas that receive less net influx. Based on our simulations, controlled subsurface drainage has the highest potential to increase groundwater levels in areas with thick peat soils and high influx of groundwater. The results apply to the study conditions, but the impacts of local terrain slope can be different, for example, in mountainous areas with bottom-fed peat soil systems.

Despite the benefits of combining the comprehensive data with the model application, the approach also had limitations. For example, our simulations underestimated the variability in soil moisture compared with the measurements (Figure 7) did not accurately reproduce all observed hydrological variability in the field (Figure 5). This implies that the hydraulic properties of the experimental site were not entirely accurately identified in the model application. Inclusion of preferential flowpaths, more comprehensive open ditch flow processes and soil frost processes into the model would likely improve the representation (e.g. Gärdenäs et al. 2006; Warsta et al. 2013; Salo et al. 2021), even though such applications in peat soils are still rare and empirical studies on the related model parameters are rare. Moreover, preferential flowpaths may have high spatial variability in peat soils (e.g. Hare et al. 2017), and for example the interface between peat and clay layers might cause vertical spatial variability of the flowpaths. Methods such as ground-penetrating radars and tracers (e.g. Hare et al. 2017) could be useful for the identification of preferential flowpaths. The modelling approach of our study spatially averaged hydraulic conductivities (Table 2) and thus did not make a distinction of features smaller than the computational grid cell size. We measured vertical hydraulic conductivity within one plot, and the use of the measurements in the model resulted in reasonable model performance and posterior ranges (Table 2), but more measurements would most likely provide more information on the spatial variability. Moreover, as the horizontal fluxes were found to be important in the current study, measurements of horizontal hydraulic conductivities would be an interesting future research direction, as such measurements are currently very rare. The comparison of simulated and measured time series in the current study showed how soil frost can induce moisture distribution, particularly in the thick peat soil (Figure 5c–d). While the model did not describe the impacts of soil freezing on hydraulic properties, the relatively high amount of measured drain discharge during the spring snowmelt period (Figure 8) indicated that frost did not markedly prevent drain discharge generation. Likely, the conductive pores were not occupied by ice (e.g. Stähli et al. 1996). We also had challenges in fitting the van Genuchten (1980) model to the water retention data. We applied a straightforward approach to describe the water retention properties and tested the plausibility in model calibration-validation, but more sophisticated approaches to describe the observed curves would most likely improve the description. Likely, the description of the water retention properties could benefit from an improved understanding of how hydrophobicity and hysteresis (e.g. Dekker and Ritsema 1996; Naasz et al. 2008; Hewelke et al. 2016) can affect the field-scale water retention dynamics. Note that water retention characteristics are typically measured as drying curves under static steady-state conditions with long equilibration periods (e.g. pressure chambers). In field conditions, the hydraulic pressure differences are highly dynamic, and thus the water retention process can differ from those measured in the lab (e.g. Weber et al. 2024). Hydraulic non-equilibrium during infiltration and drainage processes is common in soils and affects both water retention and hydraulic conductivity, which thereby do not follow a unique water retention curve as assumed in Richards' equation (Vogel et al. 2023). Moreover, these processes and characteristics can induce uncertainties in the interpretation of the measurements, for example, by causing unexpected spatial differences between the observations (see Bouma et al. 1980; Dekker and Ritsema 1996; Weiler 2005; Doležal et al. 2015). This can consequently cause a commensurability challenge between the measured (point observations) and simulated values (gridded elements). However, despite these challenges and limitations, we consider the model application to be fit for purpose and to reasonably provide new information about the studied phenomena, particularly regarding the direction of change (rather than absolute values) in the studied variables. Regarding the interpretation of the different data, it is considered beneficial to bring empirical data into a single computational modelling framework and to provide a coherent explanation of the hydrological impact of controlled drainage. While the heterogeneity of peat soils is vast, exploring the organising principles and key driving factors beyond the heterogeneity and small-scale process complexity (e.g. McDonnell et al. 2007) can provide a reasonable approach to advance the understanding of the hydrology of agricultural peat soils.

Conclusions

Based on simulations and measured drain discharge differences between plots with regular and controlled drainage, controlled drainage can markedly reduce drain discharge in cultivated peat soils. However, the impacts on groundwater levels can be clearly smaller than the adjustment of the drainage depth. This was mainly due to changing flow route contributions (groundwater outflux and other outflow components). Groundwater in- and outfluxes were shown to markedly impact the field hydrology, and thus the results show how individual field parcels can be linked to the hydrology of the surrounding areas. Moreover, if the soils are drained efficiently during the spring, controlled drainage cannot increase groundwater levels thereafter during the growing seasons when the amount of evapotranspiration exceeds the amount of precipitation and influxes.

Quantitative information on the hydrological role of controlled drainage, peat thickness and topographic conditions may be beneficial regarding the targeting of controlled drainage measures within landscapes. Controlled subsurface drainage may have the highest potential to increase groundwater levels in areas with thick peat soils and steep upslope areas, compared to thin peat layers and steep downslope areas.

The benefit of the model application was to analyse the hydrology of agricultural peat soils more comprehensively than previously and to bring different empirical data into a single computational frame for a cohesive analysis. However, there are still knowledge gaps and uncertainties (such as processes related to the observed high variability of soil moisture within the experimental plots and how groundwater fluxes can limit the effects of controlled drainage) related to the hydraulic parameters of agricultural peat soils, which can essentially differ from those of pristine peat soils.

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References

Ad-Hoc-AG Boden. 2005. Bodenkundliche kartieranleitung (Manual of soil mapping). 5th ed. Hanover, Germany: Schweizerbart.

Ahmad S, Liu H, Alam S, Günther A, Jurasinski G, Lennartz B. 2021. Meteorological controls on water table dynamics in fen peatlands depend on management regimes. Front Earth Sci. 9:630469. doi:10.3389/feart.2021.630469.

Beven K. 2006. A manifesto for the equifinality thesis. J Hydrol. 320(1-2):18–36. doi:10.1016/j.jhydrol.2005.07.007.

Bouma J, Dekker LW, Haans JCFM. 1980. Measurement of depth to water table in a heavy clay soil. Soil Sci. 130(5):264–270. doi:10.1097/00010694-198011000-00006.

Bourgault MA, Larocque M, Garneau M. 2019. How do hydrogeological setting and meteorological conditions influence water table depth and fluctuations in ombrotrophic peatlands? J Hydrol X. 4:100032. doi:10.1016/j.hydroa.2019.100032.

Christiaens K, Feyen J. 2002. Constraining soil hydraulic parameter and output uncertainty of the distributed hydrological MIKE SHE model using the GLUE framework. Hydrol Processes. 16(2):373–391. doi:10.1002/hyp.335.

De Bakker H, Schelling J. 1989. System of soil classification for the Netherlands: the higher levels. 2nd ed. Wageningen: Winand Staring Centre.

Dekker LW, Ritsema CJ. 1996. Variation in water content and wetting patterns in Dutch water repellent peaty clay and clayey peat soils. Catena. 28(1-2):89–105. doi:10.1016/S0341-8162(96)00047-1.

Dettmann U, Bechtold M, Viohl T, Piayda A, Sokolowsky L, Tiemeyer B. 2019. Evaporation experiments for the determination of hydraulic properties of peat and other organic soils: an evaluation of methods based on a large dataset. J Hydrol. 575:933–944. doi:10.1016/j.jhydrol.2019.05.088.

Doležal F, Matula S, Barradas JM. 2015. Rapid percolation of water through soil macropores affects reading and calibration of large encapsulated TDR sensors. Soil Water Res. 10(3):155–163. doi:10.17221/177/2014-SWR.

Evans CD, Peacock M, Baird AJ, Artz RRE, Burden A, Callaghan N, Chapman PJ, Cooper HM, Coyle M, Craig E, Cumming A. 2021. Overriding water table control on managed peatland greenhouse gas emissions. Nature. 593(7860):548–552. doi:10.1038/s41586-021-03523-1.

Gärdenäs AI, Šimůnek J, Jarvis N, Van Genuchten MT. 2006. Two-dimensional modelling of preferential water flow and pesticide transport from a tile-drained field. J Hydrol. 329(3-4):647–660. doi:10.1016/j.jhydrol.2006.03.021.

Grabs T, Seibert J, Bishop K, Laudon H. 2009. Modeling spatial patterns of saturated areas: a comparison of the topographic wetness index and a dynamic distributed model. J Hydrol. 373(1-2):15–23. doi:10.1016/j.jhydrol.2009.03.031.

Haahti K, Warsta L, Kokkonen T, Younis BA, Koivusalo H. 2016. Distributed hydrological modeling with channel network flow of a forestry drained peatland site. Water Resour Res. 52(1):246–263. doi:10.1002/2015WR018038.

Haavisto M. 1983. Maaperäkartan käyttöopas 1:20 000, 1:50 000. Helsinki: Maanmittaushallituksen karttapaino.

Hammond RF. 1979. The Peatlands of Ireland, to accompany New Peatland map of Ireland and Ireland Peatland map. Dublin: Foras Talúntais.

Hansen JR, Refsgaard JC, Hansen S, Ernstsen V. 2007. Problems with heterogeneity in physically based agricultural catchment models. J Hydrol. 342(1-2):1–16. doi:10.1016/j.jhydrol.2007.04.016.

Hare DK, Boutt DF, Clement WP, Hatch CE, Davenport G, Hackman A. 2017. Hydrogeological controls on spatial patterns of groundwater discharge in peatlands. Hydrol Earth Syst Sci. 21(12):6031–6048. doi:10.5194/hess-21-6031-2017.

Heikkinen J, Lång K, Honkanen H, Myllys M. 2024. Mitigation of greenhouse gas emissions by optimizing groundwater level in boreal cultivated Peatland. Wetlands. 44(6):78. doi:10.1007/s13157-024-01833-4.

Hewelke E, Szatyłowicz J, Gnatowski T, Oleszczuk R. 2016. Effects of soil water repellency on moisture patterns in a degraded sapric histosol. Land Degrad Dev. 27(4):955–964. doi:10.1002/ldr.2305.

Honkanen H, Kekkonen H, Heikkinen J, Kaseva J, Lång K. 2024. Minor effects of no-till treatment on GHG emissions of boreal cultivated peat soil. Biogeochemistry. 167(4):499–522. doi:10.1007/s10533-023-01097-w.

IUSS Working Group WRB. 2022. World reference base for soil resources. International soil classification system for naming soils and creating legends for soil maps. 4th ed. Vienna, Austria: International Union of Soil Sciences (IUSS).

Jaros A, Rossi PM, Ronkanen AK, Kløve B. 2019. Parameterisation of an integrated groundwater-surface water model for hydrological analysis of boreal aapa mire wetlands. J Hydrol. 575:175–191. doi:10.1016/j.jhydrol.2019.04.094.

Jin CX, Sands GR. 2003. The long–term field–scale hydrology of subsurface drainage systems in a cold climate. Trans ASAE. 46(4):1011.

Kløve B, Berglund K, Berglund Ö, Weldon S, Maljanen M. 2017. Future options for cultivated Nordic peat soils: can land management and rewetting control greenhouse gas emissions? Environ Sci Policy. 69:85–93. doi:10.1016/j.envsci.2016.12.017.

Laine-Kaulio H, Backnäs S, Karvonen T, Koivusalo H, McDonnell JJ. 2014. Lateral subsurface stormflow and solute transport in a forested hillslope: a combined measurement and modeling approach. Water Resour Res. 50(10):8159–8178. doi:10.1002/2014WR015381.

Lambert C, Larocque M, Gagné S, Garneau M. 2022. Aquifer-Peatland hydrological connectivity and controlling factors in Boreal Peatlands. Front Earth Sci. 10:835817. doi:10.3389/feart.2022.835817.

Lång K, Honkanen H, Heikkinen J, Saarnio S, Larmola T, Kekkonen H. 2024. Impact of crop type on the greenhouse gas (GHG) emissions of a rewetted cultivated peatland. Soil. 10(2):827–841. doi:10.5194/soil-10-827-2024.

Laurén A, Palviainen M, Launiainen S, Leppä K, Stenberg L, Urzainki I, Nieminen M, Laiho R, Hökkä H. 2021. Drainage and stand growth response in peatland forests—description, testing, and application of mechanistic peatland simulator susi. Forests. 12(3):293. doi:10.3390/f12030293.

Liu Y, Freer J, Beven K, Matgen P. 2009. Towards a limits of acceptability approach to the calibration of hydrological models: extending observation error. J Hydrol. 367(1-2):93–103. doi:10.1016/j.jhydrol.2009.01.016.

Liu Y, Youssef MA, Chescheir GM, Appelboom TW, Poole CA, Arellano C, Skaggs RW. 2019. Effect of controlled drainage on nitrogen fate and transport for a subsurface drained grass field receiving liquid swine lagoon effluent. Agric Water Manag. 217:440–451. doi:10.1016/j.agwat.2019.02.018.

Mahmood H, Schneider RJM, Frederiksen RR, Christiansen AV, Stisen S. 2023. Using jointly calibrated fine-scale drain models across Denmark to assess the influence of physical variables on spatial drain flow patterns. J Hydrol: Reg Stud. 46:101353. doi:10.1016/j.ejrh.2023.101353.

Maxwell RM, Condon LE. 2016. Connections between groundwater flow and transpiration partitioning. Science. 353(6297):377–380. doi:10.1126/science.aaf7891.

McDonnell JJ, Sivapalan M, Vaché K, Dunn S, Grant G, Haggerty R, Hinz C, Hooper R, Kirchner J, Roderick ML, Selker J. 2007. Moving beyond heterogeneity and process complexity: a new vision for watershed hydrology. Water Resour Res. 43(7). doi:10.1029/2006WR005467.

McGuire KJ, McDonnell JJ, Weiler M, Kendall C, McGlynn BL, Welker JM, Seibert J. 2005. The role of topography on catchment-scale water residence time. Water Resour Res. 41(5). doi:10.1029/2004WR003657.

Menberu MW, Marttila H, Ronkanen AK, Haghighi AT, Kløve B. 2021. Hydraulic and physical properties of managed and intact peatlands: application of the van Genuchten-Mualem models to peat soils. Water Resour Res. 57(7): e2020WR028624. doi:10.1029/2020WR028624.

Naasz R, Michel JC, Charpentier S. 2008. Water repellency of organic growing media related to hysteretic water retention properties. Eur J Soil Sci. 59(2):156–165. doi:10.1111/j.1365-2389.2007.00966.x.

National Land Survey of Finland. 2020. Elevation model 2 m [accessed 2021 Oct 4]. https://www.maanmittauslaitos.fi/en/maps-and-spatial-data/expert-users/product-descriptions/elevation-model-2-m.

Quillet A, Larocque M, Pellerin S, Cloutier V, Ferlatte M, Paniconi C, Bourgault MA. 2017. The role of hydrogeological setting in two Canadian peatlands investigated through 2D steady-state groundwater flow modelling. Hydrol Sci J. 62:2541–2557. doi:10.1080/02626667.2017.1391387.

Rasa K, Horn R, Räty M, Yli-Halla M, Pietola L. 2007. Water repellency of clay, sand and organic soils in Finland. Agric Food Sci. 16:267–277. doi:10.2137/145960607783328218.

Räsänen TA, Myllys M, Kekkonen H, Tapio S, Pitkänen T, Laatikainen M, Laine-Petäjäkangas A, Väänänen T, Palmu J-P, Kivimäki A, Oksanen J. 2023. Turvepeltolohkojen määrittely ja tunnistaminen: Maatalousmaiden turvetieto (MaaTu) -hankkeen raportti (with an abstract in English). Luonnonvara- ja biotalouden tutkimus 58/2023. Luonnonvarakeskus. Helsinki. 40 s. http://scholar.google.com/scholar?hl=en&q=National+Land+Survey+of+Finland.+2020.+Elevation+model+2m+%5BWWW+Document%5D.+%5Baccessed+2020+May+29%5D.+https%3A%2F%2Fwww.maanmittauslaitos.fi%2Fen%2Fmaps-and-spatial-data%2Fexpert-users%2Fproduct-descriptions%2Felevation-model-2-m.

Rozemeijer JC, Visser A, Borren W, Winegram M, Van der Velde Y, Klein J, Broers HP. 2016. High-frequency monitoring of water fluxes and nutrient loads to assess the effects of controlled drainage on water storage and nutrient transport. Hydrol Earth Syst Sci. 20(1):347–358. doi:10.5194/hess-20-347-2016.

Salla A, Salo H, Koivusalo H. 2022. Controlled drainage under two climate change scenarios in a flat high-latitude field. Hydrol Res. 53(1):14–28. doi:10.2166/nh.2021.058.

Salla A, Salo H, Tähtikarhu M, Marttila H, Läpikivi M, Liimatainen M,, Lötjönen Timo, Koivusalo H. 2024. Simulating controlled drainage and hydrological connections in a cultivated peatland field. Vadose Zone J. 23(6):e20387. doi:10.1002/vzj2.20387.

Salo H, Salla A, Koivusalo H. 2021. Seasonal effects of controlled drainage on field water balance and groundwater levels. Hydrol Res. 52(6):1633–1647. doi:10.2166/nh.2021.056.

Schaap MG, Leij FJ, Van Genuchten MT. 2001. ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. J Hydrol. 251(3–4):163–176. doi:10.1016/S0022-1694(01)00466-8.

Šimůnek J, Van Genuchten MT, Sejna M. 2008. Development and applications of the HYDRUS and STANMOD software packages and related codes. Vadose Zone J. 7(2):587–600. doi:10.2136/vzj2007.0077.

Soil Classification Working Group. 1998. The Canadian system of soil classification. Ottawa, Canada: NRC Research Press.

Soil Survey Staff. 1999. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. 2nd edition., U.S. Department of Agriculture Handbook 436. Washinton, DC, USA: Natural Resources Conservation Service.

Sørensen R, Zinko U, Seibert J. 2006. On the calculation of the topographic wetness index: evaluation of different methods based on field observations. Hydrol Earth Syst Sci. 10(1):101–112. doi:10.5194/hess-10-101-2006.

Stähli M, Jansson PE, Lundin LC. 1996. Preferential water flow in a frozen soil — a two-domain model approach. Hydrol Processes. 10(10):1305–1316. doi:10.1002/(SICI)1099-1085(199610)10:10<1305::AID-HYP462>3.0.CO;2-F.

Steffens K, Larsbo M, Moeys J, Jarvis N, Lewan E. 2013. Predicting pesticide leaching under climate change: importance of model structure and parameter uncertainty. Agric Ecosyst Environ. 172:24–34. doi:10.1016/j.agee.2013.03.018.

Sunohara MD, Gottschall N, Craiovan E, Wilkes G, Topp E, Frey SK, Lapen DR. 2016. Controlling tile drainage during the growing season in Eastern Canada to reduce nitrogen, phosphorus, and bacteria loading to surface water. Agric Water Manag. 178:159–170. doi:10.1016/j.agwat.2016.08.030.

Tähtikarhu M, Okkonen J. 2023. Analyzing groundwater recharge and vadose zone dynamics by combining soil moisture and groundwater level data with a numerical model in subarctic conditions. J Hydrol Eng. 28(4):05023001. doi:10.1061/JHYEFF.HEENG-5842.

Thorsøe MH, Keesstra S, De Boever M, Buchová K, Bøe F, Castanheira NL, Chenu C, Cornu S, Don A, Fohrafellner J, et al. 2023. Sustainable soil management: soil knowledge use and gaps in Europe. Eur J Soil Sci. 74(6):e13439. doi:10.1111/ejss.13439.

Turunen M, Warsta L, Paasonen-Kivekäs M, Nurminen J, Alakukku L, Myllys M, Koivusalo H. 2015. Effects of terrain slope on long-term and seasonal water balances in clayey, subsurface drained agricultural fields in high latitude conditions. Agric Water Manag. 150:139–151. doi:10.1016/j.agwat.2014.12.008.

Turunen M, Warsta L, Paasonen-Kivekäs M, Nurminen J, Myllys M, Alakukku L, Äijö H, Puustinen M, Koivusalo H. 2013. Modeling water balance and effects of different subsurface drainage methods on water outflow components in a clayey agricultural field in boreal conditions. Agric Water Manag. 121:135–148. doi:10.1016/j.agwat.2013.01.012.

van Genuchten MT. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils Soil Sci Soc Am J. 44(5):892–898. doi:10.2136/sssaj1980.03615995004400050002x.

Van Loon AF. 2015. Hydrological drought explained. WIREs Water. 2(4):359–392. doi:10.1002/wat2.1085.

Vogel HJ, Gerke HH, Mietrach R, Zahl R, Wöhling T. 2023. Soil hydraulic conductivity in the state of nonequilibrium. Vadose Zone J. 22:e20238. doi:10.1002/vzj2.20238.

Warsta L, Karvonen T, Koivusalo H, Paasonen-Kivekäs M, Taskinen A. 2013. Simulation of water balance in a clayey, subsurface drained agricultural field with three-dimensional FLUSH model. J Hydrol. 476(10):395–409. doi:10.1016/j.jhydrol.2012.10.053.

Weber TKD, Weihermüller L, Nemes A, Bechtold M, Degré A, Diamantopoulos E, Fatichi S, Filipović V, Gupta S, Hohenbrink TL, et al. 2024. Hydro-pedotransfer functions: a roadmap for future development. Hydrol Earth Syst Sci. 28(14):3391–3433. doi:10.5194/hess-28-3391-2024.

Weiler M. 2005. An infiltration model based on flow variability in macropores: development, sensitivity analysis and applications. J Hydrol. 310(1-4):294–315. doi:10.1016/j.jhydrol.2005.01.010.

Wesström I, Joel A, Messing I. 2014. Controlled drainage and subirrigation – a water management option to reduce non-point source pollution from agricultural land. Agric Ecosyst Environ. 198:74–82. doi:10.1016/j.agee.2014.03.017.

Yli-Halla M, Lötjönen T, Kekkonen J, Virtanen S, Marttila H, Liimatainen M, Saari M, Mikkola J, Suomela R, Joki-Tokola E. 2022. Thickness of peat influences the leaching of substances and greenhouse gas emissions from a cultivated organic soil. Sci Total Environ. 806:150499. doi:10.1016/j.scitotenv.2021.150499.

Yli-Halla M, Mokma DL. 2001. Soils in an agricultural landscape of Jokioinen, south-western Finland. Agricultural and Food Science. 10:33–43. doi:10.23986/afsci.5677.

Youssef MA, Liu Y, Chescheir GM, Skaggs RW, Negm LM. 2021. DRAINMOD modeling framework for simulating controlled drainage effect on lateral seepage from artificially drained fields. Agric Water Manag. 254:106944. doi:10.1016/j.agwat.2021.106944.

Yu PS, Yang TC, Chen SJ. 2001. Comparison of uncertainty analysis methods for a distributed rainfall–runoff model. J Hydrol. 244(1-2):43–59. doi:10.1016/S0022-1694(01)00328-6.