Silva Fennica vol. 55 no. 3 article id 10494
Category: research article
https://doi.org/10.14214/sf.10494

SILVA FENNICA

http://www.silvafennica.fi
ISSN-L 0037-5330 | ISSN 2242-4075 (Online)
The Finnish Society of Forest Science

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Defining guidelines for ditch depth in drained Scots pine dominated peatland forests

Hökkä H., Laurén A., Stenberg L., Launiainen S., Leppä K., Nieminen M. (2021). Defining guidelines for ditch depth in drained Scots pine dominated peatland forests. Silva Fennica vol. 55 no. 3 article id 10494. 20 p. https://doi.org/10.14214/sf.10494

Highlights

- Process-based hydrological model was applied to drained peatland forests representing a wide range of conditions in Finland.
- Ditch depth keeping the median July–August water table below 0.35 m was defined.
- Ditch depth depended on climatic conditions, stand volume, peat properties, and ditch spacing.
- Shallower ditches than recommended in practice proved to be sufficient in most situations.

Abstract

We used a process-based hydrological model SUSI to improve guidelines for ditch network maintenance (DNM) operations on drained peatland forests. SUSI takes daily weather data, ditch depth, strip width, peat properties, and forest stand characteristics as input and calculates daily water table depth (WTD) at different distances from ditch. The study focuses on Scots pine (*Pinus sylvestris* L.) dominated stands which are the most common subjects of DNM. Based on a literature survey, and consideration of the tradeoffs between forest growth and detrimental environmental impacts, long term median July–August WTD of 0.35 m was chosen as a target WTD. The results showed that ditch depths required to reach such WTD depends strongly on climatic locations, stand volume, ditch spacing, and peat thickness and type. In typical ditch cleaning areas in Finland with parallel ditches placed about 40 m apart and tree stand volumes exceeding 45 m^3 ha^{-1}, 0.3–0.8 m deep ditches were generally sufficient to lower WTD to the targeted depth of 0.35 m. These are significantly shallower ditch depths than generally recommended in operational forestry. The main collector ditch should be naturally somewhat deeper to permit water outflow. Our study brings a firmer basis on environmentally sound forestry on drained peatlands.

Keywords *Pinus sylvestris*; ditch network maintenance; drainage; forest management; peatland; process model; water table
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Received 8 December 2020 **Revised** 12 May 2021 **Accepted** 20 May 2021

1 Introduction

In Finland, peatland drainage for forestry purposes was done extensively from 1950s to early 1980s resulting in altogether 6.5 Mha area of drained sites. To maintain forest growth in areas shown suitable for forest production, ditch network maintenance (DNM, i.e., cleaning the old ditches to a depth of 0.8–1.2 m and/or digging new ones) is a common practice (Sikström and Hökkä 2016). Ditches tend to deteriorate with time and gradually lose their water transportation capacity (Heikurainen 1957; Timonen 1983; Hökkä et al. 2020), often resulting in raised water table and reduced stand growth (Heikurainen 1980; Pelkonen 1975). It has been shown that DNM can increase tree growth by up to 1.5 m^3 ha^{-1} $year^{-1}$ and its positive effect lasts for 15–20 years (Ahti et al. 2008; Sikström et al. 2020). According to 11th National Forest Inventory (2009–2012) on about 0.9 Mha area the drainage has been unsuccessful (Korhonen et al. 2017) and instead of forestry actions, active or passive restoration is recommended in such sites.

Ditch network maintenance (DNM) has adverse impacts on several ecosystem services. In particular, it is considered to cause the most harmful impact of forestry on surface water quality in Finland (Finér et al. 2010) due to increased exports of suspended solids and dissolved and particulate nutrients (Joensuu 2002; Nieminen et al. 2010; Stenberg et al. 2015; Nieminen et al. 2017). Deep ditches reaching highly humified peat layers or mineral soil are particularly severe sources of sediments and particulate nutrients (Nieminen et al. 2017). Excavating deep ditches also exposes deep peat layers to oxidation, which significantly increases emissions of carbon dioxide and nitrous oxide (Ojanen and Minkkinen 2019). Therefore, finding ditch depth that ensures sufficient drainage but is not too deep is a key-question for economically and environmentally feasible peatland forestry.

The technical guidelines for draining peatlands for forestry date back to recommendations given for initial ditching of natural peatlands. In these guidelines, ditching parameters (ditch depth and spacing) are determined with the aim to meet a pre-determined target water table depth (WTD) (Meshechok 1960; Braekke 1974, 1983; Toth and Gillard 1988) in given climatic conditions and peat properties. The targeted WTD is assessed to achieve maximum tree growth and is generally based on securing 10 % volumetric air content in surface peat (Paavilainen 1967; Päivänen 1973) or satisfying a theoretically optimal water potential in the root zone (Heikurainen et al. 1964; Heikurainen 1973). The general understanding of target WTD is that water table should stay below the tree rooting depth particularly during the late growing season (July–August), so that the root's functioning is not disturbed (Kozlowski 1982; Päivänen and Hånell 2012). Despite the attempts to determine a target WTD for undisturbed tree growth, it is not considered when DNM is put in practice (Vanhatalo et al. 2015). Thus, practical guidelines for DNM would benefit from using target WTD as a criterion for assessing the ditching parameters.

To assess when target WTD is achieved, the multitude of factors influencing WTD in peatland forest need to be considered. In addition to ditching parameters and climatic location, WTD varies considerably as a function of peat hydraulic properties and stand water use (Ahti and Päivänen 1997; Hillman 1997; Sarkkola et al. 2010; Stenberg et al. 2018). Some information from recent studies on the water use in high-volume stands (Sarkkola et al. 2010) has been utilized in the current operational drainage guidelines. However, they provide no tools to account for the combined effects of the multitude of factors affecting WTD, due to which they do not constitute a solid basis for environmentally sound DNM operations.

The goal of this study is to provide new guidelines for the planning and implementation of DNM in drained peatland forests which incorporate ditching parameters, the quality and thickness of the peat profile, stand water use, and climatic conditions. To accomplish this, we use a process-based hydrological model SUSI (Laurén et al. 2021) to determine the minimum ditch depth (later referred as the **effective ditch depth**) necessary to keep the late summer WTD below a threshold value determined based on previous literature. The study focuses on Scots pine (*Pinus sylvestris* L.) dominated stands, which are the most common targets of DNM in Finland.

2 Materials and methods

2.1 SUSI simulator

We applied the hydrological modules of SUSI simulator described in detail in Laurén et al. (2021) to model how WTD responses to drainage parameters, peat characteristics, stand volume, and climatic conditions in peatland forests. The model simulates daily WTD variation across a cross-section of a forested drainage strip (Fig. 1) based on daily weather input. It includes separate modules for aboveground water storages and fluxes, snowpack and for belowground water balance and drainage (Fig. 2).

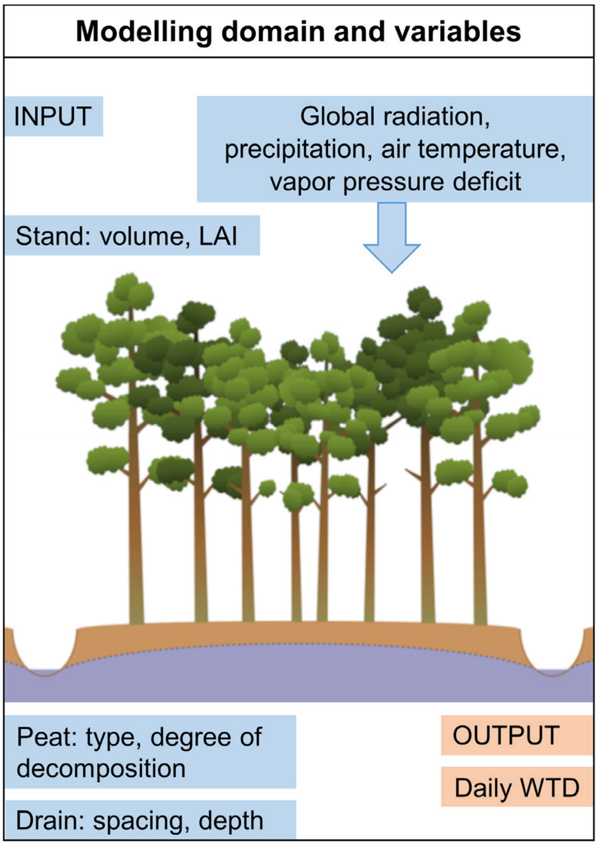

Fig. 1. SUSI model computes water storages and fluxes between two parallel ditches. SUSI calculates in daily time step water interception into canopy and ground vegetation, interception evaporation, transpiration, infiltration into soil, water table depth, and horizontal water movement to the ditches. Required meteorological inputs are global radiation, precipitation, air temperature and vapor pressure deficit. Output is daily WTD at different distances from ditch.

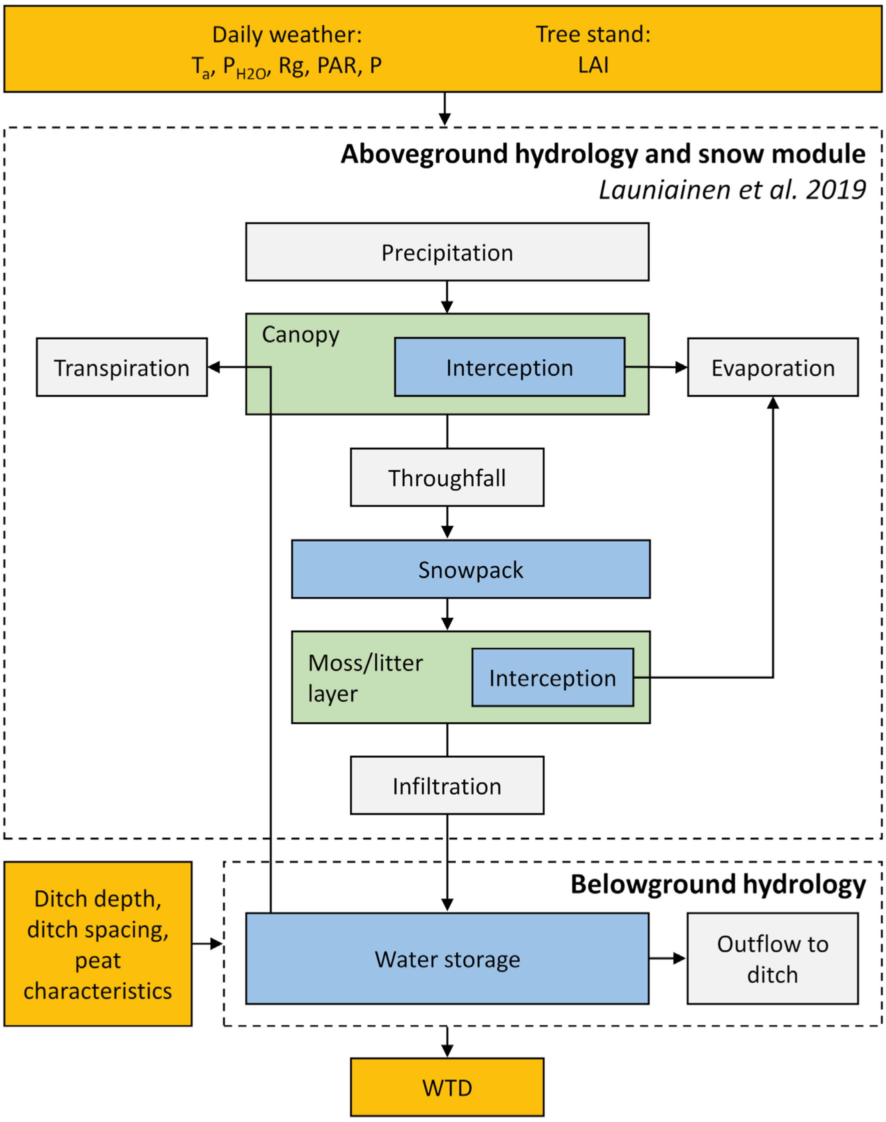

Fig. 2. Flowchart and components of the hydrological part of SUSI model. SUSI is modular and the source code is available at https://github.com/annamarilauren/susi. The repository also contains test input data for running the model.

2.2 Aboveground hydrology

Descriptions of aboveground hydrology are adopted from the SpaFHy model (Launiainen et al. 2019) which describe rainfall and snow interception both in the forest canopy and in the moss/litter layer at the forest floor, snow accumulation and melt, infiltration to soil profile and evapotranspiration (ET, mm d^{-1}) components. Stand transpiration and evaporation from the forest floor and canopy interception storage are modeled separately by Penman-Monteith equation:

$$E_i = \frac{1}{L}\frac{\Delta R_n + \rho c_p G_a D}{\Delta + \gamma\left(1 + \frac{G_a}{G_i}\right)}, \quad (1)$$

where L is latent heat of vaporization (J kg^{-1} K^{-1}), ρ is the air density (kg m^{-3}), c_p the heat capacity of dry air at constant pressure (J kg^{-1} K^{-1}), D is the vapor pressure deficit at air temperature (Pa) and R_n the available energy (W m^{-2}) which is a function of global radiation. The surface conductance G_i (m s^{-1}) and aerodynamic conductance G_a differs depending on the considered ET component E_i (see Launiainen et al. 2019). For transpiration, the canopy conductance G_i (ms^{-1}) is formulated so that it accounts for both species water use traits, stand one-sided leaf-area index LAI (m^2 m^{-2}), and environmental forcing and feedback to peat soil moisture as:

$$G_i = 1.6\left(1+\frac{g_1}{\sqrt{D}}\right)\frac{A_{\max}}{C_{a,ref}}\times\frac{1}{k_p}\ln\left(\frac{PAR+\frac{b}{k_p}}{PAR\times\exp\left(-k_p LAI\right)+\frac{b}{k_p}}\right)C_{air}\times f_S\times f_w \qquad (2)$$

here the first term represents leaf-level stomatal conductance (g_1 is a parameter reflecting plant water use strategy, $A_{\max}$ maximum photosynthetic rate per unit leaf area and $C_{a,ref}$ reference ambient CO_2 concentration, 380 ppm), the term in brackets describes upscaling from leaf to canopy level assuming exponential attenuation of radiation with canopy optical depth (*PAR* is photosynthetically active radiation at canopy top, k_p light attenuation coefficient, b half-saturation constant of photosynthetic light response and *LAI* the canopy one-sided leaf-area index (m^2 m^{-2})) and C_{air} converts the units from mol m^{-2} s^{-1} to ms^{-1}. The two last terms are dimensionless response functions representing seasonal cycle of photosynthetic capacity (Kolari et al. 2007) and soil moisture limitations. The latter provides feedback from soil water status and is here given as (Koivusalo et al. 2008)

$$f_w = \begin{cases} -\dfrac{WTD}{0.15}, -0.15 < WTD \\ \min\left(WTD+1.7,\, 1.0\right), -1.2 \le WTD < -0.15 \\ \max\left(0.5\left(\dfrac{WTD+150}{148.8}\right),\, 0.0\right), WTD < -1.2 \end{cases} \qquad (3)$$

where *WTD* is the water table depth given as a negative value down from the soil surface (m) computed by the belowground hydrology module.

The interception storages in the canopy and the organic moss/litter layer at the forest floor are both described using bucket approach. The canopy water storage capacity is linearly proportional to LAI while the forest floor storage capacity is determined based on the dry mass of the organic moss/litter layer and its field capacity. The water content in these buckets is increased by interception of rainfall/throughfall and drained by evaporation (Launiainen et al. 2019). The snowpack is described with a common degree-day approach where the melt coefficient is a function of canopy closure (Kuusisto 1984) resulting into slower snowmelt in dense stands.

The aboveground hydrology is computed assuming tree stand is uniform throughout the peatland cross-section, while local variations in transpiration rate can occur in cases f_w becomes spatially variable. The ET and snow model has been described in detail and tested for range of boreal forest sites in Launiainen et al. (2019). We apply the same generic parameterization as in their study and only modify the stand LAI and meteorological forcing according to our study aims.

2.3 Belowground hydrology

To solve the spatial and temporal variability of peat water storage and WTD, the computational domain between the ditches was divided into one-meter-wide columns. All columns have the same soil surface elevation and extend to an impermeable bottom layer, e.g. bedrock. The peat and stand properties are assumed constant throughout the cross-section. Note, that our approach does not address other ditch types than the parallel contour ditches, i.e., the main ditch should be appropriately deeper than the parallel contour ditches to permit unrestricted water outflow.

We follow a quasi-two-dimensional approach, where it is assumed that any change in water storage immediately affects WTD, and the water content above the WTD instantaneously sets to hydraulic equilibrium following the vertical profile of water retention characteristics (Skaggs 1980). In this setup, the horizontal water movement is computed using implicit solution of a diffusion-shape ground water equation:

$$C^{-1}\left(WTD\right)\frac{\partial WTD}{\partial t}=\frac{\partial}{\partial x}\left(T\left(WTD\right)\frac{\partial WTD}{\partial x}\right)+S \tag{4}$$

where C is storage coefficient (m m^{-3}) representing the change in WTD with respect to change in profile water storage (see Eq. 6), t is time (s), T is transmissivity (m^2 s^{-1}), x is horizontal distance (m) and S is the balance between infiltration and root water uptake (m s^{-1}) provided by the aboveground module. The boundary conditions are either constant hydraulic head equal to ditch depth (when WTD in the strip is higher than the ditch bottom) or no flow boundary (WTD below ditch depth).

Transmissivity is the integral of saturated hydraulic conductivity (K_{sat}, m s^{-1}) over the saturated layer:

$$T\left(WTD\right)=\int_{ib}^{WTD}K_{sat}dz \tag{5}$$

where ib is the depth of the modeled soil column (negative down from soil surface, m) and z (m) is vertical distance. The lower boundary condition is set to no-flow.

Water storage (W, m) in peat profile was obtained by integrating water content (θ, m^3 m^{-3}) with depth as:

$$W\left(WTD\right)=\int_{ib}^{0}\theta dz \tag{6}$$

Soil water potential (ψ) above the WTD was assumed to follow the hydraulic equilibrium (i.e. 0.1 m above WTD, ψ=–0.1 m) and θ was then computed from the layer water retention characteristics described using van Genuchten equation (van Genuchten 1980). For each day, the aboveground hydrology is first solved and the net sink/source term (S) is computed as the difference between daily infiltration and transpiration, and thereafter belowground hydrology is computed using adaptive timestep. Constant (Dirichlet) boundary conditions are applied at ditches when WTD is above the ditch bottom and no-flow (Neumann) boundary conditions when WTD is below the ditch bottom.

2.4 The target WTD

Several peatland studies have shown a strong relationship between mean growing season WTD and tree growth rate in drained peatland forest (Heikurainen 1980; Hökkä et al. 2008) although the underlying mechanisms are still not completely understood (Päivänen and Hånell 2012). Pelkonen (1975) claimed that water table that rises to soil surface will decrease tree growth in future years. Huikari and Paarlahti (1968) found that tree growth was generally improved when average growing season WTD deepened from 10 cm to 70 cm, but they also showed that adding phosphorus and potassium resulted in tree growth at 10 or 30 cm WTD comparable to that at 50 or 70 cm WTD.

They also reported signs of drought stress at 70 cm WTD in their southern Finland study site in Huikari and Paarlahti (1968). Furthermore, Sarkkola et al. (2012) concluded that lowering late summer water level by drainage increased tree growth only if the pre-drainage water level was closer than 35–40 cm from soil surface. These results suggest that 35–40 cm late summer (July–August) WTD may already be sufficiently deep. Given that very deep water levels induce environmental problems by exposing deep peat layers to oxidation but may not necessarily increase tree growth compared to shallower water levels, we assess the long-term July–August median WTD of 35 cm as an optimal WTD in our study. We refer this WTD threshold as the target WTD (WTD_{35cm}).

2.5 Model scenarios to define effective ditch depth

We use the presented hydrological model to determine minimum ditch depth required to meet WTD_{35cm} for a range of tree stands representing different stand volumes, site properties and ditch spacings across the climatic gradient in Finland. The model inputs are daily weather variables (global radiation, air temperature, precipitation and vapor pressure deficit), and parameters describing the tree stand (canopy height, canopy closure and LAI), peat characteristics (peat type, degree of humification) and drainage dimensions (ditch spacing and ditch depth).

Scenarios for the study were generated by varying the following model inputs:

- stand volume (affecting stand ET, Eq. 1)
- peat layer thickness, peat type and its vertical profile (affecting transmissivity (Eq. 5) and water storage (Eq. 6))
- ditch spacing (affecting ditch drainage)
- ditch depth (affecting ditch drainage)
- weather data (affecting the sink/source term S, Eq. 4)

To assess the effect of peat and subsoil hydraulic properties on WTD we constructed six different soil profiles with depth of 1.5 m. The profiles represented deep *Sphagnum* and *Carex* peat with two different vertical humification patterns (see Supplement file S1, available at https://doi.org/10.14214/sf.10494):

P1: constant degree of humification from 20 to 100 cm depth,

P2: increasing degree of humification from 20 to 100 cm depth,

and a shallow peat (30 cm deposit) profile with two different underlaying mineral soils (sand and clay).

For each profile, saturated hydraulic conductivity (K_{sat}), peat type, and degree of humification (von Post scale) are shown in Suppl. file S1. We assume that these profiles resemble the typical peat profiles in drained peat soils in Finland and in boreal peatlands in general (Päivänen 1982; Hillman 1997). Peat water retention characteristics and K_{sat} are estimated from the peat type and degree of humification (Päivänen 1973). Due to the anisotropy of the peat, we assumed that the horizontal hydraulic conductivity was tenfold greater than the vertical hydraulic conductivity in the upper 30 cm layers (Suppl. file S1, Koivusalo et al. 2008; Leppä et al. 2020b). Hydraulic properties of mineral subsoils are within typical ranges of sand and clay soils (Ronkainen 2012; Vakkilainen 2016). In the simulations, we divided the peat profiles into 0.05 m layers and the bottom of the soil column was assumed to be at –1.5 m depth in all simulations. For computational efficiency, interpolation functions for T(WTD), W(WTD) (Eqs. 5 and 6) and C(WTD) = dWTD/dW (m m^{-3}), were computed prior to the simulations and tabulated at 0.01m intervals.

We consider typical Scots pine stands in drained peatland forests, ranging from the clear-cut stage to near mature stands with the following stem volumes: 0, 45, 90, 130, and 175 m^3 ha^{-1} (Table 1). In such development stages, DNM is a standard procedure in operational peatland forestry

Table 1. Stand characteristics and leaf area index (LAI) of the simulated Scots pine drained peatland forests ranging from the clear-cut stage to near mature stands. LAI at clear-cut stage represent ground vegetation.

Stand volume, m^3 ha^{-1}	Dominant height, m	Stand LAI, m^2 m^{-2}
0	0	0.5
45	7.5	1.7
90	10.0	2.3
130	14.5	2.8
175	16.5	3.0

to maintain and improve drainage conditions. Foliar biomasses were estimated using Repola's (2009) biomass equations and converted to one-sided LAI using specific leaf area of Härkönen et al. (2015). For the scenarios here, the LAI varied from 0.5 m^2 m^{-2} (representing ground vegetation at clear-cut stage) to 3.0 m^2 m^{-2}. This LAI range covers majority of Scots pine dominated peatland forests in Finland (Table 1).

Drainage intensity was studied by varying ditch depth and ditch spacing. Six different ditch depths were used: 0.3, 0.5, 0.7, 0.9, 1.1, and 1.3 m. For ditch spacing we used values 30, 40, and 50 m, of which 40 m is the typical spacing in Finnish peatland forests.

To account for the climatic variability, ten different locations in Finland were selected (Fig. 3). For each location, 40-year (1976–2015) weather records were obtained from spatially interpolated weather observations provided by the Finnish Meteorological Institute at 10 × 10 km resolution (Venäläinen et al. 2005). The daily temperature, rainfall, global radiation, and vapor pressure deficit were used as input data for the hydrological model.

Fig. 3. Locations where SUSI was applied in the simulated scenarios.

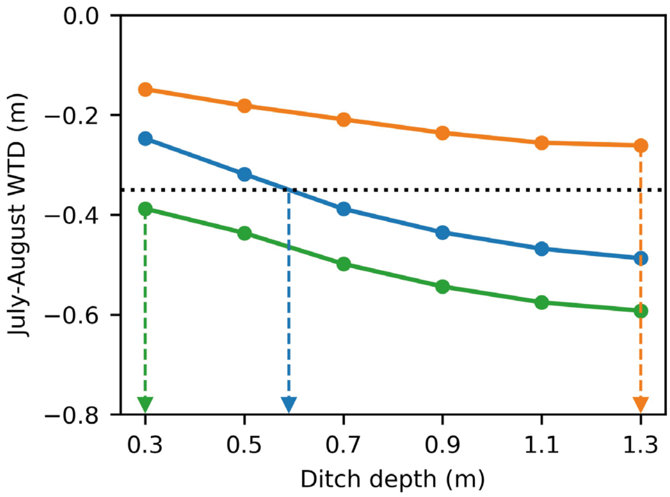

Fig. 4. Estimation of the effective ditch depth with 0.35 m target WTD in three examples. If target is not reached with 1.3 m ditch depth, the effective depth is set to 1.3 m (orange line). If target is reached with ≤0.3 m deep ditch, the effective depth is assigned as 0.3 m (green line).

For each model scenario daily WTDs were simulated for the 40 year-period and median WTD for late summer (July–August) was computed for further analyses. The effective ditch depth corresponding to median WTD of 0.35 m was finally obtained using linear interpolation (Fig. 4).

2.6 Model testing

The main uncertainties in the model are related to peat hydrological characteristics, which are not easy to estimate and may vary within a site. Since the purpose of this study is to provide general guidelines we will not focus on the results of specific sites. However, we tested the model performance against measured time series from two locations (southern and northern Finland, see Stenberg et al. 2018). Both sites were pine peatlands drained over 50 years ago and monitored for WTD during growing season 2006–2012. The southern site was a mature Scots pine stand having 157 m^3 ha^{-1} total volume, growing in a poor dwarf shrub site on thick (3 m) *Sphagnum* peat. Ditch spacing was 30 m and ditch depth 0.5m. The northern site was a Scots pine thinning stand with 100 m^3 ha^{-1} total volume growing in a medium blueberry site on an over 1 m thick *Carex* peat and 25 m ditch spacing and 0.85 m ditch depth. The results against measured time series showed generally good agreement, especially when focusing on the period of interest, July–August (Fig. 5). However, for the southern site the measured late fall and winter WTD levels were clearly deeper than those predicted by the model (Fig. 5c).

Another comparison was made against published inventory data describing the connection between stand volume and late growing season water table depth (Sarkkola et al. 2010). These data represented different site and stand conditions (Scots pine and Norway spruce (*Picea abies* (L.) Karst.) dominated stands) from southernmost Finland to southern Lapland. When peat profile P2 was used in simulation the SUSI model predicted very similar WTDs than those observed in Sarkkola et al. (2010) (Fig. 6). With profile P1 SUSI model predicted somewhat deeper WTD for low volume stands than those observed in Sarkkola et al. (2010).

The hydrological model of SUSI simulator has also been successfully applied in two recent studies, which provide further confidence on WTD predictions (Leppä et al. 2020b; Laurén et al. 2021).

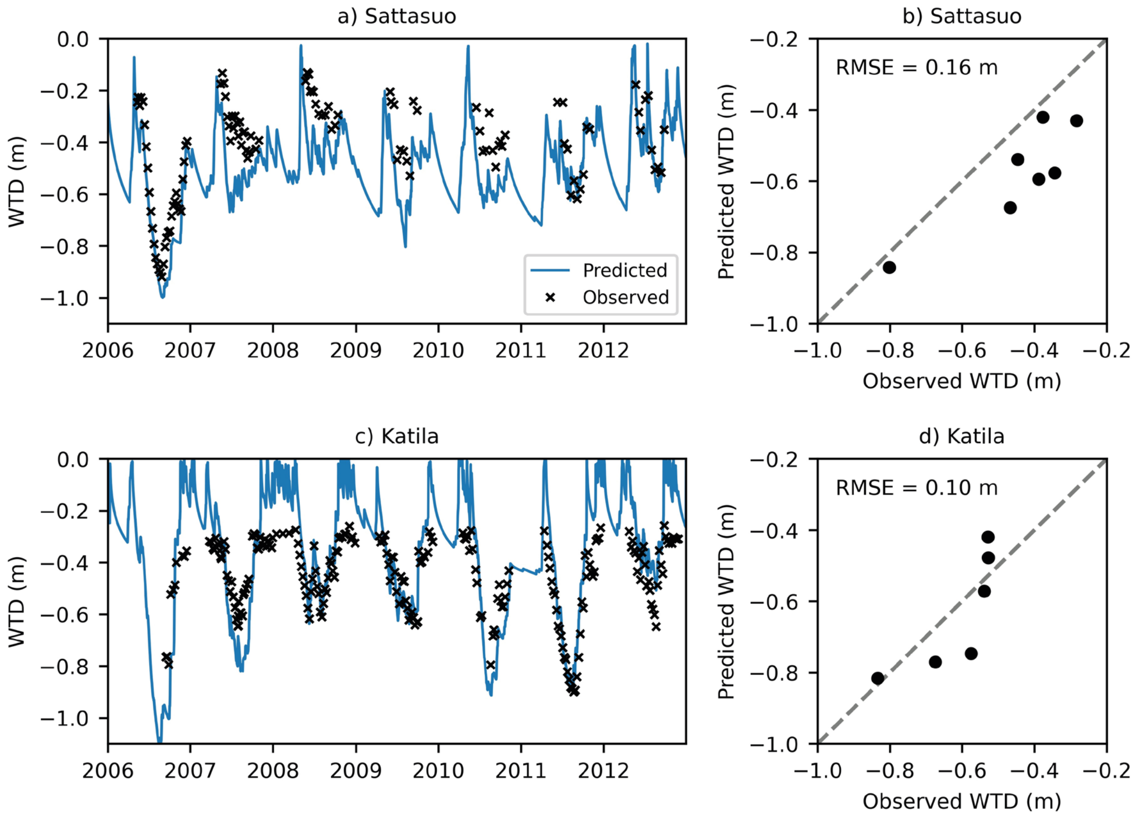

Fig. 5. Testing the model against manually measured WTD data for seven years for a–b) Sattasuo (Rovaniemi, northern Finland) and c–d) Katila (Tuusula, southern Finland). Peat type is *Carex* in Sattasuo and *Sphagnum* in Katila. Peat profile P2 was used in the simulations in both sites. In Sattasuo, measured data includes 50 groundwater tubes. In Katila, there were 35 groundwater tubes. Modeled and daily mean values of the measured WTD levels are presented in the figures a and c. Comparison of predicted and observed July–August mean WTD is presented in the figures b and d.

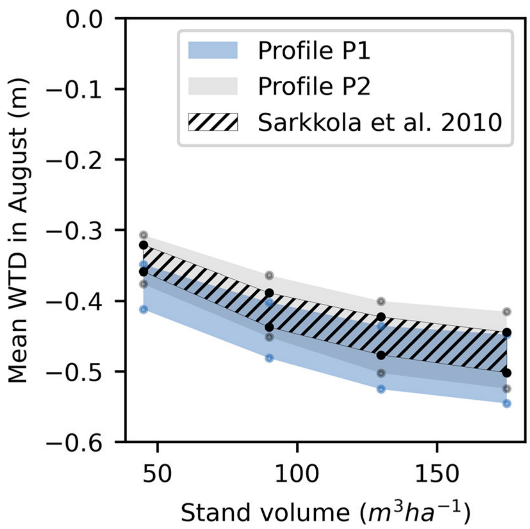

Fig. 6. Comparison of the predicted mean August WTD and the statistical model by Sarkkola et al. (2010). The comparison includes all 10 climatic locations (see Fig. 3) with *Carex* peat, 0.5 m ditch, and 40 m ditch spacing. The shaded or hatched area represents the range in simulated climatic locations.

3 Results

3.1 Late summer WTD

Median July–August WTDs for the different combinations of input variables for 40 m ditch spacing are shown in Fig. 7. Suppl. files S2 and S3 show the respective results for the other ditch spacings. For all ditch depths the water table was closer to surface in northern than southern Finland, as well as in low-volume stands compared to high-volume stands (Fig. 7). In case of thick peat layer, the stand volume was more important in regulating late-summer WTD than the ditch depth. The effect of stand volume leveled off when it exceeded 130 m^3 ha^{-1}. On average, WTD was 0.17 m closer to the surface at clear-cut (0 m^3 ha^{-1}) than at 45 m $^3ha^{-1}$ stands (Fig. 7).

The WTD was, on average, 0.11 m deeper in *Carex* peat than in otherwise similar *Sphagnum* peat in profile P1. In the more humified profile P2, the difference in WTD was smaller (0.08 m). In case of shallow peat layer, subsoil hydraulic characteristics had a dominant role in controlling WTD. In poorly conducting clay subsoil most of the lateral water movement to ditch network occurs in the peat layer and the role of ditch depth was minimal (Fig. 7). In contrast, when stand volume increased from 0 to 175 m^3 ha^{-1} the WTD deepened by 0.14–0.29 m. In sandy subsoil the WTD was not correlated with stand volume and remained about the same level as ditch depth.

3.2 Effective ditch depth

Figure 8 shows the effective ditch depth required to meet the WTD_{35cm} criteria, i.e., that median late-summer WTD is below –0.35 m from the surface. The effective ditch depths were strongly affected by peat and subsoil hydraulic properties, ditch spacing, stand volume, and climatic conditions. In *Carex* peat, simulations indicated that <0.9 m deep ditches would suffice to reach the target WTD_{35cm} (Fig. 8c) in clear-cut phase but at stand volumes exceeding 45 m^3 ha^{-1} even shallower ditches are sufficient both in southern and northern locations. In *Sphagnum* peat, <0.9 m deep ditches would suffice for stand volumes exceeding 45 m^3 ha^{-1} (Fig. 8c) but deeper ditching is required in clear-cuts. With 30 m ditch spacing, <1.0 m deep ditches were sufficiently deep in all simulations (Fig. 8a). With 50 m spacing, target WTD_{35cm} was met with the maximum ditch depth of 1.3 m in neither *Carex* nor *Sphagnum* peat clear-cuts (Fig. 8e), while 0.7 m ditches sufficed in *Carex* peat already when stand volume exceeded 45 m^3 ha^{-1} (Fig. 8e). In *Sphagnum* peat, only the largest volume stands (≥130 m^3 ha^{-1}) indicated sufficiently low water level even if <0.9 m deep ditches were applied (Fig. 8e). In many cases, deepening ditches further to 1.3 m did not guarantee that the target WTD_{35cm} would be reached.

Increasing degree of humification with peat depth (profile P2) strongly affected both effective ditch depths and the differences between *Sphagnum* and *Carex* peat. In the more humified *Sphagnum* peat profile P2, almost two times deeper ditches were needed with 40 m spacing than in respective *Carex* peat profile for reaching the target WTD_{35cm} (Fig. 8d). A *Carex* peat profile indicated sufficiently low water table depth (WTD_{35cm}) with 0.7 m deep ditches even in northern Finland, if stand volume was at least 45 m^3 ha^{-1} (Fig. 8d). In the humified *Sphagnum* peat P2 profile, only the largest volume stands could be drained to target WTD_{35cm} in northern Finland with 40 m ditch spacing and the ditch depth range considered (Fig. 8d). With narrower ditch spacing (30 m), <0.9 m deep ditches were sufficiently deep also in case of *Sphagnum* peat except in clear cuts (Fig. 8b). With 50 m ditch spacing, WTD_{35cm} was not reached in the *Sphagnum* peat P2 profile in northern Finland no matter how deep ditch depths and large stand volumes were applied in the simulations (Fig. 8f).

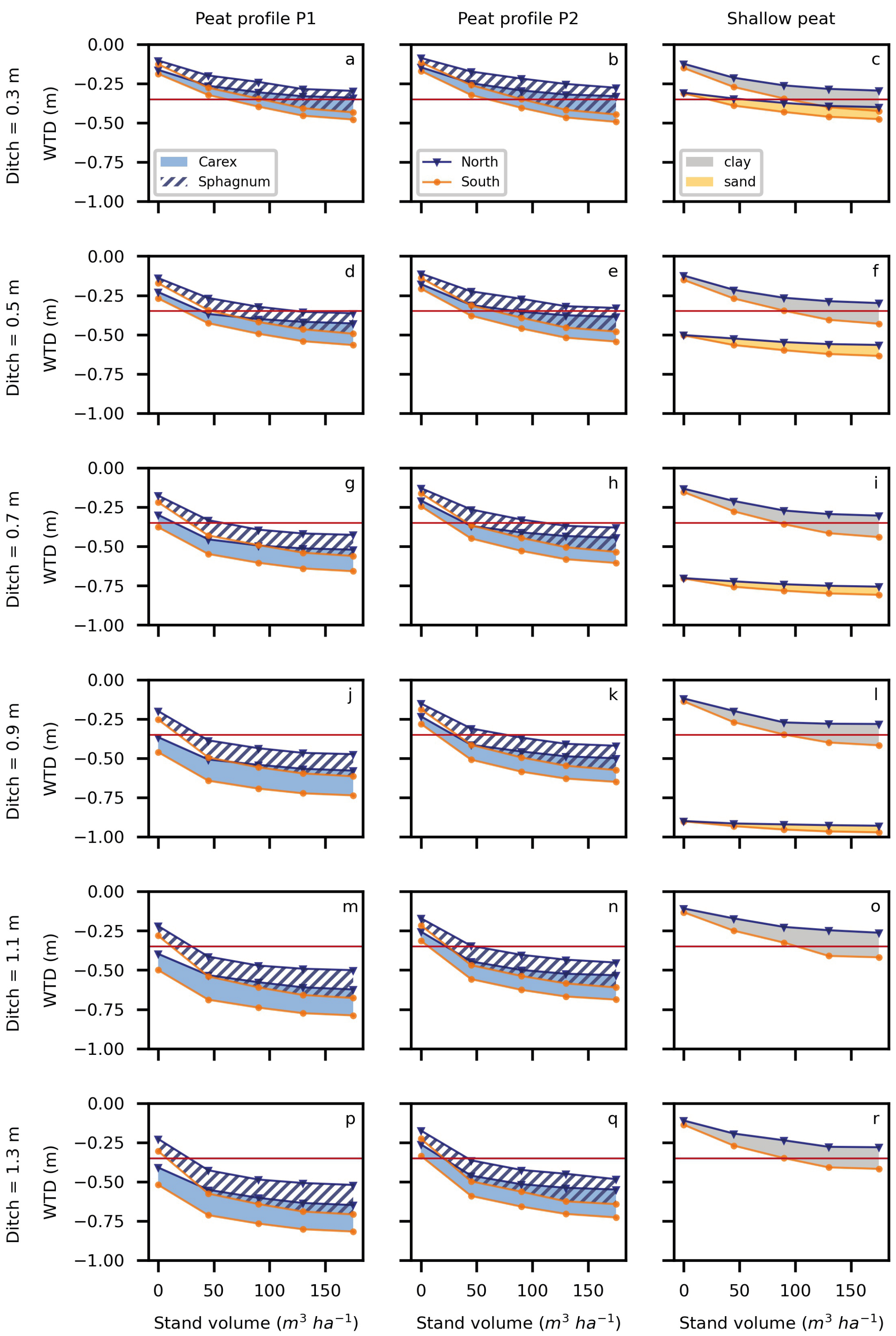

Fig. 7. Median of July–August WTDs (m) for different peat profiles (P1, P2 and shallow peat) with various ditch depths and stand volumes with ditch spacing of 40 m. The shaded or hatched area represents the range in simulated climatic conditions; the lower limit (orange dots) represents the southernmost and upper limit (blue triangles) represents the northernmost climate. In subfigures o and r, the WTD for sand subsoil profile falls below –1 m and is thus not shown. The red lines mark the –0.35 m WTD.

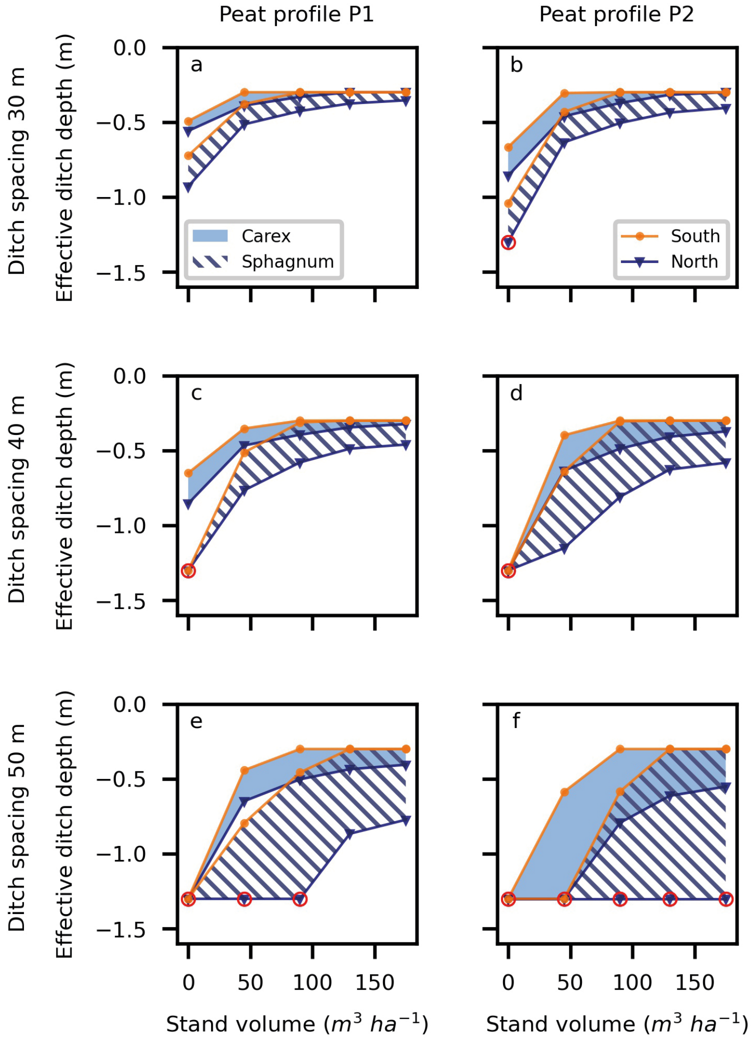

Fig. 8. The effect of peat profile (P1, P2), peat type, ditch spacing, and stand volume on effective ditch depths. Shaded or hatched area represent the range in effective ditch depths within the simulated climates, northernmost representing its lower part (blue triangles), and southernmost the upper part (orange dots). Effective ditch depths are limited between –0.3 m and –1.3 m. Target WTD (0.35 m) is not reached with the effective depths that are marked with red circle.

4 Discussion

The motivation of this study was the fact that the most harmful forestry-induced load to water courses in Finland is suspended solids originating from DNM operations (Finér et al. 2010; Nieminen et al. 2017). The current practical guidelines of DNM (Vanhatalo et al. 2015) are unspecific and permit digging of unnecessary deep ditches that lead to harmful environmental impacts. With more detailed guidelines it is likely that the suspended solid loads can be reduced. Site-specific guidelines are also needed to maintain the carbon storage of the peat layer in the drained peatlands (Ojanen and Minkkinen 2019). Keeping the aerobic peat layer above the water table as thin as possible – concurrently enabling unlimited tree growth – results in smaller decomposition rates and CO_2 emissions. This improves the sustainability of peatland forestry also in terms of carbon balance.

Our results show that in addition to technical drainage parameters (ditch depth and ditch spacing), the biological drainage by tree stand, climatic conditions as well as peat and subsoil hydraulic properties have decisive roles in determining WTD in peatland forests (Braekke 1983, Leppä et al. 2020a, b). It is beneficial and necessary to account for those effects when planning DNM operations.

The results also support the interpretation that tree stand water use may dominate over artificial drainage in controlling late summer WTD in well-stocked tree stands (Sarkkola et al. 2010, 2012, 2013). According to Sarkkola et al. (2010), WTD deepens 20–30 cm along increasing stand volume up to 150 m^3 ha^{-1}. Contrary to that, increasing ditch depth by ditch cleaning in young and mature stands has only 1–3 cm impact in WTD (Ahti and Päivänen 1997).

Our simulations suggest that in most cases clearly shallower ditches than those currently recommended in silvicultural guidelines (0.8–1.3 m, Vanhatalo et al. 2015) are sufficient, with the exception of forest clear-cut areas. Our results can guide the choice of excavation depth or postponing DNM if ditches still are deep enough.

In northern locations, deeper ditches are needed than in the south. However, the latitudinal difference is minor especially in moderately humified *Carex* peat, and ditches shallower than 0.9 m (with the typical 40 m ditch spacing) seem sufficient even at clear-cut phase. More humified *Carex* peat does not require particularly deep ditches either, except in clear-cuts. *Sphagnum* peat which has lower hydraulic conductivity (Päivänen 1973; Vompersky and Sirin 1997), however, requires clearly deeper ditches in northern than southern Finland, but even deep ditches may not be able to drain the profile.

Effective ditch depth was also affected by ditch spacing. With 50 m ditch spacing, the impacts of peat type, peat humification, and location were pronounced in such way that WTD_{35cm} could not be met in the northern locations with *Sphagnum* peat profile P2 with the studied maximum ditch depth (1.3 m). Narrowing ditch spacing to 40 m and 30 m resulted in that WTD_{35cm} was reached except at the clear-cuts in humified *Sphagnum* peat in the north.

At the clear-cut phase when tree stand interception and transpiration are small, the role of ditch drainage is more important. In operational forestry, ditch cleaning is generally recommended to support the growth of young seedling stands in connection with clear-cut and regeneration. That recommendation and our calculations do not, however, consider that mounding is a common site preparation method in drained peatlands after clear-cut in operational forestry (Nieminen 2003; Saarinen et al. 2013; Hytönen et al. 2020). Thus, the seedlings grow in about 10–20 cm high mounds, which may clearly decrease the need for any deeper ditches than in young and mature stands. Additionally, shallow complementary ditches may be dug in connection with a mounding operation. Furthermore, because of their superficial root systems, high WTD is unlikely to limit seedling growth (Saarinen et al. 2013) as much as it limits the growth of young and mature tree stands.

In case a shallow peat layer (here 0.3 m thick) overlies highly conducting till or sandy subsoil, water table is generally nearly equal to ditch depth and thus shallow ditches reaching the highly conductive layer are sufficient (Koivusalo et al. 2008). In case where the peat overlies poorly conducting soils, ditches deeper than the peat layer do not contribute much to drainage either; in contrast they often seriously deteriorate the water quality (Joensuu et al. 1999; Nieminen et al. 2010; Stenberg et al. 2015). In these cases, maintaining biological drainage through tree stand evapotranspiration (e.g. continuous cover forestry, Nieminen et al. 2018) is likely a more feasible alternative. The results also imply that humified peat is difficult to drain sufficiently just by deepening the ditches, but in favorable climate conditions in southern Finland the growing tree stand can effectively lower WTD also in humified peat.

The current recommendations for ditch depth in DNM operations for sites with peat thickness of 0.3 m or less are 0.6–0.9 m in private forestry (Vanhatalo et al. 2015), and 0.6–0.7 m in state's forests (Metsähallituksen ... 2014). Our results showed that ditches do not need to be significantly deeper than the thickness of peat deposit in shallow-peated areas. According to Korhonen et al.

(2017), 30% of drained peat soils in Finland have a peat layer shallower than 0.3 m. The 30% share corresponds to an area of 1.4 mill. ha, where significantly shallower ditch depth than in forestry recommendations could be used without compromising the growth of peatland forests.

We used long-term median July–August water table depth (WTD_{35cm}) as the threshold for determining sufficient drainage conditions for tree growth in peatlands. This choice was based on studies conducted by Pelkonen (1975), Huikari and Paarlahti (1968), and Sarkkola et al. (2012) which showed that good tree growth does not necessarily require deeper water levels. The chosen target WTD of 35 cm depth resulted in 61 cm effective ditch depth on average in the simulation data. With 30 or 40 cm target WTD the respective effective ditch depths were 54 and 69 cm, i.e., 5 cm change in target WTD induced 7 or 8 cm change in ditch depth. The largest changes were 12 and 13 cm in humified *Sphagnum* peat and the smallest changes were 1 and 2 cm in shallow peat with sand subsoil. Thus, choosing a shallower or deeper target WTD would cause largest changes in effective ditch depth in sites where the peat drainability is poorest.

We assessed the WTD_{35cm} criterion and the maximum effective ditch depth (1.3 m) to also account for what is realistic and feasible under true conditions in the field. Exceptionally rainy summers may raise WTD near soil surface no matter how effectively peatlands are drained (Sarkkola et al. 2010). Thus, it is not possible to build a drainage system that provides good drainage in all weather situations. Our 40-year simulation data also revealed variation between years. An assessment of the distribution of the WTD's reached with the effective ditch depths in individual summers showed that in 80% of the cases (79% for thick peat layer cases), mean July–August WTD falls between –0.2 and –0.7 m. Additionally, 18% and 2% of the values fall above WTD –0.2 m and below WTD –0.7 m, respectively. It should also be noted that while shallow ditches (<0.5 m) may already be sufficiently deep for tree growth, excavating such ditches may be unfeasible because it is technically difficult to ensure sufficient slope and water flow.

The model approach for determining required ditch depth is applicable for practical forestry, and can be extended also to more fertile spruce-dominated peatlands. Most of the variables that are used in determining the effective ditch depth are easily obtained and include stand location, stand volume, and ditch spacing. Peat hydrologic characteristics, in turn, are laborious and uncertain to measure directly. However, they can be approximated from site classification as done here. In general, *Carex* peat is commonly found in drained composite pine mire sites (i.e., PtkgII and MtkgII sites according to Laine et al. 2012) which are the most common targets of DNM. *Sphagnum* peat is more common in low-productive pine mire sites (PtkgI and VatkgI). The peat profile P1 is likely more commonly found in the field, but decomposition of peat increases with time since drainage. To communicate our results to practitioners, the results from model scenarios (Fig. 8) are combined into a simple summary model that allows determining effective ditch depth for a range of locations, site properties and stand volumes and can be loaded from: https://colab.research.google.com/drive/1wJT-oAv5REIBnKRmvuirrbzrrLDztp38?usp=sharing.

5 Conclusions

We evaluated minimum required ditch depth to ensure adequate drainage conditions across Finnish Scots pine dominated peatland forests using hydrological modeling. Assuming that 0.35 m median late growing season WTD is sufficient to sustain tree growth in drained peatland forests, excavating deeper ditches than about 0.9 m is necessary only in certain situations. These involve young seedling stands in clear-cut areas, highly-decomposed *Sphagnum* peat sites, and location in northern Finland. However, in clear-cut areas site preparation by mounding can partly compensate for the need of deeper ditch depth. The results suggest that in shallow-peated sites (approx. 1/3 of the drained area in Finland) ditches that reach the conductive mineral subsoil are sufficient and digging deeper ditches is unnecessary from drainage point of view.

The results provide new and condition-specific recommendations for planning ditch network maintenance in pine dominated stands. For operational forestry, the results of this study are compiled into a practical tool to determine the effective ditch depth in different situations (locations are those used in this study).

The source code for SUSI is distributed under MIT-licence from https://github.com/annamarilauren/susi. The repository also contains test input data for running the model.

Acknowledgements

The authors wish to acknowledge CSC – IT Center for Science, Finland, for computational resources. The study was partly funded by the ERF-project Vesiensuojelun laatuloikka – menetelmäkehitys Etelä-Savossa A73482 (2018–2020) and by Academy of Finland (no. 296116, 310203, 311925, 325168, 326818, 296116, 323997, and 323998).

Supplementary files

S1.pdf; Table S1. Degree of humification (von Post scale) and hydraulic conductivity in the soil profiles used in the simulations,
S2.pdf; Figure S2. Median of July–August WTDs (m) for different peat profiles (P1, P2 and shallow peat) with various ditch depths and stand volumes with ditch spacing of 30 m,
S3.pdf; Figure S3. Median of July–August WTDs (m) for different peat profiles (P1, P2 and shallow peat) with various ditch depths and stand volumes with ditch spacing of 50 m,

available at https://doi.org/10.14214/sf.10494.

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