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Analysis of water balance and runoff generation in high latitude agricultural fields during mild and cold winters

H. Koivusalo, M. Turunen, H. Salo, K. Haahti, R. Nousiainen and L. Warsta

ABSTRACT

High-latitude conditions in northern Europe are characterised by short growing seasons (May–August) and long dormant seasons. Alternating mild and freezing conditions lead to variable snow accumulation–melt cycles affecting runoff generation, and consequently the loss of nutrients and sediments from agricultural fields. We assessed water balance in two subsurface drained clayey agricultural fields of different slopes (1% and 5%) in southern Finland to discern changes between mild and cold winters. The water balances of the two field sections were produced with a spatially distributed 3D hydrological model. Simulated snow water equivalent (SWE), drain discharge, tillage layer runoff and groundwater outflow from a 7-year period were examined during the dormant seasons (September–April) in relation to the North Atlantic Oscillation (NAO) index, which characterises phases related to mild and cold winters in northern Europe. Mild periods (positive NAO) were associated with more frequent runoff events, which were sustained throughout mild winters with lower SWE and shorter time of snow cover. Understanding and quantifying the water balance through periods of different weather patterns is essential as climate change is projected to increase the occurrence of positive NAO phases challenging the control of nutrient and sediment losses from agricultural fields.

Key words | agriculture, hydrological modelling, NAO index, runoff, subsurface drains, water balance

H. Koivusalo (corresponding author)
M. Turunen
H. Salo
K. Haahti
L. Warsta
Department of Built Environment,
Aalto University School of Engineering,
P.O. Box 15300,
Aalto FI-00076,
Finland
E-mail: *harri.koivusalo@aalto.fi*

R. Nousiainen
Natural Resources Institute Finland (Luke),
Vakolantie 55,
Vihti FI-03400,
Finland

INTRODUCTION

Northern agricultural areas are characterised by short growing seasons (May–August) with relatively high levels of summer evapotranspiration and long dormant seasons with low evapotranspiration due to decreased net radiation and cold temperatures. Precipitation and snowmelt drive runoff generation, which is more intensive during the times of low evapotranspiration. The presence of soil frost and snowfall events and the cycles of snow accumulation and melt strongly affect the winter and spring runoff behaviour, e.g., a long snow accumulation period increases the potential for snowmelt-induced large runoff volumes (Jamieson *et al.* 2003; Su *et al.* 2011; Turunen *et al.* 2015). High snow cover and increasing energy during late spring may generate rapid melt and high runoff peaks, whereas low snow cover and early melt may reduce spring runoff. Spring hydrological conditions can substantially impact environmental loads, since the occurrence of large runoff volumes on bare soil surface outside the growing season can cause elevated erosion and transport of sediment and nutrients to surface waters (e.g., Puustinen *et al.* 2007; Su *et al.* 2011; Øygarden *et al.* 2014). Future climate change in Finland and northern Europe may influence wintertime conditions, e.g., by increasing wintertime precipitation and freeze–thaw fluctuations, decreasing days with snow cover, and reducing snow depth (Jylhä *et al.* 2004, 2008). These changes are expected to affect runoff generation, erosion and nutrient losses during the off-season (Puustinen *et al.* 2007; Hägg *et al.* 2013; Øygarden *et al.* 2014; Huttunen *et al.*

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2015). The changing hydrological conditions may challenge water protection policies, because more efficient means to control sediment and nutrient losses are needed outside the growing season (Huttunen *et al.* 2015; Rankinen *et al.* 2016). The hydrological processes leading to runoff generation are however complex, and future model predictions subject to uncertainties (Clark *et al.* 2016). Understanding runoff, erosion and nutrient loss processes at the source areas of environmental pollution are among the key factors for the assessment and development of mitigation measures.

It has been proposed that the weather conditions of the winter seasons are, to a large extent, controlled by the North Atlantic Oscillation (NAO) index, which describes the air pressure difference between the Icelandic region and the Azores region (e.g., Rodwell *et al.* 1999; Scaife *et al.* 2014). The NAO has two phases: the negative phase can be clearly associated with cold and snowy winters, and the positive phase with mild and wet winters in northern Europe (e.g., Kim & McCarl 2005). Climate change is projected to induce an upward trend to the NAO index, which increases the occurrence of positive NAO phases (Gillett *et al.* 2003). Thus, studying long-term hydrological data which include positive and negative NAO phases offers a method to assess how changing climate conditions can impact the hydrological processes of agricultural fields. However, such method has not been previously applied to quantify the impacts of changing climate on all water outflow components. Furthermore, the NAO phases may be predictable months ahead (Scaife *et al.* 2014), and hereby studying the hydrological processes and environmental loads under the different phases might provide the means to target the most effective water protection measures to years when the risks of high loads are elevated.

Process-based hydrological models provide an approach to quantify and understand cold region hydrological processes by providing a closure of the water balance and quantification of its components at field scale. The field-scale water balance results further support the assessment of nutrient losses and erosion, which are bound to hydrological variability. Models that support the simulation of snow and frozen soil processes are available for application in agricultural areas (e.g., Larsson & Jarvis 1999; Abrahamsen & Hansen 2000; Luo *et al.* 2000; Kroes *et al.* 2008; Warsta *et al.* 2012). One-dimensional (1D) models are well suited for describing the vertical transport of water stored in soil and snow, the main water balance components, and their temporal dynamics. However, 1D approaches are less suited for describing variable site topography, irregular drainage layouts, or assessing the impact of soil conservation measures which are distributed within the fields and, therefore, 2D or 3D modelling approaches have emerged (Mohanty *et al.* 1998; Gärdenäs *et al.* 2006; Hintikka *et al.* 2008). 3D hydrological models including wintertime process descriptions, such as freezing/thawing and snow accumulation/melt, and providing a description of spatially distributed features (e.g., Refsgaard *et al.* 2010; Šimůnek & Šejna 2011; Warsta *et al.* 2012) have the potential to enhance the understanding of runoff generation under varying meteorological conditions in high-latitude agricultural fields.

The objective of this study was to investigate the generation of drain discharge, surface runoff and groundwater flow in clayey agricultural fields during off-season periods with mild and cold winters, categorised based on the NAO index (NOAA-NWS 2015). The two studied field sections with different slopes (1% and 5%) are located in southern Finland, where the growing seasons are short and variable winter conditions with air temperature fluctuations around the freezing point are frequent, resulting in strongly altering snow accumulation and melt cycles. Water balance components of the fields were simulated based on recent modelling studies (Koivusalo *et al.* 2015; Turunen *et al.* 2015) that applied a spatially distributed 3D hydrological model to simulate water flow processes in the two field sections. The simulation results allowed the study of all water outflow components, including groundwater outflow, of which observations are rarely available. The available simulation results of the field sections covered a period of 7 years (2008–2014), including six off-season periods (September–April) which were the main focus of the analysis. The simulated snow variables, runoff components, as well as measured local meteorological conditions during off-seasons were analysed in relation to NAO.

MATERIALS AND METHODS

Site description and measurements

The study sites comprise two field sections of the Gårdskulla Gård experimental field in southern Finland (60°10′32″N,

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24°10′17″E; Figure 1). The field is subsurface drained with tile drains (diameter of 0.05 m) installed in the 1940s at 1 m depth below the field surface and with a 16 m drain spacing. The slopes of the field sections 1 and 2 were 1% and 5%, respectively. The field is located in the coastal agricultural area of clay soils and mildly undulating topography in the municipality of Siuntio. Soils within the field area are classified as Vertic Luvic Stagnosols (FAO 2007). The local climate is characterised by the mean air temperature of 6 °C and mean annual precipitation of 700 mm during the study years from 2008 to 2014. A change in land use occurred in both field sections during this period. Field section 1 was used for crop cultivation until the end of 2011 and thereafter for cultivation of perennial grass, while field section 2 was crop-cultivated until 2010 and then turned to a pasture land. No soil tillage was applied in either field section after the change of land use.

Turunen *et al.* (2015) studied the same two field sections and modelled the water balance of the fields during 2008–2012 using the hydrological FLUSH model (Warsta *et al.* 2013). This simulation period was further extended by 2 years by Koivusalo *et al.* (2015) who presented preliminary results of the 7-year simulation period. A short overview of the meteorological and the hydrological data used as model input and for the calibration–validation procedure is given here, while further details can be found in Turunen *et al.* (2015), Äijö *et al.* (2014) and Vakkilainen *et al.* (2008).

The subsurface drainage networks in the fields were instrumented to automatically measure drain discharge with a frequency of 15 min (Datawater WS vertical helix water meters, Maddalena, Povoletto, Italy). The area of the monitored subsurface drainage network was 5.7 ha in section 1 and 4.7 ha in section 2 (Figure 1(b)). In the downslope parts of the field sections, shallow interception drains (diameter 0.05 m) with coarse gravel as trench backfill were installed at the depth of 0.4 m to collect tillage layer runoff. The drains measuring tillage layer runoff (dark blue lines in Figure 1(b)) gathered both surface runoff and shallow lateral water seepage at the top soil layer (tillage layer). The tillage layer runoff was recorded with a 15 min time interval and the local drainage area of the drains was 3.3 ha in section 1 and 3.0 ha in section 2. The monitored field drainage areas (for subsurface drain discharge and tillage layer runoff) in sections 1 and 2 were delineated on the basis of the instrumented subsurface drain networks and the terrain

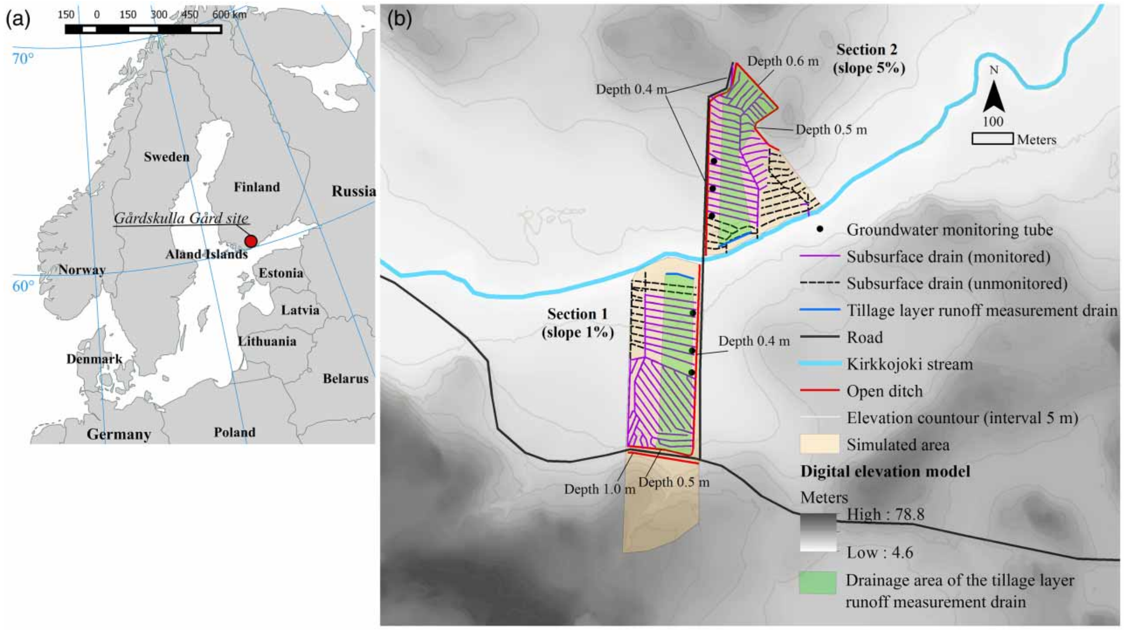

Figure 1 | Location of the Gårdskulla Gård experimental field (a) and layout of two monitored field sections (b). Part (b) contains data from the National Land Survey of Finland (MML) Topographic Database 08/2015.

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topography controlling the surface runoff and tillage layer flow (Äijö *et al.* 2014).

In addition to the drain discharge and tillage layer runoff measurements in the two sections, precipitation, snow water equivalent (SWE) and the level of the groundwater table were manually measured on site. Soil characteristics (porosity, water retention curves) were determined from soil samples. Rainfall was recorded every 15 min using a RAINEW 111 tipping bucket rain gauge (RainWise Inc., Bar Harbor, ME, USA), while winter precipitation (including snowfall) was measured manually weekly/biweekly. SWE and groundwater table level were manually observed weekly/biweekly during field visits from 2008 to 2014. Meteorological variables, including year-round precipitation (used to disaggregate manual winter precipitation measurements to hourly data), air temperature, relative humidity, wind speed and global radiation were obtained from three weather stations of the Finnish Meteorological Institute, located at the distances of 10–47 km (Turunen *et al.* 2015). The form of precipitation (snowfall or rain) was described as a function of air temperature, and rainfall and snowfall estimates were corrected for gauging errors with coefficients of 1.05 and 1.3, respectively (Førland *et al.* 1996).

Field hydrology simulations

The simulated hourly values for water balance components were available from the two field sections for the 7-year study period, 2008–2014 (Koivusalo *et al.* 2015; Turunen *et al.* 2015). The simulations were conducted with FLUSH, which is a spatially distributed hydrological model developed for simulating water flow processes in clayey subsurface drained agricultural fields (Warsta 2011; Warsta *et al.* 2013). FLUSH divides the computational area into 2D overland and 3D subsurface domains. Water flow in the subsurface domain follows the dual permeability approach, in which the total pore space is divided into mobile soil matrix and macropore systems. The model takes into account the dynamic changes of soil macroporosity by simulating the soil shrinking and swelling processes (Kroes *et al.* 2008) caused by drying and wetting of clay soil. The model simulates wintertime processes based on an energy balance snow model (Koivusalo *et al.* 2001) and a frozen soil description (Karvonen 1988). FLUSH produces model outputs including hourly runoff components (subsurface drain discharge, surface runoff, groundwater outflow), soil moisture conditions (e.g., groundwater depth), snow variables (e.g., snowfall, SWE) and soil temperatures.

The field areas used for the simulations (Koivusalo *et al.* 2015; Turunen *et al.* 2015) are shown in Figure 1(b). In section 1, the area comprises 12.4 ha including the upslope area outside of the field, as Turunen *et al.* (2015) found that this area has a hydrological connection to the field. The field receives groundwater flow from the upslope area (4.6 ha), but surface runoff from the upslope area is cut off by a roadside open ditch. The area of the steeper field section 2 is 7.8 ha. The boundary conditions of the model domains are described by no-flow interfaces at the upslope ends of the simulated areas and the Kirkkojoki stream water level at the downslope ends (for a more complete description see Turunen *et al.* (2015)).

The model parameterisation for the two studied fields was established by Turunen *et al.* (2015), who calibrated and validated the model against measured SWE, subsurface drain discharge, tillage layer runoff and groundwater levels in the two sections in Gårdskulla Gård. The calibration period in both sections was 2008–2010 and the calibration was conducted by manually adjusting a limited set of snow model, drainage and soil parameters, including roughness height in the snow model and drainage and soil hydraulic parameters in the flow model. Values for the rest of the parameters were derived from available field data on soil properties and previous applications of the model (Turunen *et al.* 2013; Warsta *et al.* 2013). Turunen *et al.* (2015) validated the model against data from 2011 to 2012. Koivusalo *et al.* (2015) made preliminary computations to extend the model simulations to the period of 2008–2014. In the current study, the parameterisation of Koivusalo *et al.* (2015) was applied with a denser grid (4×4 m^2 cell size) to achieve a better computational resolution and description of the hydrological processes. The updated model simulation results and yearly model performance (modified efficiency of Legates & McCabe (1999)) for drain discharge and tillage layer runoff for the monitored areas of the two field sections over the whole 7-year period (2008–2014) are presented in Figure 2. The model performance is likely affected by the changed land use (Figure 2) and use of time-varying

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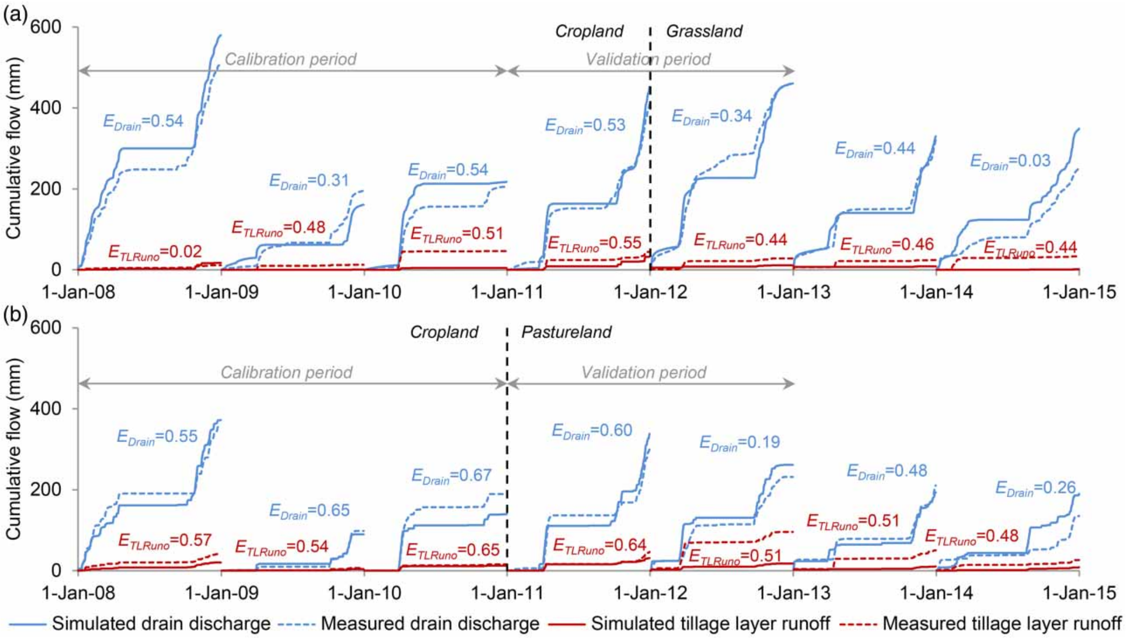

Figure 2 | Measured and simulated annual cumulative drain discharge and tillage layer runoff in field sections 1 with 1% slope (a) and 2 with 5% slope (b) during 2008–2014 showing calibration and validation periods, as well as land use type. The modified efficiency of Legates & McCabe (1999) is shown for the drain discharge and tillage layer runoff for every year. The fluxes are computed as flow volume per monitored drainage areas.

parameters could improve results against measurements. Since the objective of this study is to analyse how weather patterns alone affect water balance, the model results are useful for removing the impact of land use changes. Turunen *et al.* (2015) calibrated the model against data of the crop cultivation conditions, thereby the model results are a realisation of crop land conditions throughout the 7 years of simulation.

Analysis of NAO, meteorology and field water balance

The NAO index (NOAA-NWS 2015) was used to describe the six off-season periods (September–April) of the 7-year study period. The mean NAO indices for the off-season periods were computed from the monthly NAO indices available from NOAA-NWS (2015). A positive NAO index was associated with mild winters and a negative NAO index with cold winters.

The off-season NAO index was evaluated against mean off-season temperature, precipitation and snow cover variables (fraction of snowfall, mean SWE) to understand the effect of NAO on local climate. Temperature and precipitation were measured variables while snow cover variables were available from FLUSH outputs. The relation of NAO to these variables was explored by means of linear correlation (R).

Runoff generation during the off-seasons in the two field sections was examined in relation to NAO in order to identify differences between mild and cold winters. Daily runoff components aggregated from the hourly model outputs produced by FLUSH were used for this purpose. In this approach, the use of continuous hydrological variables that represented unchanged land use enabled an extended analysis beyond the monitored subareas of the fields, and included runoff components (groundwater outflow) that were not measured in the field. The analysed time series included SWE, subsurface drain discharge, tillage layer runoff and subsurface groundwater flow to the Kirkkojoki River (see Figure 1). In this analysis, extending over the entire fields, the tillage layer runoff included surface runoff (to ditches and stream) and water seepage to the interception drains and the shallow open ditches (see Figure 1), whereas groundwater flow represented the seepage of water into the Kirkkojoki stream. Runoff components were analysed as mean monthly outflows of off-season periods against NAO and as daily values categorising them based on positive and negative off-season NAO indices.

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RESULTS AND DISCUSSION

Overview of field water balance

Figure 3 presents simulated SWE and the yearly accumulated water balance components from 2008 to 2014 for the entire drainage areas of the field sections. The fluxes are computed as flow volume per simulated catchment area (12.4 ha in section 1 and 7.8 ha in 2). The studied years represented a large range of meteorological conditions, as shown by the changes in annual water balance components and SWE (Figure 3). There were winter seasons with little snow on the ground (the lowest annual max SWE 22 mm) and winters with a sustained period of snow cover (the highest annual max SWE 176 mm). The two major components of the water balance were evapotranspiration during the growing season and subsurface drain discharge occurring mostly during the times outside of the growing season. Annual evapotranspiration varied less between the years than annual subsurface drain discharge, which reflects the variation of off-season precipitation. Previously, also Jin & Sands (2003), who assessed long-term field-scale water balances in a subsurface drained field in Iowa (USA), noticed that evapotranspiration and drain discharge dominated the water balance and interannual variation was higher in drain discharge than evapotranspiration. In the current study, the main difference between the flat field section 1 (Figure 3(a)) and the steep field section 2 (Figure 3(b)) is the higher groundwater flow to the stream in the steep section. Tillage layer runoff was a small component in the annual water balance of both field sections, even though low permeability clay soils are prevalent in the area. The low amount of surface runoff indicates that the hydraulic conductivity of macroporous soil is high enough to enable the infiltration of the majority of rainfall and snowmelt, which in these local climatic conditions typically have moderately low intensities. The share of water outflow via drain discharge and tillage layer runoff was studied earlier (e.g., Seuna & Kauppi 1981; Uusitalo *et al.* 2007), but all water flow pathways including groundwater flow were rarely quantified for agricultural fields. Figure 3(a) also presents runoff that is generated at the area upslope of field section 1 and diverted by the road ditch.

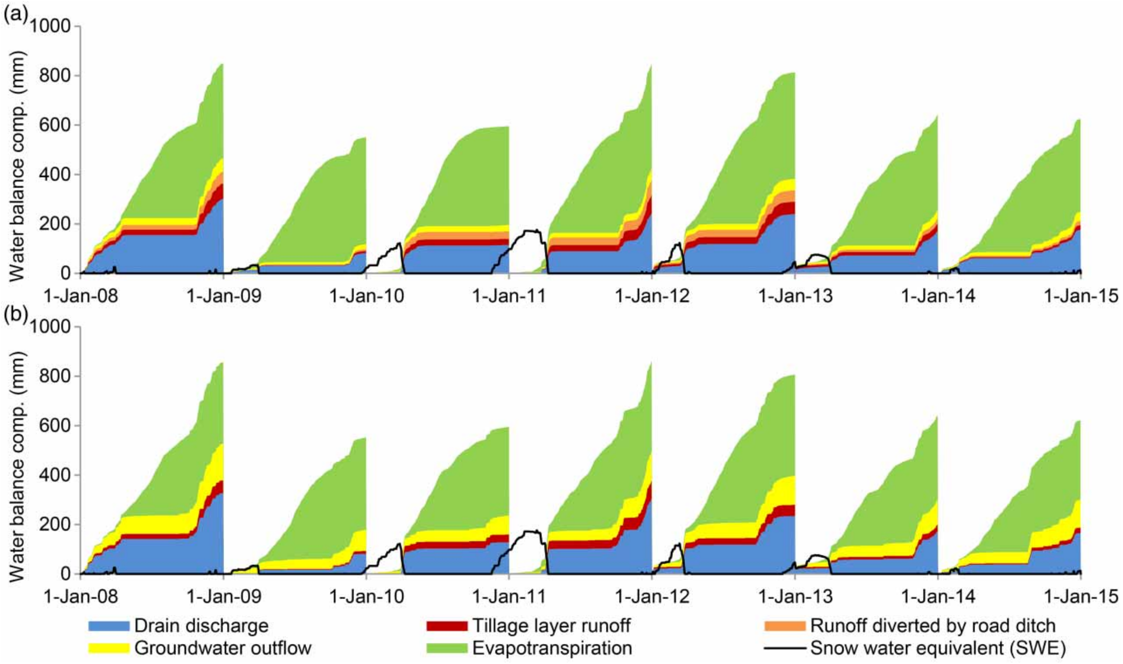

Figure 3 | Cumulative water balance components from 2008 to 2014 in Gårdskulla Gård for the flat field section 1 including the upslope area ((a) slope 1%, 14.6 ha) and the steep field section 2 ((b) slope 5%, 7.8 ha).

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NAO against mean off-season variables

The mean monthly off-season NAO index was most clearly reflected in the mean air temperature ($R = 0.84$, $p = 0.04$, Figure 4(a)). The mean monthly precipitation (September–April) of the studied years was not clearly related to NAO, although the highest precipitation occurred with the highest positive NAO (Figure 4(b)). Figure 4(c) shows that the three lowest values of snowfall fraction and mean SWE out of the six values occurred during positive NAO and the three highest values with negative NAO, but the relationships were not significant ($p > 0.05$). However, air temperature showed a significant correlation with the fraction of snowfall ($R = -0.93$, $p = 0.01$) and the snowfall fraction correlated further with the mean SWE ($R = 0.89$, $p = 0.02$).

Figure 4(d)–4(f) show the mean monthly off-season runoff components from the two sections with different slopes. Here, the runoff components were computed by dividing the flow volumes by the area of the cultivated field (7.8 ha in both field sections). Precipitation was clearly the main driver of the runoff components, which all had a significant correlation with precipitation ($p < 0.04$). The difference between the sections is seen as higher drain discharge and tillage layer runoff from the flat field section 1 and higher groundwater flow from the steep field section 2. The groundwater flow entering section 1 from the upslope area increases subsurface drain discharge in section 1. The differences between the mild and cold periods cannot be clearly seen in runoff components that are aggregated measures of the entire off-season periods (Figure 4(d)–4(f)). However, some of the runoff components in the steeper field section 2 (Figure 4(d) and 4(e)) showed a stronger correlation with NAO than precipitation, which may be a reflection of air temperature impact on the form of precipitation. The clearly warmer off-seasons and weakly higher precipitation in Gårdskulla during positive NAO was in line with Kim & McCarl (2005), who reported that the relation between NAO and off-season weather patterns reflects the warmer and wetter European winters during positive NAO.

Daily SWE and runoff during mild and cold off-seasons

The time series of daily SWE and total runoff envelopes for the periods of positive and negative NAO are shown in Figure 5. The envelopes of SWE illustrate how the off-season NAO phase reflects amount of snow in the study site (Figure 5(a)). In the study region the air temperature

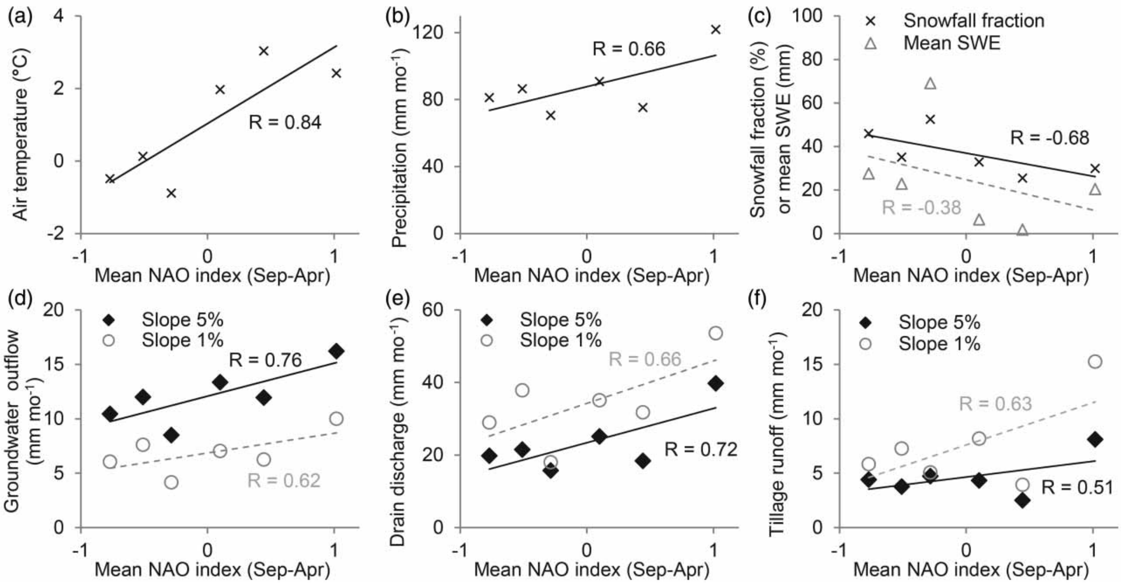

Figure 4 | Mean monthly air temperature (a), precipitation (b), fraction of snowfall and mean SWE (c), modelled groundwater outflow (d), modelled subsurface drain discharge (e), and modelled tillage layer runoff (f) in the two field sections (1% and 5% slope) of Gårdskulla Gård during September–April as a function of mean monthly off-season NAO index for the years 2008–2014.

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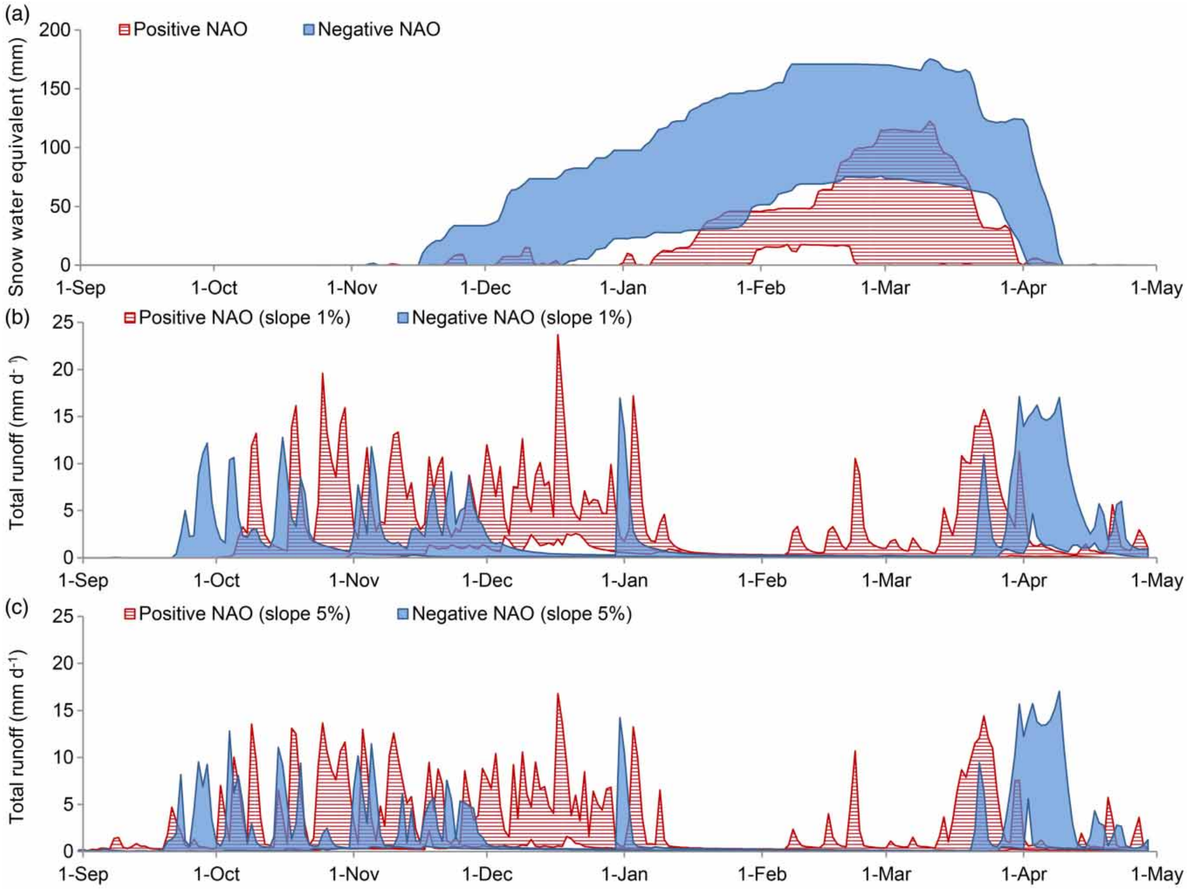

Figure 5 | Envelopes of SWE (a) and total runoff from the field sections with 1% slope (b) and 5% slope (c) during periods (September–April) of positive and negative NAO in the Gårdskulla Gård experimental field during 2008–2014.

frequently fluctuated around the freezing point, which led to a strong impact of weather patterns on snow accumulation and melt. The probability of longer lasting and higher snow cover is evident during the off-season periods with negative NAO. Figure 5(b) and 5(c) further demonstrate the difference in early winter runoff, when the snow accumulation period is delayed during mild winters. Increasing occurrence of rainfall-induced runoff events leads to greater risks for erosion and nutrient losses. Additionally, Figure 5(b) and 5(c) illustrate that during the spring after mild winters melting can occur during scattered and extended periods of time.

The distributions (upper 50% tail) of daily intensities of the runoff components during off-season characterised by positive and negative NAO phases in the two field sections are shown in Figure 6. The subsurface drain discharge events are frequent during mild winters and positive NAO, when subsurface drain discharge occurs over rainy periods with elevated flow regime (Figure 6(a) and 6(d)). The off-seasons of negative NAO are characterised with seasonal snow packs lasting longer and leading to drain discharge during autumn rainfalls before the snow accumulation and during spring snowmelt after the winter. The most long-lasting and high-intensity drain discharge events occurred at the time of spring snowmelt, which is a sustained period of high runoff generation compared to the generation of rainfall-induced dynamic runoff events during mild autumns and winters (positive NAO). The highest intensities of drain discharge (volume per field area) are nearly the same for the periods of different NAO and the sections of different slopes (Figure 6(a) and 6(d)), which is explained by the sink term description for the subsurface drainage in

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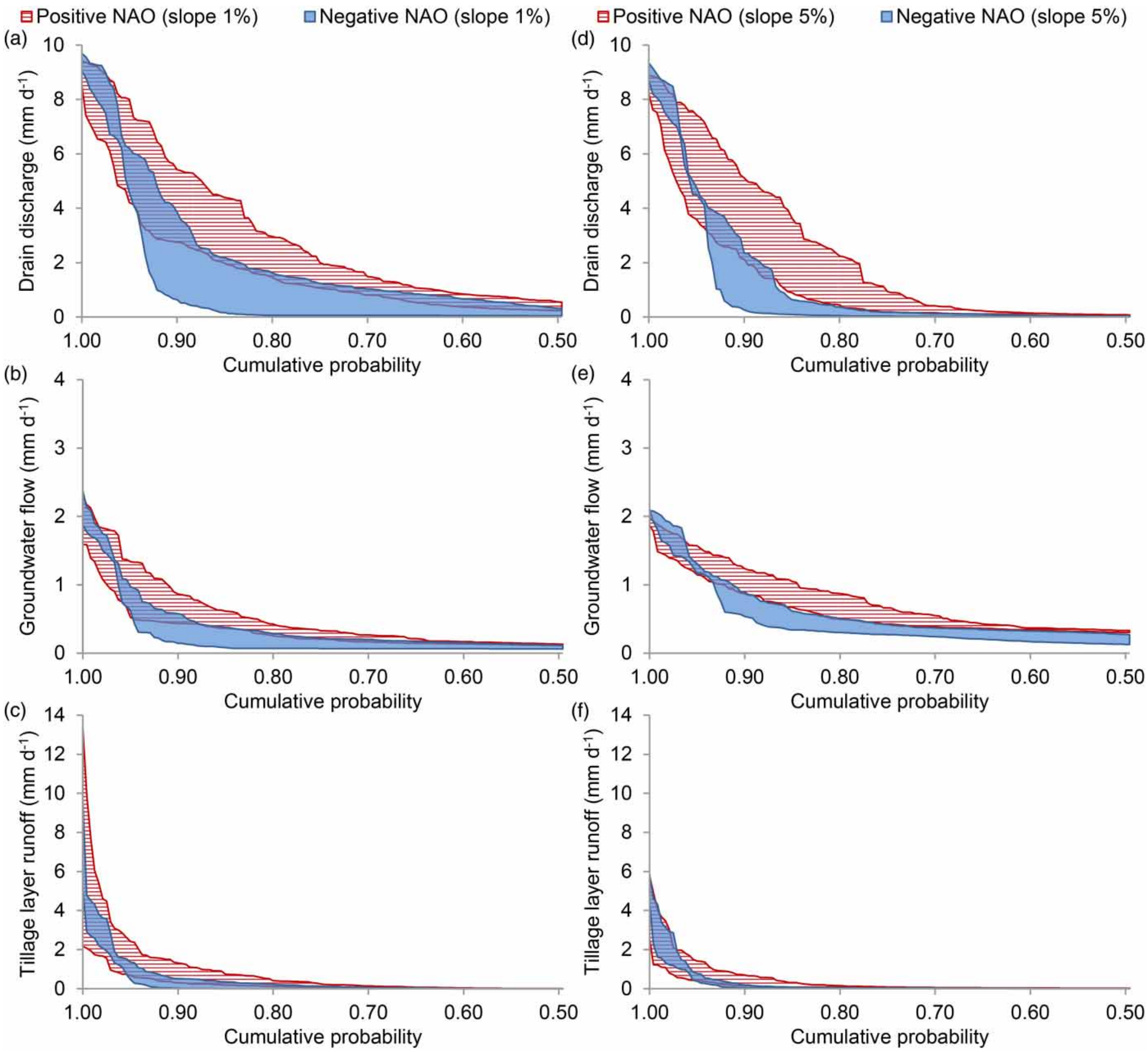

Figure 6 | Upper 50% cumulative distribution of daily subsurface drain discharge intensities during the periods with positive and negative NAO index for the section with 1% slope (a) and 5% slope (d), cumulative distribution of daily groundwater outflow intensities for the section with 1% slope (b) and 5% slope (e), and cumulative distribution of daily tillage layer runoff intensities for the section with 1% slope (c) and 5% slope (f) in the Gårdskulla Gård experimental field during 2008–2014.

FLUSH. The subsurface drains remove water from the system but the model does not simulate pipe flow, and thereby is unable to account for pipe pressurisation and the drainage capacity of the pipe. The simulation of the highest drain discharge events would benefit from the inclusion of a pipe flow description, which would control the magnitude of the discharge peaks (e.g., Henine *et al.* 2014).

Compared to subsurface drain discharge, the distributions of daily groundwater outflow from the field sections (Figure 6(b) and 6(e)) showed a similar relation to weather conditions. The slope of the field section and the upslope hydrological connection in section 1 had a stronger impact on the groundwater outflow volume than the changing NAO and snow conditions. This demonstrated how the field or catchment characteristics, such as the terrain topography, can impact how the hydrology of the area responds to the NAO phases and snow conditions. The slow hydrological processes of those areas where groundwater outflow dominates may be less sensitive to the changing NAO phases than in other types of areas. The

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distribution of daily tillage layer runoff showed how increasing slope decreased its peak values. Distributions of tillage layer runoff (Figure 6(c) and 6(f)) showed no clear differences between periods of mild and cold winters.

The results of this study indicate the high sensitivity of snow conditions, water balance and runoff generation to the variation in temperature regime at high latitude regions. Winter air temperature fluctuates around the freezing point affecting the snow conditions and, as a result, the water balance and runoff generation become sensitive to variation in temperature regime. These winters are crucial periods for water protection measures, as there have been concerns about increasing sediment and nutrient losses during mild winters (e.g., Granlund *et al.* 2007; Øygarden *et al.* 2014). For example, Rankinen *et al.* (2016) found that increasing total nitrogen concentration in large river basins could be explained by climatic factors and Puustinen *et al.* (2007) reported higher sediment loads during mild rather than cold winters in agricultural fields in Finland. Øygarden *et al.* (2014) summarised catchment studies and climate change scenarios from the Baltic region. They showed nitrogen fluxes correlated with runoff volumes, even though the variation between different catchments was large. In the light of the current results, the climate warming and increasing winter precipitation pose the highest risks on the edge of snow-covered areas, such as southern coastal Finland, where frequent occurrence of runoff events may become common.

CONCLUSIONS

FLUSH was applied to produce a quantification of water balance in two clayey agricultural field sections with different slopes in Gårdskulla Gård in southern Finland, where the growing seasons are short and variable winter conditions with air temperature fluctuations around the freezing point are frequent. The 7-year study period included six off-season periods (September–April), of which three were characterised by the positive mean NAO index (mild winter) and three by the negative mean NAO index (cold winter). Evapotranspiration in the studied high-latitude site was the dominant water component during the growing seasons from May to August, while drain discharge dominated the water balance during the periods outside the growing season from September to April.

Annual differences in precipitation were strongly reflected in the annual volumes of drain discharge, whereas annual evapotranspiration showed lower variation between the years. The increase of slope in the field area decreased the volume of subsurface drain discharge and increased groundwater outflow to the stream at the downslope end of the field. The variability in the form of precipitation and further in snow accumulation was related to the weather patterns classified by the NAO index during the period outside of the growing season.

Mild periods with positive NAO were associated with the increased frequency of off-season runoff events, which were sustained throughout wet periods with minor snow depths. Tillage layer runoff in the near surface layers of the field showed higher intensities on the flat field section, but its occurrence depended more on the intensities of rainfall and snowmelt instead of the periodical weather patterns. Understanding and quantifying the water balance and all major water outflow components through periods of different weather patterns is essential in choosing suitable mitigation measures and control nutrient and sediment losses. The NAO index as a measure of mild (positive NAO) and cold (negative NAO) periods demonstrated how the snow accumulation and runoff components respond to alternating wet and cold winter conditions.

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