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Impacts of ditch cleaning on hydrological processes in a drained peatland forest

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Abstract

One fourth (5.5 Mha) of forests in Finland are growing on peatlands that have been drained to improve forest growth. Forestry operations such as cuttings and ditch network maintenance in these areas may increase export of suspended solids and nutrients, and deteriorate water quality in receiving lakes and rivers. Mitigation of the deterioration calls for understanding how forest management operations affect peatland hydrology. A process-based simulation model FEMMA was applied to quantify the effects of ditch network maintenance on peatland water balance. The model has separate computation routines for evapotranspiration in tree stand and understorey vegetation, snow accumulation and melt, water movement in unsaturated and saturated soil, and drainage. Hydraulic characteristics of peat, as well as different drainage designs can be parameterised in the model. The model was applied in artificially delineated research catchments in northern Finland, where the ditch network was maintained by cleaning and digging the ditches deeper. The simulation results indicated that ditch cleaning affected the water balance slightly and the effect was dependent on stand characteristics and soil structure. When the growing stock volume was low and poorly conductive soil extended close to the soil surface, ditch cleaning increased evapotranspiration. In stands with a high stock volume and a thick topmost layer of highly conductive soil, evapotranspiration was less affected. In the study catchments, the effect of ditch cleaning on runoff was small compared to the error between measured and modelled runoff.

1 Introduction

Forest cuttings in the middle of 20th century exceeded the annual growth of the stock volume in Finland. In order to increase timber production, peatland areas were artificially drained with open ditches and reclaimed for forestry. In late 1960s' and early 1970s' more than 250 000 hectares of pristine peatlands were ditch-drained annually

(Kenttämies, 2006). The drainage activities decreased gradually until late 1990s', when practically no drainage was conducted in pristine peatlands. The ditches deteriorate with time (Hökkä et al. 2000) and can decrease the growth of tree stands, which calls for a maintenance of the ditch network, i.e. digging supplementary ditches or cleaning old ditches. The demand for the ditch network maintenance has increased and is currently estimated to be about 160000 hectares per year (Tomppo, 2005). According to national forest inventory data from 1996 to 2003 about one fourth of managed forests in Finland are located on peatlands (Tomppo, 2005). The share of peatlands drained for forestry is about 54% of the total peatland area in Finland.

The hydrological effects of drainage of pristine peatlands have been studied widely (e.g., Kaitera, 1955; Mustonen and Seuna, 1971; Starr and Päivänen, 1981; Ahti, 1987; Prévost et al, 1999). Holden et al. (2004) provides an extensive review about drainage effects on peatland hydrological and hydrochemical processes. It is well established that drainage of peatlands has both short- and long-term effects on hydrological processes, and that the effects are dependent on local conditions. Drainage may decrease or increase low flow and peak flow volumes depending on peat type and structure, hydraulic characteristics of drainage network, location of drained area within the catchment, and vegetation response to drainage. The total volume of runoff often increases as the surface soil layers become dryer, the wetland vegetation degenerates, and evapotranspiration decreases immediately after the drainage. The long-term impact of successful drainage of peatland is seen as increased growth and biomass production of tree stands (e.g. Seppälä, 1969; Hökkä, 1997). Increased height and leaf area index (LAI) of the tree stand result in higher canopy interception and transpiration, which gradually leads to a decrease in total runoff volumes. A well-growing and densely-stocked tree stand may have a decisive role in the water balance of a drained peatland. Päivänen and Sarkkola (2000) suggested that maintenance of a ditch network is not necessarily required, when the volume of the growing stock is sufficiently large for efficient interception and transpiration. A question of major importance for practical forestry is to assess whether ditch network maintenance is required, or whether the water uptake of the forest stand is large enough to maintain favourable moisture conditions in the root zone. Drainage of peatland also has long-term influences on the structure of the topmost peat layers. Decreasing soil moisture content enhances subsidence and decomposition of peat and can alter the soil hydraulic properties (Holden et al., 2004).

Ditch network maintenance deteriorates water quality of receiving streams especially by increasing the loads of suspended solids (Joensuu, 2002). Erosion and sediment transport to the receiving water bodies are most conspicuous during the first years after the digging operations, but long-term loading can be seen both in suspended solids and nutrients such as mineral nitrogen and potassium. The water cycle and the flow pathways are crucially important factors behind the water quality processes.

While the hydrological effects of draining pristine peatland are well studied, it is not fully known whether ditch network maintenance has a similar effect on the water cycle of a peatland forest ecosystem. Joensuu et al. (1999, 2001, 2002) studied how ditch maintenance affected runoff, erosion, sediment transport, and nutrient loads by comparing infrequent (biweekly–monthly) measurements from a large set of small catchment pairs. One pair included a treated catchment and a control catchment, both of which had been drained from one to three decades before the maintenance. Clear effects of the ditch maintenance on water quality were detected, but the effects on measured runoff were less visible. Accordingly, ditch network maintenance presumably had no significant effects on the flow volumes leaving the research sites. Päivänen and Sarkkola (2000) also suggested that forest thinning and ditch maintenance had minor impacts on hydrology in terms of measured water table elevation. Ahti and Päivänen (1997) reported that the ditch network maintenance alone resulted in a drop of ca 0.05 m in the highest levels of the water table. The data and methods used in these studies did not support an evaluation of the ditch maintenance effects on water cycle as a whole.

Hydrological modelling is an appealing option for estimating the impacts of forest management practices on hydrological processes. A model calibrated against data contains a logical sequence of process descriptions explaining the relationship between input (meteorological) and output (hydrological) variables. Examples of combining experimental and model simulation results in explaining the influence of forest management (clear-cutting) on water and nutrient cycles are presented in Kokkonen et al. (2006), Koivusalo et al. (2006), and Laurén et al. (2005). In these case studies, a hydrological and nitrogen transport model FEMMA included a separate process description for simulating how forest canopy affects interception, transpiration, snow accumulation, snowmelt, and soil water regime. Such a process description makes a distinction between water balance components in a forest ecosystem. Given the fact that a large proportion of forests are growing on drained peatland areas in Finland, it is important to include a computation routine for simulating the effects of ditching on the water balance of a forest ecosystem.

Inclusion of drainage is a standard option in many simulation models that are used in agricultural water management (e.g., Skaggs, 1980; Jarvis, 1994; Oztekin et al., 2004; Oosterbaan et al., 1996). Amatya et al. (1997) and Skaggs et al. (2006) have implemented ditch drainage scheme into a forest ecosystem model. Dunn and Mackay (1996) demonstrate through a modelling case study that drainage has an important influence on hydrology and that the direction of change caused by the drainage may not be intuitive. Mathematical modelling is a useful aid in testing hypotheses about the mechanisms behind the drainage effects.

This study is based on exploiting unpublished hydrological data from Tilanjoki, northern Finland, where four artificial catchments were formed using ditch delineation. The areas were newly drained in 1969 and twenty years later two of the areas were subject to ditch network maintenance, i.e. cleaning and deepening of the ditches. FEMMA model was modified to include drainage fluxes and simulate the hydrological effects of ditch cleaning. The objective was to compose from field measurements and simulation results a holistic view of changes in hydrological processes after the ditch cleaning. The purpose of the model application was to bind together snow, water table level, and runoff measurements, and to simulate how ditch cleaning affects interception, transpiration, snow processes, moisture content of peat layers, and runoff in different forest stands. Quantitative assessment of hydrological fluxes and pathways in drained peatlands serves for further estimation of ditch cleaning impacts on water quality at the catchment outlet.

2 Site description and field data

Tilanjoki research area is located in the northern Finland at the border between two municipalities, Utajärvi and Puolanka (Fig. 1a). There are large peatland areas drained for forestry within the region. Mean annual temperature in the area was 1°C and precipitation was 550 mm/a during 1971–2000.

The peatland in Tilanjoki was drained for the first time in 1969, four experimental catchments were delineated in 1983, and ditch cleaning was conducted in two of the catchments in 1989 (Fig. 1b). Spacing of the ditches ranges from 28 to 43 m, the depth of the ditches prior to the cleaning was 0.3–0.5 m, and 0.8 m after the cleaning.

Runoff at the outlet of each catchment was measured using v-notched weirs and limnigraphs plotting the height of the water level at the weir. Inside the four catchments there were altogether 39 measurement sites, where snow depth and depth of the level of water table was measured at three points in each site (Fig. 1b, c). Air temperature, relative humidity, and precipitation were recorded at two weather stations near the outlets of catchments 1 and 4. In addition to on-site meteorological measurements, precipitation, air temperature, relative humidity, wind speed, and cloudiness were available from nearby stations operated by the Finnish Meteorological Institute in Särkijärvi (Utajärvi), Vaala and Puolanka (Fig. 1a).

The measurement period for hydrometeorological variables was from 1983 until 1994. The frequency of manual snow and groundwater level measurement was once in 1–2 weeks. Printed graphs of runoff and air temperature were processed in order to produce daily time series of the measurements.

Tree stands in the study catchments are dominated by Scots pine (*Pinus sylvestris*

L.) with a minor admixture of pubescent birch (*Betula pubescens* Ehrh.) and Norway spruce (*Picea abies* L. Karst.). Stand characteristics, as well as characteristics of dominant trees (100 largest trees per ha), including height, diameter at breast height (DBH), and tree density were measured from sample plots establishes in 39 measurement sites. In 1983, 1989, and 1995 the percentage of Scots pine trees from the total stand volume was 91%, 90 %, and 89%, respectively. The stand volumes in the measurement sites ranged from 1.6 to 154 m^3/ha and the median volume was 30 m^3/ha in 1983. The understorey vegetation was composed of *Spaghnum* moss, sedges, and dwarf shrubs.

The soil in Tilanjoki is composed of a peat layer underlain by mineral soil. The thickness of peat layer varies considerably among the 39 measurement sites, ranging from 0.07 m to more than 1.5 m. In 37 sites subsoil is sand or till.

3 Methods

A simulation model, FEMMA, was calibrated and tested against hydrological measurements in Tilanjoki and applied to assess the impacts of ditch maintenance on water balance components. FEMMA is a forest ecosystem model that separates the processes of overstorey and understorey interception and transpiration, snow accumulation and melt, soil- and ground water interactions, and streamflow. In the current study, FEMMA uses daily time series of air temperature, precipitation, relative humidity, wind speed, and downward short and long-wave radiation as an input. FEMMA has earlier been applied in investigating how clear-cutting affects water and nitrogen fluxes in hillslopes comprising mineral up-slope and peat down-slope areas (Koivusalo et al., 2006; Laurén et al., 2005).

In the current study, the model has undergone changes that were introduced to 1) improve the description of the canopy model in morphologically young and sparse peatland forests, 2) facilitate computation of the drainage flux as a water balance component, 3) improve prediction of the water table level, and 4) formulate a spatial description of a modelling domain for a drained peatland forest. The next paragraphs briefly address these changes together with a general description of FEMMA.

3.1 Canopy and snow models

Based on input data characterising meteorological conditions above the canopy, the canopy model simulates downward short and long-wave radiation, wind speed, and throughfall beneath the forest canopy. Relative humidity and air temperature are assumed not to be affected by the canopy. The process descriptions are given in detail in Wigmosta et al. (1994), Koivusalo and Kokkonen (2002), and Koivusalo et al. (2006).

The canopy model accounts for the interception of rainfall and snowfall in the overstorey vegetation (trees), and for the interception of rainfall in the understorey vegetation (field and ground layer). Whenever the ground is snow-covered, interception in the understorey is disregarded. The stand density gives the fraction of the ground that is covered by the overstorey. In the current version of the model, the method presented by Raupach (1994) and Schaudt and Dickinson (2000) is applied to parameterize the zero plane displacement height and the roughness height as a function of the stand density (canopy closure) and crown ratio (see Sect. 3.4.). The parameterization ensures that aerodynamic resistance decreases, when canopy closure approaches either full coverage in a dense forest or zero in a very sparse forest. The density of the understorey canopy is set to the value of one.

Potential evaporation of intercepted water is computed separately for the overstorey and understorey vegetation according to a combination equation of the Penman–Monteith type where the stomatal resistance is set to zero. Evaporation of the intercepted water occurs at the potential rate until all intercepted water is depleted. Transpiration, which is initiated after the canopy has become dry, is controlled by the stomatal resistance. The stomatal resistance is controlled by leaf area index (LAI), soil temperature, water vapour pressure deficit, photosynthetically active radiation (PAR), and soil moisture. Evaporation from the soil surface is neglected, because the moss and undecomposed litter covering the ground are assumed to block evaporation from the peat surface.

The snow model simulates snow surface energy balance, heat conduction through the snowpack into soil, snowmelt, liquid water retention in snow, melt water discharge out of the snowpack, and compaction of snow. The model has been described in more detail in Koivusalo et al. (2001, 2006).

3.2 Characteristic profile model

Soil and ground water interactions in FEMMA are described based on the characteristic profile approach of Karvonen et al. (1999). In the case of a drained peatland, the characteristic profile is a vertical one-dimensional column residing between the drainage ditch and the midpoint between two parallel ditches. Soil water movement and runoff generation processes are simulated using daily series of throughfall/snowmelt as an input from the canopy and snow submodels. The characteristic profile model is quasi-two-dimensional in the sense that vertical and lateral water fluxes are computed alternately. The soil column is divided vertically into soil layers and water fluxes between the layers are computed according to the Richards equation (Richards, 1931). Transpiration is extracted from the soil layers residing within the root zone. Infiltration into a soil column is controlled either by the current air-filled pore volume of the topsoil layer or by the hydraulic conductivity between the soil surface and the topsoil layer. Water that cannot infiltrate is transported laterally to the ditch as surface runoff.

In order to simulate the effect of drainage on transpiration, the soil moisture control on transpiration has been changed from earlier applications of FEMMA. Schwärzel et al. (2006) studied moisture dynamics and evapotranspiration in a drained peatland and presented a relationship between the root zone pressure head and the ratio of actual and potential evapotranspiration. The relationship was adopted in FEMMA to characterise how excessive soil moisture or soil drying in the root zone decrease transpiration. The stomatal resistance r_s is given by

$$r_s = r_{s\,\min} f_1^{-1}(T_{\text{soil}}) f_2^{-1}(\Delta e) f_3^{-1}(\text{PAR}) f_4^{-1}(\theta) \quad (1)$$

where $r_{s\,\mathrm{min}}$ is the minimum stomatal resistance, $f_1(T_{\mathrm{soil}})$ is a function describing the influence of the soil temperature T_{soil} on r_s, $f_2(\Delta e)$ defines the influence of the vapour pressure deficit Δe on r_s, f_3 (PAR) defines the influence of the photosynthetically active radiation (PAR) on r_s, and $f_4(\theta)$ depicts in the influence of the soil moisture θ on r_s. The functions $f_1(T_{\mathrm{soil}})$, $f_2(\Delta e)$, f_3 (PAR) are given in Nijssen et al. (1997) and the soil moisture function is illustrated in Fig. 2. When the pressure head of a computation node in the root zone is between −0.15 m and −0.70 m, soil moisture does not limit transpiration. Schwärzel et al. (2006) sketch the relationship down to a pressure head of about −1.2 m, where the ratio of actual and potential evapotranspiration is about 0.5. In this study, the function $f_4(\theta)$ is assumed to further decrease toward zero, when the pressure head approaches the wilting point (dashed line in Fig. 2).

After the vertical fluxes and the resulting groundwater level of a column have been solved, the lateral flows to drainage ditches are computed. When there is snow on the ground, surface runoff is delayed using a linear storage. Lateral drainage flow within the soil column is computed according to Hooghoudt's drainage equation (e.g., El-Sadek et al., 2001). The method assumes steady state recharge and drainage fluxes and allows a description of soils with different values of an effective saturated hydraulic conductivity above and below a ditch depth. The water level in the ditch is set equal to the elevation of the ditch bottom and it prescribes a boundary condition for the drainage flow computation. Ditch cleaning changes the boundary condition when the ditches are dug deeper.

In earlier applications lateral groundwater flow was included in the model to account for subsurface flow in saturated soil (e.g. Kokkonen et al., 2006). In the current study, drainage flow is assumed to be the only lateral subsurface flow mechanism in peatlands drained with open ditches. After the drainage flow ceases no groundwater flow is assumed to occur. The sum of two runoff components entering a ditch – surface runoff and drain flow – forms the total runoff.

3.3 Assumptions behind the parameterisation of ditch cleaning

In FEMMA only direct hydrological effects of ditch cleaning are considered. It is assumed that subsidence of peat soil has mainly occurred during the years following the initial drainage, and that the structure of the peat does not change during the five-year period following the ditch cleaning. The saturated hydraulic conductivity is assumed to be significantly higher in topmost soil layers compared with subsoil, and this difference is not influenced by the ditch cleaning. The effect of the cleaning operation on the forest biomass is not simulated. Temporal changes in forest properties, such as LAI, canopy density, and tree height are estimated based on measured forest characteristics (see Sect. 3.4.). Understorey vegetation is assumed to adapt immediately to changed soil moisture conditions, i.e. there is no degeneration of old species or invasion of new species. Both overstorey and understorey transpiration are limited by excessive soil moisture conditions or soil drying as described in Fig. 2. Changes in channel flow processes caused by ditch cleaning are ignored, because the flow delay caused by the ditch network is likely to be shorter than the daily modelling time step in the studied research catchments.

3.4 Parameterisation of Tilanjoki experimental catchments

One characteristic profile, i.e. a soil column between two parallel drains, was prescribed for each measurement site where snow depth, snow water equivalent (SWE), and water table level had been measured. As the number of snow observation points per site (three snow depths and one SWE) did not warrant the calibration of canopy and snow model separately for each site, the model was not calibrated against snow data. Instead, the snow model parameters were adopted from Koivusalo et al. (2006).

The input data for the snow and canopy model were from the closest weather stations. Downward short- and long-wave radiation fluxes were estimated based on air temperature, simulated clear-sky radiation, and cloudiness index (see e.g. Tarboton and Luce, 1996). Daily air temperature is averaged from temperature graphs measured on-site during 1983–1988 and 1993–1994, but the missing temperature values over these years and all temperature values during 1989–1992 were estimated as the mean temperature of the closest two weather stations (Särkijärvi and Puolanka). On-site temperature measurements during 1989-1992 were not used, because they deteriorated the performance of the snow model.

Forest stand characteristics for each site were prescribed according to available inventory data from years 1983, 1989, and 1995. The stand properties between the measurement times were estimated with linear interpolation. In order to derive LAI at each site, the needle biomass of Scots pine was computed from the stand properties in the following way. A two-parameter Weibul distribution characterizing the stand DBH distribution was fitted against the measured arithmetic mean DBH of the stand and the mean DBH of the dominant trees. Once the Weibul distribution was created, the needle biomass was computed for ten discrete DBH classes using the biomass function proposed by Hakkila (1979). The biomass for different DBH classes was subsequently multiplied with the stem number and the specific needle area to produce the estimate of LAI. Finally, the relationship between the effective winter leaf area index and the forest density (Pomeroy et al., 2002) was applied to derive canopy closure directly from the LAI estimate. Figure 3 illustrates the distribution of LAI and canopy closure in the measurement sites of Tilanjoki. The estimated values of LAI and the canopy closure were used in the parameterisation of the overstorey vegetation. The LAI for the understorey vegetation was fixed to a value of 1.0.

The parameters of the functions controlling stomatal resistance are fixed to the values reported in Nijssen et al. (1997), except for the parameter defining the minimum stomatal resistance ($r_{s\,\mathrm{min}}$), which was calibrated against water table level and runoff measurements. In earlier studies with a similar model for simulating transpiration, the value of minimum stomatal resistance for coniferous trees has ranged from 100 to >1000 s/m in (e.g. Wigmosta et al., 1994, Nijssen et al., 1997; Whitaker et al., 2003, Koivusalo et al., 2006). The rest of the canopy model parameters are set according to Koivusalo et al. (2006) with the exception of the new parameter, the crown ratio, which is set to a value of 3.5 (see e.g., Schaudt and Dickinson, 2000).

Tilanjoki area is characterized by shallow peat thickness in most of the measurement sites. In this study, topsoil refers to the shallow peat layer, except in two sites (7 and 8) with a deep peat formation, where the topsoil refers to peat layer above the depth of the ditches. Subsoil refers to all material below the topsoil. The depth of the topsoil was measured at the groundwater tube located midway between two ditches. Spatial distribution of subsoil layers was interpreted from ground penetrating radar measurements. Spatial data indicate that the measurement sites are scattered through an area where subsoils are composed of peat, till, and sand. Spatial data together with water table measurements were utilized to prescribe the dominant type of subsoil at the measurement sites. Water table after the ditch cleaning tends to drop lower at sites with sandy subsoil compared to sites with peat or till at the bottom (see Fig. 4 as an example). The dominant subsoil type was assumed to be sand at sites where water table dropped deep in the soil during summer dry periods and where bottom sandy deposits were located close to the measurement site according to the spatial data. In sites where water table remained close to the soil surface, the subsoil type was set to till or peat according to the spatial data.

Water retention curves for the peat soils were described separately for the layer extending down to a depth of 0.3 m from soil surface, and for the peat layer below the depth of 0.3 m. The retention characteristics for these two peat layers were adopted from Päivänen (1973), who tabulated water retention characteristics at different depths and for different bulk densities of *Sphagnum* peat. In the current study, parameters of the van Genuchten (1980) function were fitted against the data from Päivänen (1973). Temporal changes in peat characteristics were neglected. On-site measurements of particle size distribution and the relationship of Jauhiainen (2004) were used to derive the water retention characteristics of mineral soils.

In addition to defining the thickness of the peat layer in each measurement site, a depth to an interface between a highly conductive upper soil layer and a less conductive lower soil layer was deduced from water table measurements in each site. In Fig. 4

behaviour of water table during a rainy year of 1987 is encircled. Water table remained close to the surface at all sites and varied less in time during the wet summer of 1987 compared to other years in Tilanjoki. The depth of an interface between soil zones having high and low hydraulic conductivity was set equal to the median level of the measured water table in the summer of 1987 (May-September). It was found out that this depth of highly conductive upper soil layer differed from the depth of the peat layer, which indicates that the depth of the peat layer in the midpoint between two drains is not a good indicator of the conductivity structure of the soil. The values of saturated hydraulic conductivity for the different soil zones were calibrated against measured water table elevation in three different measurement sites and measured runoff from catchment 3. The three calibration sites shown in Fig. 1 were number 7 (peat subsoil), 26 (sand subsoil), and 30 (till subsoil). In addition to $r_{s\,\mathrm{min}}$ and soil conductivity values, the time constant (0.2 1/d) of the linear storage that delays surface runoff was adjusted in the model calibration.

In the model setup the depth of the drainage ditch was set to 0.5 m prior to the ditch cleaning and 0.8 m after the cleaning that was carried out in study catchments 1 and 3 in autumn 1989. Changes in the depth of the ditches by erosion, sedimentation, and vegetation growth were disregarded.

The hydrological model is applied separately in each measurement site to simulate runoff input that enters the ditch network. In this study, total runoff from the study catchments was modelled as an equally weighted average runoff from measurement sites 1–11 in Catchment 1, from sites 13–19 in Catchment 2, from sites 23–37 in Catchment 3, and from sites 20–22 plus 38–39 in Catchment 4 (Fig. 1).

4 Results and discussion

4.1 Snow

Ditch network maintenance changes soil moisture regime and soil temperature, but it is not likely to change snow accumulation and melt in a short time scale. However, modelling of snow accumulation and melt is a prerequisite for a holistic assessment of hydrological processes in peatland forests.

The median value of Nash and Sutcliffe (1970) efficiencies (Fig. 5) between the measured and modelled snow water equivalent is 0.63 for all sites and the mean absolute error is 11 mm. Figure 6 presents the best snow simulation result at site 30 (Efficiency coefficient = 0.81, mean abs error = 8.1 mm) and the worst result at site 8 (Efficiency coefficient = −0.73, mean abs error = 19 mm). The simulations suggest that the meteorological variables are not consistent with snow measurements in Tilanjoki during some winters. For example, in winter 1992–1993 the measured snow water equivalent clearly decreases in December, whereas the simulated water equivalent increases. Because snowmelt has a major role in the formation of spring floods, these deficiencies in snow simulation increase errors in reproducing runoff.

The direct hydrological effects of ditch cleaning were studied by running the model at sites 1–11 and 23–37 with and without cleaning for years 1990–1994. According to the model, the cleaning of the ditches has no detectable short-term effects on snow accumulation and melt. Long term effects of the ditch cleaning would be seen, if the growth of the tree stand were increased.

4.2 Water table level

Field measurements indicate that the ditch cleaning clearly decreases the water table levels at some sites, whereas the effect is negligible at other sites. The model was applied to shed light on the causes behind the varying measurements.

Figure 7 shows the values of efficiency coefficients and mean absolute error between the simulated and measured depth of the water table level for measurement sites 1–39. The efficiency values in calibration sites (7, 26 and 30) range from 0.13 to 0.70 and mean absolute error from 3.0 to 9.5 cm. The median efficiency in the validation sites is 0.08 and the median of absolute errors is 9.6 cm. Figure 8 presents modelled and measured water table levels in sites 3 and 34, where the model had the best (efficiency coefficient = 0.75, mean absolute error = 7.2 cm) and worst (efficiency coefficient = −1.2, mean absolute error = 20 cm) performance, respectively. Site 3 had sand as subsoil type, and site 34 had till subsoil. The calibrated value of the hydraulic conductivity in the top soil layer (100 cm/h) is very high compared to the conductivities for sand subsoil (3.5 cm/h), till subsoil (0.75 cm/h), or peat (0.01 cm/h).

Figure 9 illustrates the simulation results for the time period following the ditch cleaning in sites 7 and 8, where the stand volume in 1995 was 50 and 159 m^3/ha, respectively, and the subsoil is peat. The depth of conductive soil layer is 0.25 m in site 7 and 0.52 m at site 8. The dynamics of water table is different between these two sites, which is mainly explained by the different depths of the conductive soil layer. The simulated effect of the ditch cleaning on water table level is small, when subsoil has a low value of hydraulic conductivity. Figure 10 shows the results for sites 3 and 25 with stand volumes of 17 and 195 m^3/ha, respectively, with sandy subsoil, and with depths of conductive layers of 0.32 m and 0.25 m, respectively. The effect of ditch cleaning on water table level is clear in sites with more conductive subsoil layers, such as sand. The large difference in stand volume does not affect the water level response to the ditch cleaning in Figs. 9 and 10.

Sensitivity of computed water table level to a perturbation in the ditch depth was studied by increasing the depth of the ditches by 1% for the time period after the ditch cleaning. The perturbation decreased the mean water table level by 0.63, 0.78, and 0.11% in sites where subsoil was sand, till, or peat, respectively. The level of the water table is sensitive to the ditch depth particularly in sites with coarse subsoil material.

4.3 Runoff

Accurate measurements of runoff in Tilanjoki were challenged by remote location of the site and harsh field conditions, which easily mask the effect of the ditch cleaning on runoff. Even though runoff from catchment 3 was used in the model calibration, the model results against measured daily runoff remained poor. The efficiency coefficients for the all four catchments during 1983 and 1993 were 0.54 (C1), 0.62 (C2), 0.60 (C3, calibration data), and 0.54 (C4). Deficiencies in the snow simulation results are one of the most important factors affecting the model performance.

Yearly examination of runoff data reveals that measurements during some years were more successful than during other years. Year 1984 before the ditch cleaning and year 1991 after the cleaning were studied in more detail to assess how ditch cleaning affects runoff. Figure 11a presents measured daily runoff at catchments 3 and 4 during 1984 together with the modelled runoff at catchment 4. Measured runoff from the catchment 3 is only slightly higher than runoff from the control catchment 4. The efficiency coefficient between the measured and modelled runoff at C3 is 0.74, whereas the efficiency coefficient between the measured runoff series of the two catchments is 0.96. After ditch cleaning in 1991 (Fig. 11b) the measured runoff series from the two catchments are less similar (efficiency coefficient = 0.72), because the treated catchment 3 yields higher runoff relative to catchment 4 than earlier in 1984. The modelled runoff in 1991 at catchment 3 with and without ditch cleaning (Fig. 11c) shows that the modelled effect of the cleaning is less than the effect seen in the measured data (Figs. 11a and b). The efficiency coefficient between the modelled and measured runoff series at catchment 3 is 0.65 in 1991. The efficiency coefficients suggest that the ditch cleaning effect on runoff is less than the error between measured and modelled runoff.

Sensitivity of computed runoff to a perturbation in the ditch depth was explored by increasing the depth of the ditches by 1% from the value of 0.8 m after the ditch cleaning. The resulting change in total runoff was less than 0.02% in all four catchments, which indicated that runoff was insensitive to a small change in the ditch depth.

4.4 Simulated water balance components

The modelled effect of ditch cleaning on the components of annual water balance in treated catchments 1 and 3 is seen as an increased air-filled pore space in soil, but the effect on water fluxes is small (Table 2). Ditch cleaning has an opposite impact on the two runoff components, but the net effect is that annual runoff is not affected by the cleaning of the ditches. These results characterise average behaviour within the research catchments and the small simulated changes are in line with earlier investigations about hydrological impacts of ditch network maintenance (e.g., Joensuu, 2002; Päivänen and Sarkkola, 2000).

More detailed information about the effects of ditch cleaning is produced by exploring how water balance components change in various forest stands and soil structures. According to Fig. 12a ditch cleaning increases mean air-filled pore space in all sites and the effect is largest in sites with small depths of the highly conductive upper soil layer. Figure 12b suggests that transpiration either increases or decreases after the ditch cleaning. This response is explained by the soil moisture limit in Fig. 2, where excessively high or low soil moisture restricts transpiration. In soils with a small depth of a highly conductive layer and low LAI, soil moisture in the rooting zone is often close to saturation. Drainage in this case shifts the soil moisture regime drier toward the optimum transpiration range, where moisture does not limit transpiration. In sites where the highly conductive top soil layer extends deeper than about 0.3 m or LAI is larger than about 1.2, transpiration remains higher when ditch cleaning is not conducted. When soil moisture conditions in the root zone are within the optimal range before ditch cleaning, there is a chance that drainage shifts root zone soil moisture to the range where soil drying starts to limit transpiration. In this case, ditch network maintenance is an unnecessary treatment. The effect of ditch cleaning on transpiration in different stands is reflected in the changes of total runoff (Fig. 11c). Ditch cleaning increases runoff in sites where transpiration decreases and vice versa. It needs to be noted that these results are sensitive to the parameterisation of the relationship between soil moisture in the root zone and transpiration (see Sect. 3) The finding that ditch cleaning has minor effect on transpiration in some situations has practical relevance. Assuming dependency between transpiration and tree growth the results suggest that ditch cleaning may not be necessary when stand volume of the forest is sufficiently large (50–100 m^3/ha) or top soil layer with a high hydraulic conductivity is sufficiently deep (0.3 m or deeper in the current model parameterisation).

It must be reminded that the results about the effects of ditch cleaning on water balance components are based on model simulations. Available data alone do not support identification of small changes in hydrological fluxes following ditch cleaning.

5 Conclusions

A hydrological model was applied to assess how ditch cleaning affects water balance components during a period of five post-treatment years. The model application is subject to a number of assumptions: 1) the effect of ditch cleaning on the growth of the forest biomass is neglected during the five-year study period, 2) excessively high or low soil moisture limits transpirations in the root zone, 3) the structure of the soil is not affected by ditch cleaning, and 4) there is no degeneration of peatland vegetation species or invasion of new species after the maintenance.

Simulated canopy and snow processes were not affected by ditch cleaning during the post-treatment years. Water table level was lowered and air-filled pore volume in soil increased, when the water level in ditches dropped due to ditch cleaning. Ditch cleaning had no clear effect on transpiration and runoff volumes at the catchment scale.

Model results from different sites revealed that the hydrological effect of ditch cleaning was dependent on the volume of the forest stand and the hydraulic structure of soil. Ditch cleaning increases transpiration and decreases runoff in poorly drained sites with a small overstorey vegetation (LAI<1.2) and a small depth (<0.3 m) of a highly conductive topmost soil layer. In sites with a larger forest stand and a thick topmost layer of conductive soil the cleaning of the ditch network has a minor influence on the water cycle and therefore, ditch cleaning in such sites is unnecessary. The effect of ditch cleaning on annual runoff volumes is small compared with the uncertainties related to measuring and modelling runoff. Since there are no direct measurements of transpiration and soil moisture, the relatively large effects of ditch cleaning on these hydrological components were not validated against data.

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Table 1. Mean annual water balance components (mm/a) during 1990-1994 for measurement sites located in catchments 1 and 3. The difference (mm/a) between the cleaning and no-cleaning conditions is shown in parentheses.

	Catchment 1		Catchment 3	
	No cleaning	Cleaning	No cleaning	Cleaning
Precipitation	561	561 (±0)	561	561 (±0)
Throughfall beneath overstorey	480	480 (±0)	474	474 (±0)
Throughfall on ground/snow	456	456 (±0)	450	450 (±0)
Overstorey evaporation	81	81 (±0)	87	87 (±0)
Understorey evaporation	24	24 (±0)	24	24 (±0)
Snow evaporation	14	14 (±0)	14	14 (±0)
Snowmelt/rain	448	448 (±0)	442	442 (±0)
Overstorey transpiration	48	48 (+0)	58	57 (−1)
Understorey transpiration	89	97 (+8)	102	102 (±0)
Total Evapotranspiration	256	264 (+8)	285	284 (−1)
Drainage flow	304	306 (+2)	279	287 (+8)
Surface runoff	10	1 (−9)	7	1 (−6)
Total runoff	314	307 (−7)	286	288 (+2)
Mean air volume in soil	105	145 (+40)	83	114 (+31)

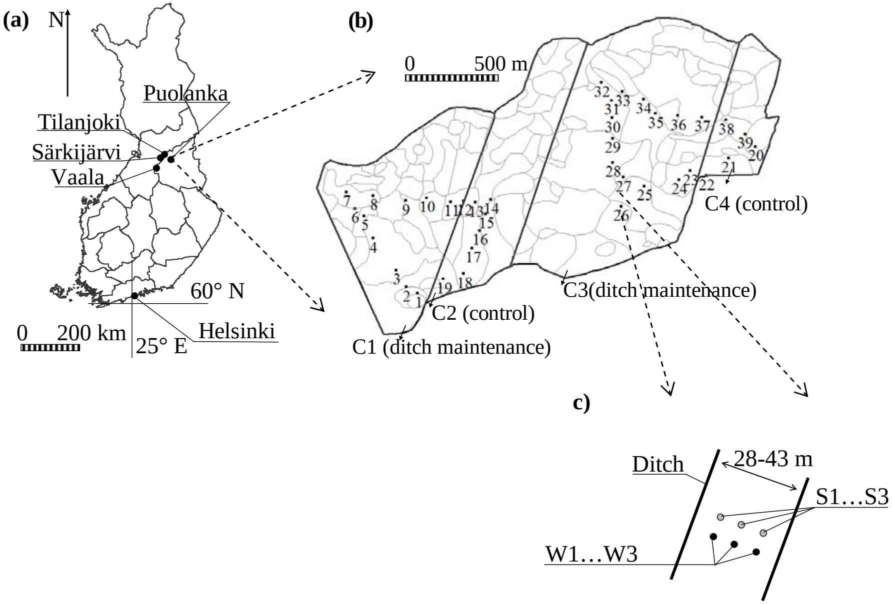

Fig. 1. Location of Tilanjoki and weather stations in Särkijärvi, Puolanka, and Vaala **(a)**, layout of 4 research catchments (C1. . . C4) and 39 measurement sites **(b)**, and layout of a measurement site between two ditches. W1. . . W3 refer to water table measurement locations and S1. . . S3 to snow measurements. Forest compartments with different tree stand properties are delineated with gray lines in (b).

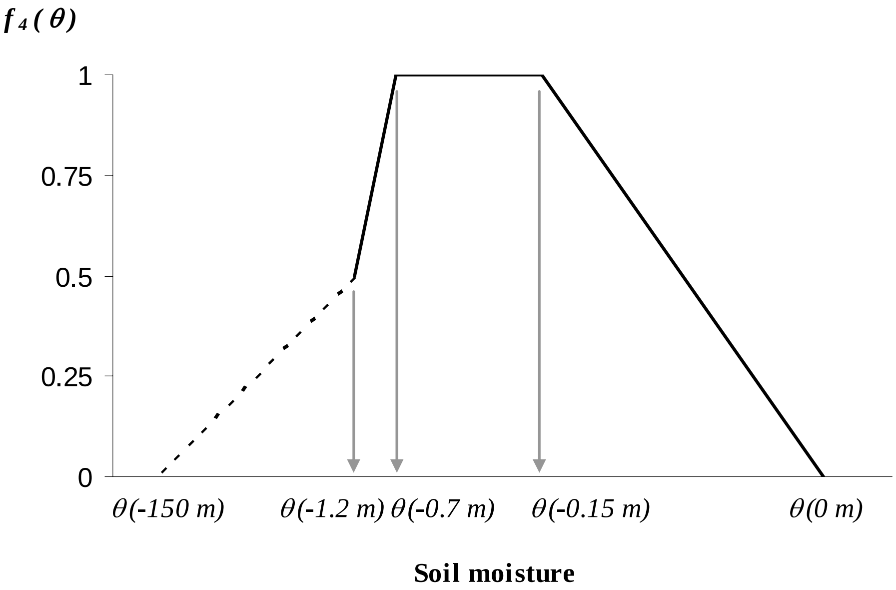

Fig. 2. Relationship between θ (pressure head) and function $f_4(\theta)$, where θ is soil moisture content. Soil moisture does not limit transpiration, when $f_4(\theta)$ is equal to 1.0.

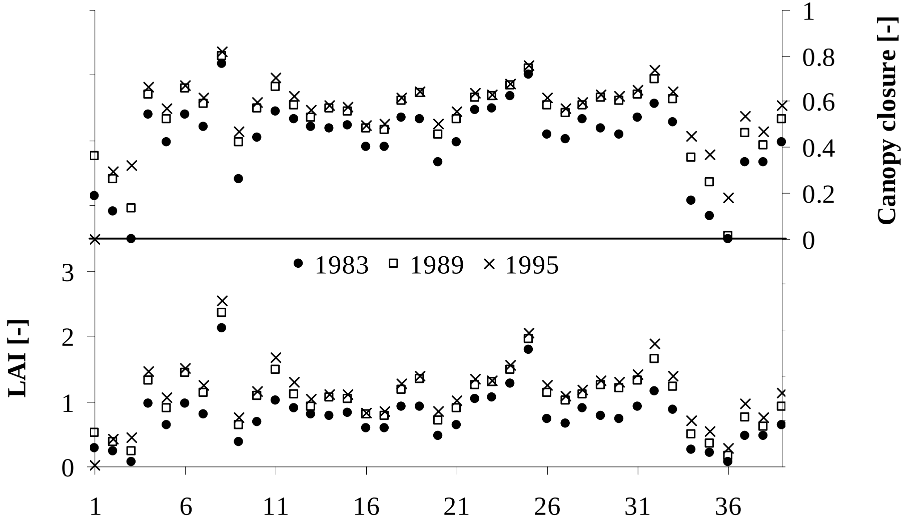

Fig. 3. Estimated values of LAI and canopy closure in years 1983, 1989, and 1995 in 39 measurement sites of Tilanjoki.

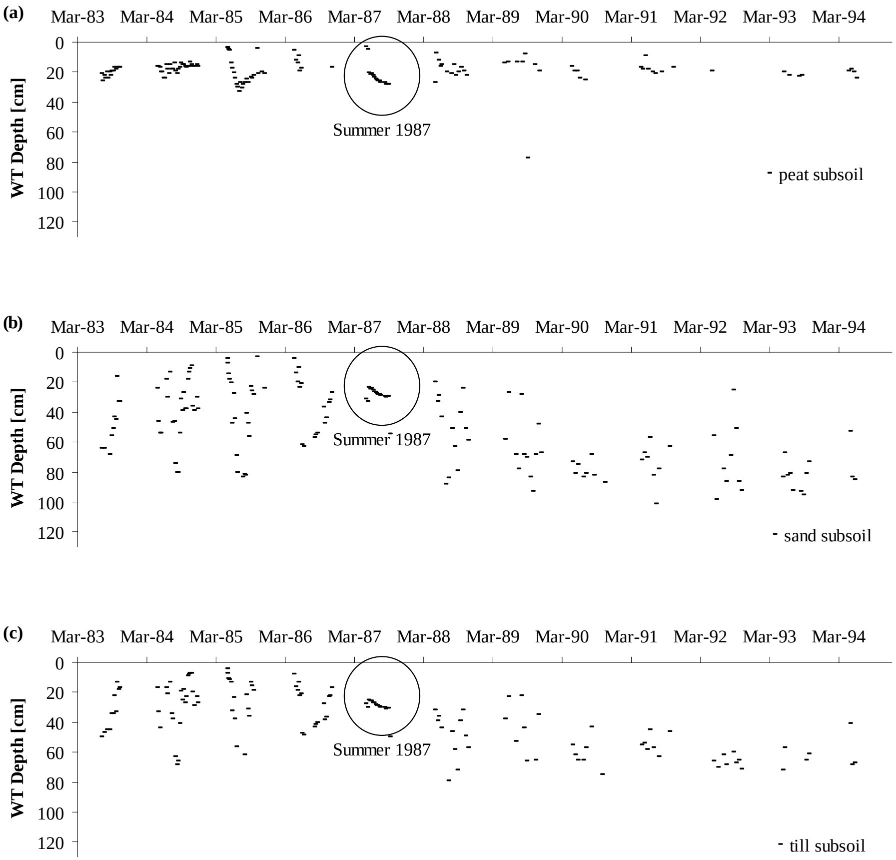

Fig. 4. Measured depth of the water table level (WT) in measurement site 7 with peat subsoil **(a)**, site 26 with sand subsoil **(b)**, and site 30 with till subsoil **(c)**. Measured values during the wet summer of 1987 are circled.

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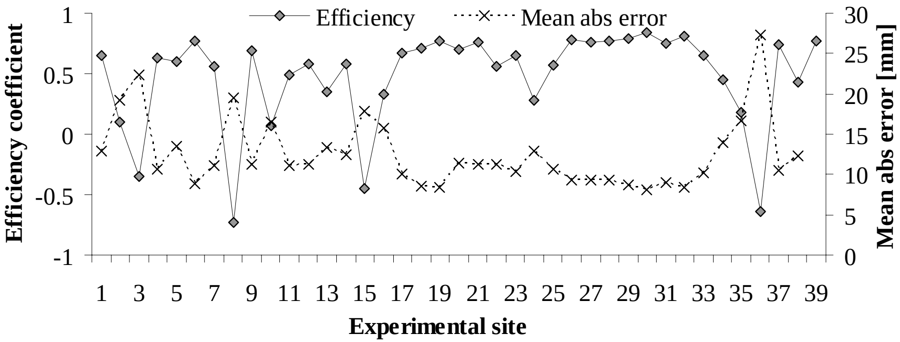

Fig. 5. Efficiency coefficients and values of mean absolute error between measured and modelled snow water equivalent in 39 measurement sites.

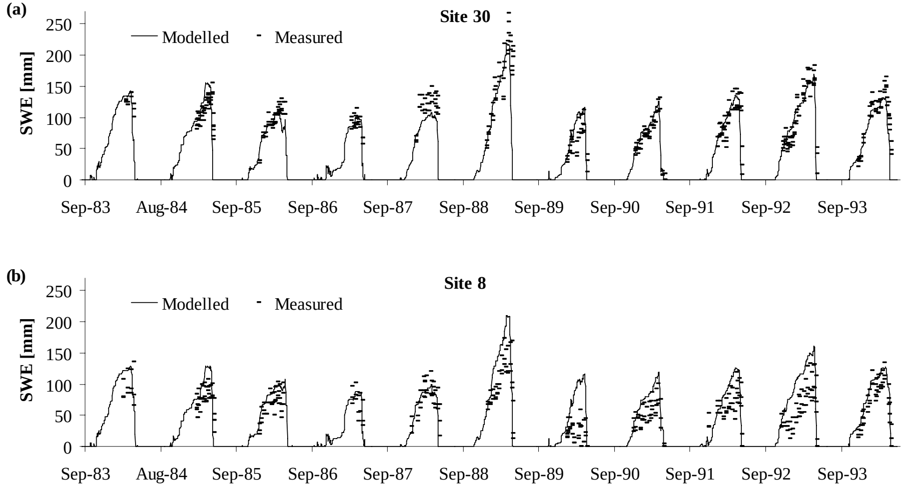

Fig. 6. Simulated snow water equivalent (SWE) and measured SWE at three points in site 30 **(a)** and site 8 **(b)**.

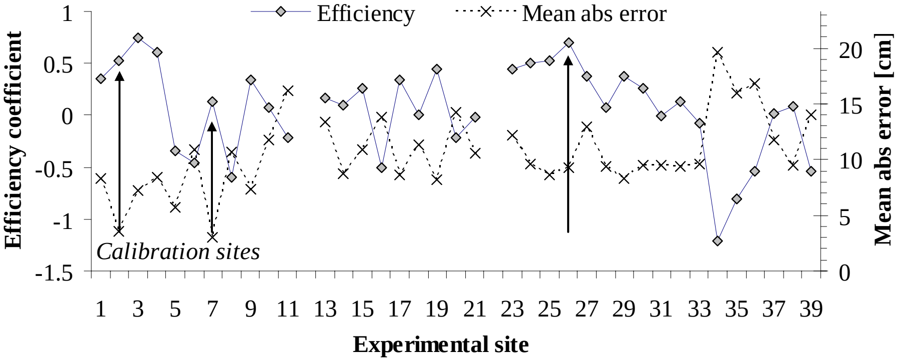

Fig. 7. Efficiency coefficients between the measured and modelled water table level in 39 measurement sites. Measurements in three sites 7, 26, and 30 were used in the model calibration.

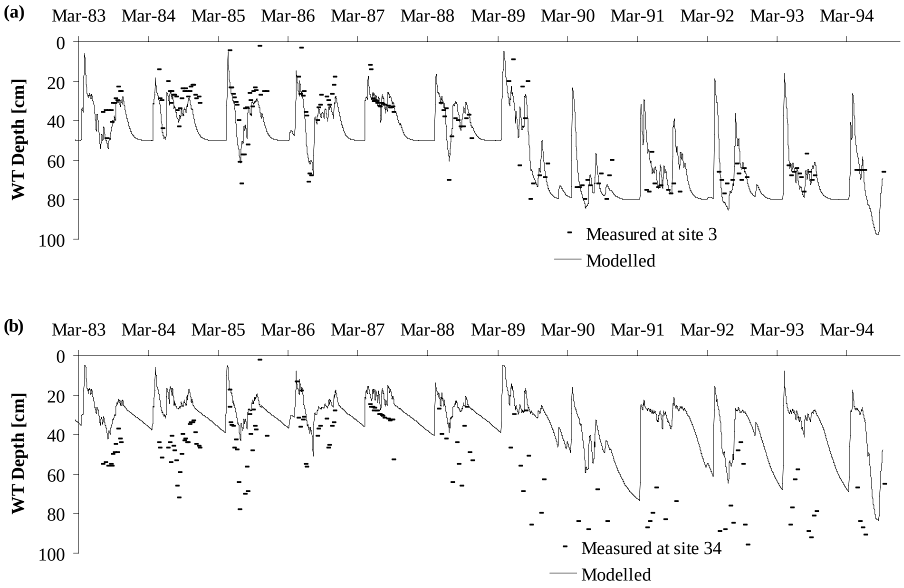

Fig. 8. Measured and modelled water table levels in sites 3 **(a)** and 34 **(b)**.

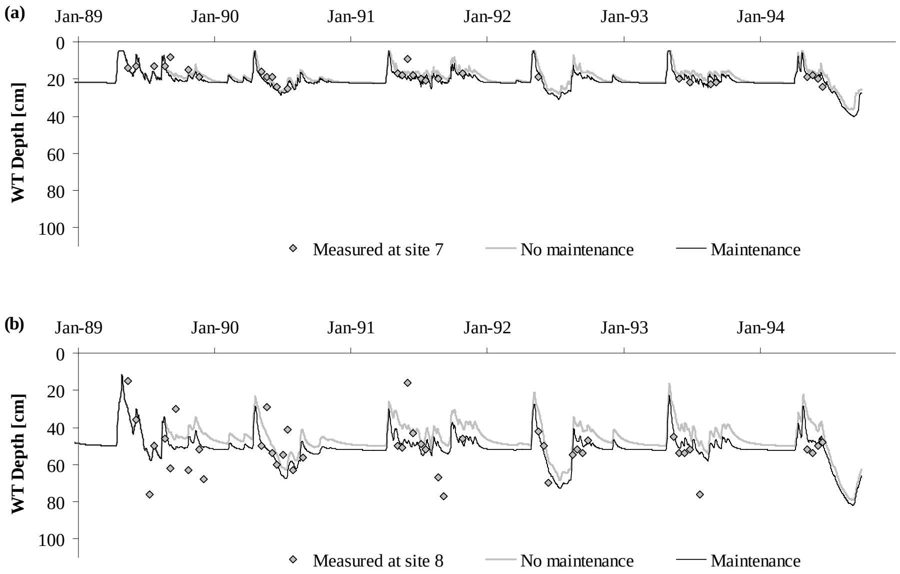

Fig. 9. Simulated depth of water table level with and without ditch cleaning, and measured depth (ditch network is maintained) in site 7 **(a)** and site 8 **(b)** with peat subsoil.

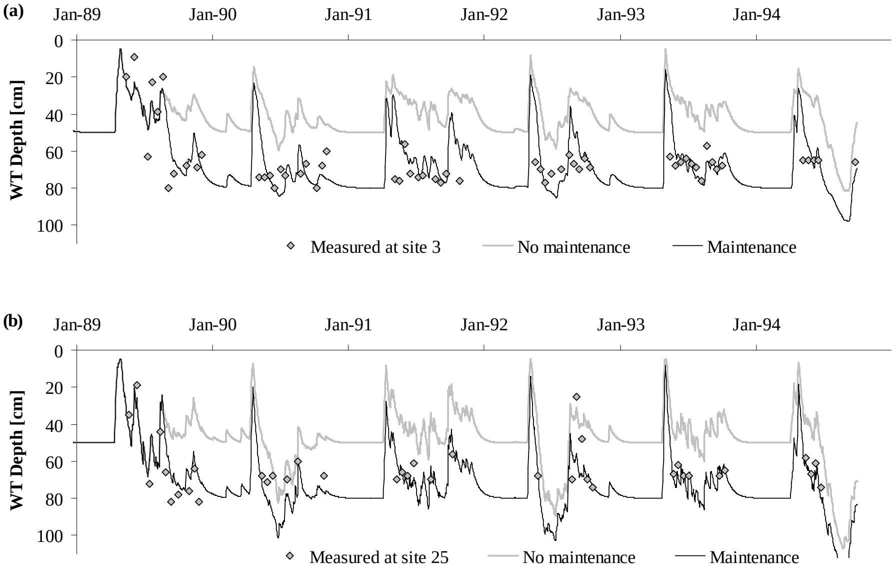

Fig. 10. Simulated depth of water table level with and without ditch cleaning, and measured depth (ditch network is maintained) in site 3 **(a)** and site 25 **(b)** with sandy subsoil.

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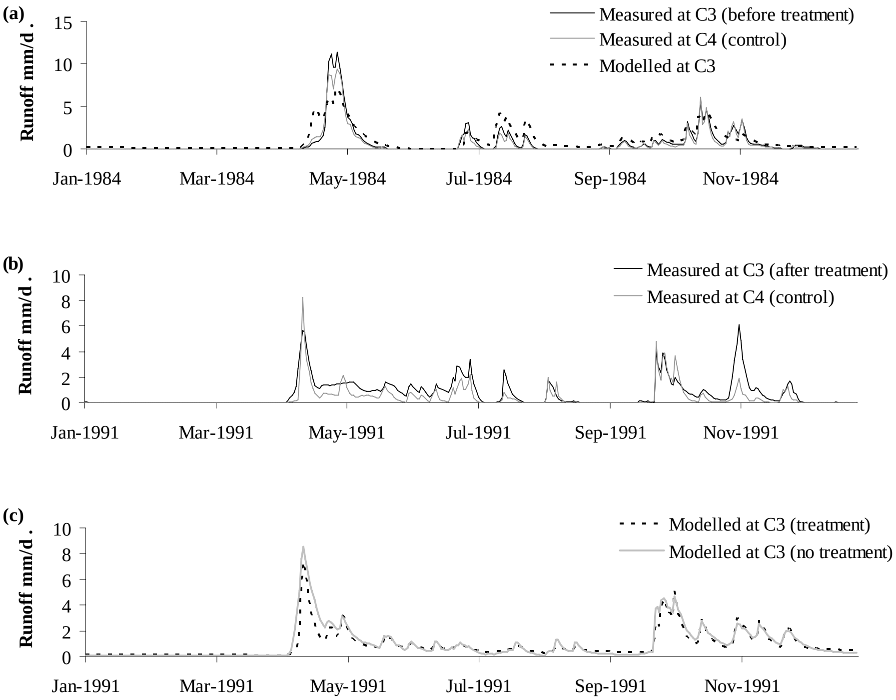

Fig. 11. Measured runoff from catchments C3 and C4, and modelled runoff from catchment C3 in 1984 **(a)**, measured runoff from catchments C3 and C4 in 1991 **(b)**, and modelled runoff from catchment C3 with and without ditch cleaning **(c)**. Ditch cleaning was conducted in 1989.

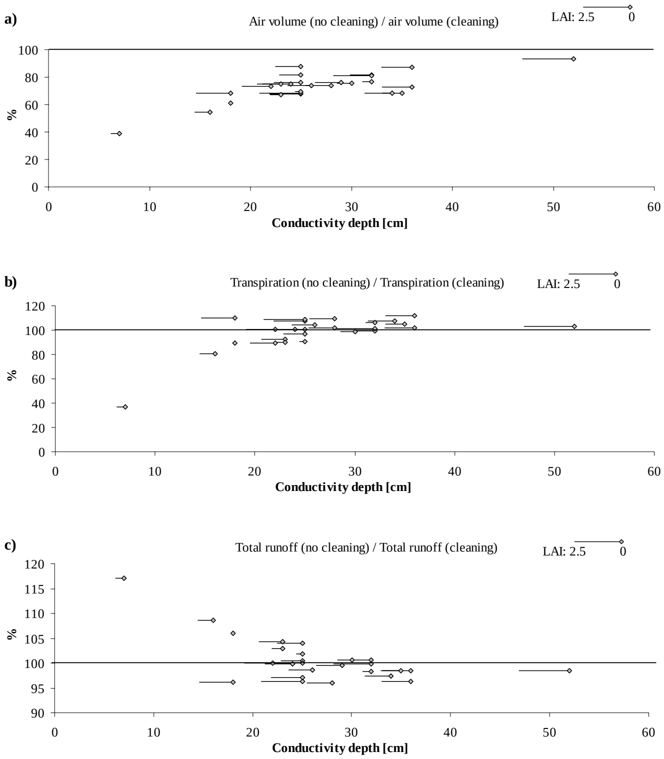

Fig. 12. Change in the air-filled pore space of soil between no cleaning and cleaning conditions in sites with different depth of a highly conductive upper soil layer and different LAI **(a)**, change in transpiration between no cleaning and cleaning conditions in sites with different depth of the conductive layer and LAI **(b)**, and change in runoff between no cleaning and cleaning conditions in sites with different depth of the conductive layer and LAI **(c)**. The change (%) is computed by dividing the long term average value for the no cleaning conditions by the average value for the cleaning conditions.