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Mapping suitable cultivated peatlands for mitigating greenhouse gas emissions by water table management

Master's thesis for the degree of Master of Science in Technology submitted for inspection.

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Abstract

More than half of the greenhouse gas (GHG) emissions of croplands originate from the oxic layer of cultivated peatlands due to drainage and agricultural practices, although only 10% of croplands in Finland are located on organic soils. One of the most effective ways of mitigating GHG emissions is to the raise water table level (WTL) in drained peatlands leading to waterlogged conditions of peat layer and turning them closer to their natural state and GHG emissions sinks.

The main objective of this study was to develop a method for mapping and locating agricultural fields that are suitable for rewetting or for cultivation with raised WTL using controlled drainage. Additionally, this study aimed to develop tools to implement the Medium-term Climate Change Plan of the government for 2030. The purpose was that the methods and results of this study can be utilized in further actions, therefore, they were aggregated into suitable datasets.

The region of Pohjois-Pohjanmaa (65˚N, 26˚E) was selected for the study area due to its high occurrence of deep layered peatlands. Fields in extensive cultivation and feed production were considered as best available for rewetting. The analysis was mainly done with spatial software QGIS Desktop 3.4.4 with GRASS 7.4.4. First, field parcels containing deep layered peat and desired cultivation type were identified, resulting in approx. an area of 2.3% extensive cultivation and 25% feed production from field parcels partly or totally on deep layered peat in the region of Pohjois-Pohjanmaa. Rewetting these areas would lead to an estimated reduction of 0.44 Mt CO2 eq. annually. After this, areas suitable for rewetting on the basis of weather conditions were identified. Yearly difference between precipitation and potential evaporation (mm) in 2017 produced the same results as in the first part of this study about possible rewetting areas, but a noticeable drop was observed when analyzing on the basis of the weather in 2018. This raised uncertainty, and more accurate results would be achieved by using weather data from a longer period of time. For topographical analysis, two example catchments were selected and Digital Elevation Model (DEM), Depth to Water (DTW) and Topographical Wetness Index (TWI) were implemented for estimating water movements in soil and wetness of soil due to terrain elevations. Lastly, the feasibility of hydrological modelling for this type of study was discussed. As a summary, the results showed that the method developed can be implemented for any other areas too and could be utilized by e.g. in land use planning by policymakers.

Keywords cropland, gis, hydrology, peatland, rewetting, topography

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Tiivistelmä

Yli puolet viljelymaiden kasvihuonekaasupäästöistä muodostuu turvepeltojen hapettuneesta pintakerroksesta, vaikka vain 10% Suomen viljelymaista on orgaanisella maaperällä. Yksi tehokas keino vähentää kasvihuonekaasupäästöjä kuivatuilta viljelymailta on nostaa pohjaveden pintaa, mikä tekee maan turvekerroksesta vettyneen. Näin turvemaa muuttuu luonnontilaisemmaksi ja myös kasvihuonekaasupäästöjen nieluksi.

Työn tavoitteena oli kehittää menetelmä paikantamaan maatalouspeltoja, joilla voitaisiin nostaa pohjavedenpintaa eli jotka soveltuvat vettämiseen tai kosteikkoviljelyyn säätösalaojituksella. Tarkoituksena oli myös osaltaan edistää Valtioneuvoston esittämiä keskipitkän aikavälin ilmastopolitiikan kasvihuonekaasujen päästövähennystavoitteita vuoteen 2030. Tarkoituksena oli tutkimuksen menetelmien ja tuloksien hyödyntäminen tulevaisuudessa, joten ne koottiin yhteen käyttökelpoiseksi aineistoksi.

Tutkimusalueeksi valittiin Pohjois-Pohjanmaa (65˚N, 26˚E) paksuturpeisten peltojen runsaan esiintymisen vuoksi. Analyysi toteutettiin pääosin QGIS Desktop 3.4.4 with GRASS 7.4.4 paikkatieto-ohjelmistolla. Ensimmäiseksi tunnistettiin laajaperäisen viljelyn peltoja ja tuotantonurmialueita sisältävät peltolohkot, jotka esiintyvät osittain tai kokonaan paksuturpeisella maalla. Tulokset osoittivat, että näistä peltolohkoista noin 2,3 % oli laajaperäisen viljelyn peltoja ja noin 25 % tuotantonurmea. Näiden alueiden vettäminen vähentäisi arviolta 0,44 Mt CO2 ekv. vuosittain. Tämän jälkeen määritettiin alueet, jotka soveltuvat vettämiseen sadannan ja haihdunnan eron perusteella. Vuoden 2017 sääaineiston analysointi tuotti samat tulokset kuin edellä, mutta huomattava pudotus havaittiin mahdollisissa vettämiseen soveltuvissa alueissa vuoden 2018 sääolosuhteiden perusteella. Tämä herätti epävarmuutta ja tarkempiin tuloksiin vaadittaisiin säätietoa pidemmältä ajalta. Kahdelta valuma-alueelta arvioitiin maaperän veden virtauksia sekä maan märkyyttä käyttäen korkeusmallia (DEM), maanpinnan etäisyyttä pohjavedenpintaan (DTW) ja topografista kosteusindeksiä (TWI). Lopuksi pohdittiin hydrologisen mallinnuksen mahdollisuuksia tämän tyyppisessä tutkimuksessa. Tulokset osoittivat menetelmän hyödyntämismahdollisuudet myös muille alueille sekä esimerkiksi maankäytön suunnitteluun.

Avainsanat gis, hydrologia, topografia, turvemaa, vettäminen, viljelymaa

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List of symbols and abbreviations

C		Carbon
CH_4		Methane
CO_2		Carbon dioxide
DEM		Digital Elevation Model
DTW		Depth to Water
GHG		Greenhouse gas
GIS		Geographical Information Systems
LUKE		Luonnonvarakeskus (Natural Resources Institute Finland)
N_2O		Nitrous oxide
P	[mm]	Precipitation
E_p	[mm]	Potential evaporation
T	[˚C]	Air temperature
TWI		Topographical Wetness Index
WTL		Water table level

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1 Introduction

1.1 Background

A significant amount of greenhouse gas (GHG) emissions is generated from cultivated organic soils in areas where peatlands are typical (Regina et al., 2019), such as the Nordic Countries. Peatlands and bogs cover roughly 1/3 of the land area in Finland (Ministry of Agriculture and Forestry (MMM), 2012). Only 10% of the soil in croplands in Finland is organic (containing 12% of carbon (C)), and yet 50-60% of total emissions from agriculture are originated from organic soil croplands. Drainage is essential for cultivation of peatlands (Regina et al., 2019). It changes soil conditions significantly by degrading peat layer and decreasing the water table level (WTL) and therefore allowing more oxygen to be available for organic material to produce nitrous oxide (N_2O) and carbon dioxide (CO_2) compared to conditions on natural peatlands (Petrescu et al., 2015; Leppelt et al., 2014; Regina et al., 2015). However, avoiding or banning cultivation is not usually an option in countries with high proportion of peatlands as in Finland, where over 60% of fields in municipalities can be situated on organic soils. Additionally, there exist farms where the total field area is on organic soils. Due to the amount of fields on organic soils, regional planning and cooperation with farmers is required, and improved reduction actions of GHG emission from cultivated lands. (Kekkonen et al., 2019)

Mitigation actions for GHG emissions from agricultural lands should be developed. Locating abandoned or uncultivated fields, or fields where cultivation type could be improved or changed, would allow sustainable intensification, i.e. combining environmental benefits with productivity and thus leading to the removal of poor fields and better management of useful fields. Ministry of the Environment (2017) has proposed actions for reducing GHG emissions in the agricultural sector. These actions mainly involve mitigating emissions from organic soils. One option is to raise the WTL by controlled drainage system, which is estimated to reduce emissions by 0.14 Mt CO_2-eq. in the effort sharing sector.

Avoiding new drainage is the most preferred way of mitigating GHG emission from cultivated peatlands (Regina et al., 2015). However, this is not always possible in the essential production lands. Thus, several studies suggest that raising WTL, for instance for rewetting and paludiculture (i.e. cultivation in rewetted conditions), is an efficient way for mitigating GHG emissions generated in cultivated organic soils (e.g. Kekkonen et al., 2019; Untenecker et al., 2016; Joosten & Clarke, 2002; Röder & Osterburg, 2012).

1.2 Objectives of this study

The objective of this study was to develop a method for mapping and locating agricultural fields that are suitable for rewetting or for cultivation with controlled WTL. The analysis was based on processing land use and hydrological data with Geographical Information Systems (GIS) including cropping history and peat depth. As mentioned before, raising the WTL is one of the GHG emission mitigation measures in the Government Report on Medium-term Climate Change Plan for 2030 (Ministry of the Environment, 2017) and this study aims to develop tools to implement the climate plan.

The specific aims of this study were:

1. To identify different types of agricultural lands suitable for WTL raise
2. To identify the hydrology of the areas which could be rewetted
3. To implement specific software and models for the step-by-step evaluation of the areas
4. To understand the aim of raising the WTL in drained peatlands and its effect on water resources and GHG emissions mitigation

In order to achieve the goals of this study, a literature review on the background information of cultivated peatlands is presented, followed by the description of the study site and datasets needed. After that, the analysis steps and methods are presented and described. Finally, the results of the analysis are produced, aggregated, presented, and discussed.

2 Literature review

2.1 Description of peatlands

A peatland consists of a layer of peat at the surface. Thickness of peat is defined to be at least 30 cm in order to categorize the land as peatland. They can be vegetated or non-vegetated. (Rydin & Jeglum, 2006) Peat is organic material generated when dead plant material is decomposed, but lack of oxygen in waterlogged conditions results in incomplete decomposition. Therefore, plant material is accumulated as peat. (Joosten & Clarke, 2002; Rydin & Jeglum, 2006) Besides organic matter, peat also contains minerals. Peat soils are usually drained for cultivation, since the use of nutrients and minerals of peat require oxic conditions, which is prevented by high WTL in natural peatlands. (Rydin & Jeglum, 2006). Most of the cultivated peatlands in Finland have originally been *Carex* peat, which is categorized as rich in nutrients. There also are cultivated peat soils from peat formed of *Sphagnum* mosses that have typically been poor in nutrients. (Myllys 1996, as cited in Regina et al., 2015) Evaluating the characteristics of managed peatland, usually it can be assumed that the specific peatland has the same mineral content as the surrounding peat soils, whereas the depth of the peat on specific area is not dependent on the surrounding soils. These, of course, are dependent on whether there are any areas nearby in their natural state. (Grønlund et al., 2008).

The WTL is correlated with the oxygen content of the peat (Rydin & Jeglum, 2006). Natural peatlands have high water content and thus accumulate CO_2 and N_2O in waterlogged conditions (Röder & Osterburg, 2012; Bechtold et al., 2014; Liimatainen et al., 2018). When the rate of decomposition, i.e. organic matter breakdown into inorganic substances, is lower than the rate of biomass production, peatlands capture C (Joosten & Clarke, 2002). In contrast, natural peatlands emit methane (CH_4) because of the presence of methanogenesis in anaerobic conditions (Schrier-Uijl et al., 2014). When peat soils are drained for cultivation, the depth of aerated layer increases. Therefore, organic material is oxidized and GHG emissions are generated in forms of CO_2 and N_2O, whereas CH_4 emissions might be reduced. (e.g. Schrier-Uijl et al., 2013; Rydin & Jeglum, 2006). The presence of oxygen leads to mineralization of nitrogen (N) and nitrification (Liimatainen et al., 2018). In the peat layer above the WTL, GHG emissions are continuously generated (Regina et al., 2015). In addition, amounts of manure and fertilizers on managed peatlands increase N_2O emissions, while N_2O emissions in natural lands do not have such a significant role (Schrier-Uijl et al., 2014).

Besides GHG emissions production from drained and cultivated peatlands, peat soils are subsided after drainage. This is due to the effects of soil loss from soil organic matter being mineralized and compaction. (Grønlund et al., 2008) In other words, drainage leads to increased humification, and loss of water and pore spaces collapsing are causing shrinkage (Rydin & Jeglum, 2006). Subsidence rates of peat are typically between 0.5 and 4 cm per year (Grønlund et al., 2008; Wösten et al., 1997).

2.2 Field drainage

Drainage of peatlands is essential when turning them into cultivation. Approximately 60% of the field area in Finland has a subsurface drainage network, and 25% is drained with open ditches. Therefore, only 15% of the field area is not drained. (Äijö et al., 2009) Most of the drainage networks in Finland have been installed between the years 1960 and 1980 (Äijö, 2017). The purpose of the drainage is to remove the excess water from the field, i.e. reducing surface and subsurface flows by lowering the WTL (Stenberg et al., 2018). Instead of water being percolated to groundwater (natural hydrological cycle), it is collected into drains and directed away from field. Due to flat terrain, impermeable soil and annual climate fluctuations in Finland, drainage network plays an important role in agriculture. (Äijö, 2017)

Distance between lateral drains is adjusted to secure sufficient drainage and depends on design runoff, hydraulic conductivity of the soil, distance of impermeable soil layer to drain and the slope of the land. In cultivated peatlands in Finland, the distance between lateral drains usually lies between 8 and 14 m and they are installed at the depth of 1.2 m below soil surface. In general, when the slope of the field is greater, the distance between the drains is also longer. Collector drains direct the water from lateral drains towards the main (open) ditch. (Äijö, 2017)

The age of the drainage system affects the drain depth, since peat subsides due to drainage. The older drainage network installations have lowered drain depth and, therefore, WTL nearer to the surface of the soil. (Regina et al., 2015). Subsidence of peat may lead to soil becoming too wet for arable use, thus leading to transforming lands into pasture or grasslands, or abandonment of the peatland (Kløve et al., 2017).

2.3 Hydrology

2.3.1 Water balance

Identifying water balance at a catchment or peatland scale is essential for evaluating the amount of water resources within the area.

Water balance is described as a sum of the inputs, outputs and storage of water. This requires information of water movements, including groundwater movements, within a specific time interval (Rydin & Jeglum, 2006). Water balance is at the simplest form as

$$P + Q_{in} = E_p + Q_{out} + \Delta S, \tag{1}$$

where P is the precipitation (mm) from rain or snow and E_p is the potential evaporation from surface soil. Evaporation is defined by transformation of liquid water in the soil into water vapor and thus water removed from surface. Therefore, E_p is the total amount of evaporation that would occur if available water storage was adequate. It is dependent on meteorological variables, such as air temperature (T), radiation, humidity and wind speed, and vegetation and soil parameters. (Allen et al., 1998) Q_{in} refers to the water inflows into the studied area and Q_{out} to the runoff out from study area towards streams, which can be surface, subsurface or groundwater flow. ΔS is the change in water storage over a time period.

Gong et al. (2012) studied a regional water table model for boreal peatlands for prediction of spatial-temporal climate change effect on the WTL. They presented that the WTL in peatlands is a function of soil water storage, driven by the balance between discharge and recharge of water, P and evapotranspiration. Thus, the level of water depends on hydraulic properties of the soils as well as the age of the drainage system. (Regina et al., 2015).

Due to drainage systems in cultivated lands, water movements are different compared to soils in their natural condition. In drained peatlands, water balance is controlled by hydraulic conductivity and water retention properties, efficiency of drainage (i.e. spacing and depth of ditch), thickness of peat layer, mineral soil type underneath, vegetation properties and topography. Hydraulic conductivity of peat generally decreases in deeper layers and thus reduces the impact of drainage on soil moisture. Water balance is forced by meteorological conditions. (Stenberg et al., 2018) Gong et al. (2012) found that the WTL in drained peatlands is more resistant to changes in P and T than WTL in natural peatlands. When the WTL rises above drain depth, water from the saturated zone of the soil flows into the drains and subsurface drainflow is formed (Warsta et al., 2013). P may be the only source of water into a drained field since there is no recharge, i.e. no surface water flows into the area. Thus, water balance can roughly be estimated by only the difference between P and E_p, with a consideration of T as well as snow accumulation and melt.

2.3.2 Topography for evaluating hydrology

One of the most significant factors affecting the WTL is local topography (Haahti et al., 2012). In general, fields located at lower terrains than their surroundings are probably wetter than fields with plain or lower elevations surroundings. Topography is one of the main factors affecting water movements in soils, because water flow and accumulation happen as a result of gravitational potential energy (Murphy et al., 2009). Therefore, an investigation of Digital elevation model (DEM), Depth to Water (DTW) and Topographical wetness index (TWI) is an essential part of evaluating soil moisture distribution within a catchment, or single peatland.

DEM defines terrain elevations as relation to sea level. It is a good indicator for analyzing hydrology, especially water movements on surface and in soil within certain area since the WTL usually correlates with ground elevations. Additionally, slope of the area can be calculated from DEM. Slope can be used for estimating whether water is staying in a specific area or flowing towards lower elevations.

DTW defines the computational distance from soil surface to the WTL. It is based on the slope and distance to surface water, i.e. it determines the elevation difference between a particular location and the nearest location of surface water, such as a ditch or a stream. (Murphy et al., 2009) In general, the higher the surface elevation, the greater the value of DTW and the drier the soil is. Considering areas for raising the WTL, it is more reasonable to look for areas with low DTW. This is because areas with small values of DTW are expected to have water close to the surface of the soil for a notable time of the year (Murphy et al., 2009). DTW is calculated with flow accumulation using a threshold value for channelized stream flow. 4 ha area threshold is found to function with varying terrains (Murphy et al., 2009). Decreasing threshold area value to, e.g., 1 ha would allow detecting more areas which would become wet due to snow melting or high *P*. (Murphy et al., 2011) Murphy et al. (2009) also studied that using a threshold value of 1.5 m for DTW (i.e. DTW ≤ 1.5 m) was a good indicator for detecting wet areas.

TWI is defined as

$$TWI = \ln\left(\frac{a}{tan\beta}\right), \tag{2}$$

where *a* is the local upslope area draining through a grid cell, *tanβ* is the local surface slope (along the flow direction) and *β* is the angle of the slope (Beven & Kirkby, 1979; Launiainen et al., 2019; Murphy et al., 2011). Lower values of TWI indicate terrains with steep slopes, and the accumulation of runoff is not likely to be generated, or the contributing area is small. Thus, higher values represent wetter areas, i.e. wetness of soil increases in areas with decreasing slope and increasing flow accumulation. TWI is effective for estimating the locations of water pools and pathways where water flows topographically from higher ground elevations to lower. (Murphy et al., 2011)

Murphy et al. (2009; 2011) stated, that DTW is better for modeling wider wet soil areas than TWI. This is explained by TWI indicating flow accumulation as lines in the wet areas, e.g. streams, instead of representing wet soil areas as a whole. DTW evaluates the distribution of soil moisture.

2.4 GHG mitigation options by water table management

GHG emissions from peatlands are controlled by the WTL (Renger et al., 2002) and restoring hydrological conditions on peatlands is the most promising way to mitigate emissions from these lands (Regina et al., 2019).The methods of mitigating GHG emissions with the raised WTL are more efficient in areas with deep peat depth (peat layer thickness > 60 cm (Lilja et al., 2009)), since the mitigation effect lasts longer in such conditions. In Finland, most of the cultivated peat soils have a peat layer of 0.6 m. (Kekkonen et al., 2019)

Raising the WTL close to soil surface is likely to increase methane (CH_4) emissions from peatlands (e.g. Regina et al., 2015). As mentioned in Section 2.1, methanogenesis happens in anaerobic conditions due to the raise of the WTL. However, production rates of CH_4 depend on the peat type (Rydin & Jeglum, 2006). Hahn-Schöfl et al. (2010) found that the amount of CH_4 emitted from peatlands depends also on the presence of fresh organic matter sources in peat generated from wet conditions such as plant litter and roots. They stated that less or negligible amount of CH_4 is generated when there was only peat without any fresh organic matter. Thus, the amount of CH_4 depends on the amount of plant litter in anaerobic conditions as well as how much new vegetation will produce fresh organic matter litter.

There might be a possibility for gradually shifting field areas in intensive cultivation, i.e. an ongoing food production site or any other vital cropland in active use, to mineral soils and therefore releasing peat area for managing the WTL. This requires the availability of mineral soils in the surroundings of the field. Availability of mineral soils is considered if less than 15% of the field area in a region is on organic soil. (Kekkonen et al., 2019)

2.4.1 Rewetting

Rewetting is an action where drained peatlands are restored closer to their natural state by raising the WTL. The aim is to stabilize the WTL close to the peat surface. Water table is an indicator of water content in peat soils, since water content of the top peat layer correlates with the WTL (Hökkä et al., 2016). Total rewetting in drained peatlands can be done, e.g., by excavating a feeder ditch that leads water into the field and by blocking (filling) the drainage ditches.

When considering rewetting, peatland and its surroundings must meet the requirements of suitable hydrology (Kekkonen et al., 2019), topography, vegetation and crop type, peat type and depth, and underlying soil type (Stenberg et al., 2018). Additionally, one has to make sure that the neighboring areas are not disturbed due to the actions of rewetting and there is no water scarcity (Kekkonen et al., 2019). It is easier to restore recently drained peatlands than peatlands being drained for a longer time due to the subsidence (Vasander et al., 2003).

Primary areas for rewetting are peatlands on deep peat depth that are in extensive use. These are fields that are not in food or fodder production. Thus, intensive cultivation areas are not primary areas for rewetting. It is more reasonable to rewet peatlands with deep than shallow peat layer, since the process is usually permanent and with deep peat depth the benefits are greater. It can be assumed that even if only part of the field parcel (field parcel: uniform area that is outlined by e.g. ditch and managed by the same landowner (Agency for Rural Affairs in Finland, 2016)) is in extensive use, the whole field parcel will be in extensive use in the future. (Kekkonen et al., 2019)

Managed peatlands are sources of GHG emissions and C (see Section 2.1) thus rewetting as an action for turning these lands into C and GHG emissions sinks is widely studied (e.g. Schrier-Uijl et al., 2013; Kekkonen et al., 2019; Liimatainen et al, 2018). Gong et al. (2012) stated that the WTL is one of the most important factors affecting the accumulation of C in soils. Schrier-Uijl et al. (2013) studied the effects of rewetting on the C balance and GHG emissions on intensively managed, drained, agricultural peatlands. They found that former agricultural peatland, which was rewetted, acted as a C and GHG sink, and the dominant ecosystem GHG emission in extensively cultivated peatland was CO_2. Herbst et al. (2012) studied mitigation of GHG emissions on a wetland, in which the WTL was restored and unregulated, and found that it was a C sink during the whole experiment period. Thus, rewetting is estimated to reduce CO_2 emissions significantly, and keeping N_2O emissions approximately neutral. However, a major share of this reduction estimation comes from rewetting intensive cultivated deep organic soils, which (as stated before) requires shifting cultivation to mineral soils, and thus rewetting available organic soils. For instance, rewetting approximately 23280 ha of deep layered, extensively cultivated organic soils is estimated to reduce GHG emissions by 0.56 Mt CO_2 eq. annually (Kekkonen et al., 2019).

2.4.2 Paludiculture

Paludiculture is an action where cultivation is done in rewetted conditions. It requires ending the current cultivation and finding crops that thrive in wet conditions. (Wichtmann et al., 2016) Secondary areas (since primary areas are for extensive cultivation) for rewetting are peatlands on deep peat depth with feed production (usually grassland) as cultivation type. On feed production sites it is possible to raise the WTL and still cultivate fodder. There are several plants suitable for cultivation in wetted conditions as well as trees, that can grow on a wet peatland (Ministry of the Environment, 2017). For example, optimum WTL, which still allows grass cultivation but reduces GHG emissions, would be at 30 cm below soil surface. This level reduces both CO_2 and N_2O emissions. (Regina et al., 2015) In addition, annual and perennial grass cultivations are in some cases categorized as intensive cultivation but can be still considered suitable for rewetting.

2.4.3 Controlled drainage

One practical method for raising the WTL is the controlled drainage system. The controlled drainage system is an option that allows continuing agricultural production also in intensive cultivation areas after raising the WTL, since raising the WTL could be done occasionally. This would support continuation of more diverse cultivation and be an easier option politically. (Regina et al., 2015)

Figure 1 presents the average hydrological cycle in Finland and illustrates the period when the demand for rewetting by controlled drainage is the most urgent. As Figure 1 shows, during the summer (May till August), precipitation deficit is at its greatest and evaporation is greater than precipitation, thus rewetting is mostly needed. However, in Finland during the time when there is the highest need for rewetting, i.e. the driest period, rewetting may not be technically possible to implement naturally, since there is not enough water available. In contrast, Figure 1 also shows estimated time periods for the most probable time of the year when water reserves for managing the WTL should be adequate. In the spring the estimation is based on snow melting and in the autumn the estimation is based on increased precipitation and decreased evaporation.

Usually in Finland, the WTL in the fields is at the lowest during the summer period. Due to meltwater in the spring and increased rainfall in the autumn, the WTL is at the highest. Thus, the highest need for raising the WTL by controlled drainage system occurs during the summer. However, the WTL rise can be higher between harvest and sowing when it does not inhibit crop growth.

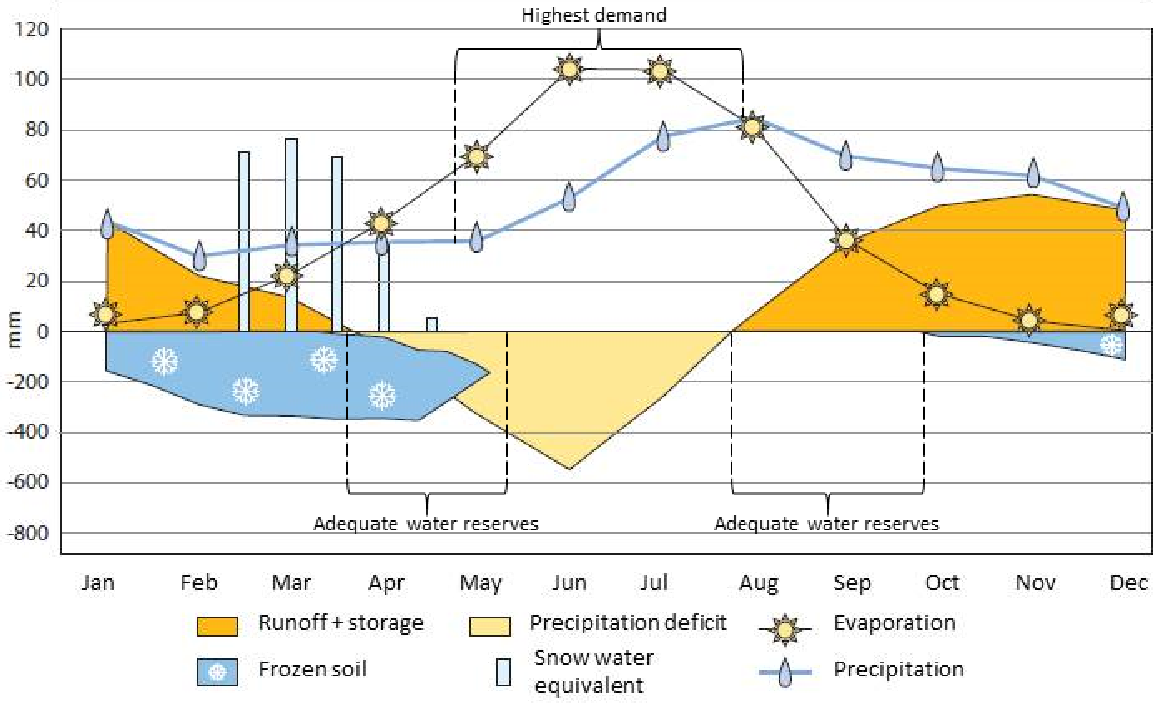

Figure 1. Demand for raising the WTL with controlled drainage system and the most probable periods of the year when the water reserves are adequate for the raise (modified from Äijö et al., 2009).

Controlled drainage system regulates the amount of discharge in drainpipes by weirs in control wells. This allows raising the WTL periodically and decreases the amount of nutrient, solid matter and pesticide loads into waters. (Äijö et al., 2009) Technically, controlled drainage system is efficient if the average slope of the land parcel is not more than 2%, and the water conductivity of the soil is good, which applies to peat. In general, peatlands with slope less than 2% are suitable for controlled drainage system. (Varsinais-Suomen ELY-keskus, 2017)

One environmental benefit of managing the WTL by controlled drainage system is that in deep layered peatlands that are on or near acid sulfate soils, rewetting prevents also the acid sulfate soil layer from oxidation. This decreases the generation of sulfides (sulfuric acid), and thus rewetting also mitigates the risks from acid sulfate soils, such as acidification of soils and runoff waters and therefore the generation of aluminum and heavy metals. In general, wet deep peat layer keeps the possible acid sulfate soil away from oxidation. (Uusi-Kämppä et al., 2013)

2.5 State of cultivated peatlands in Finland

There are approximately 260000 ha of cultivated organic soils in Finland. This is 10% of the total agricultural land area. (Kekkonen et al., 2019) The amount of organic soils in Finland has increased from 8 to 11% between 1990 and 2016 (Regina et al., 2019). Regionally the largest area, over 64400 ha, of cultivated peatlands is located in Pohjois-Pohjanmaa ELY Center (Centres for Economic Development, Transport and the Environment in Finland) (total land area 3681843 ha (MML, 2019)), and the second largest in the Etelä-Pohjanmaa region with an area of over 42600 ha of cultivated peatlands (total land area 1344415 ha

(MML, 2019)). The share of organic soils of all cultivated areas in the Pohjois-Pohjanmaa region is 26%, and in the Etelä-Pohjanmaa region 17%. (Kekkonen et al., 2019)

Majority, 166000 ha of 260000 ha of cultivated peatlands are categorized as having a deep peat depth (more than 0.6 m). The distribution of deep layered peatlands in Finland is shown in Figure 2.

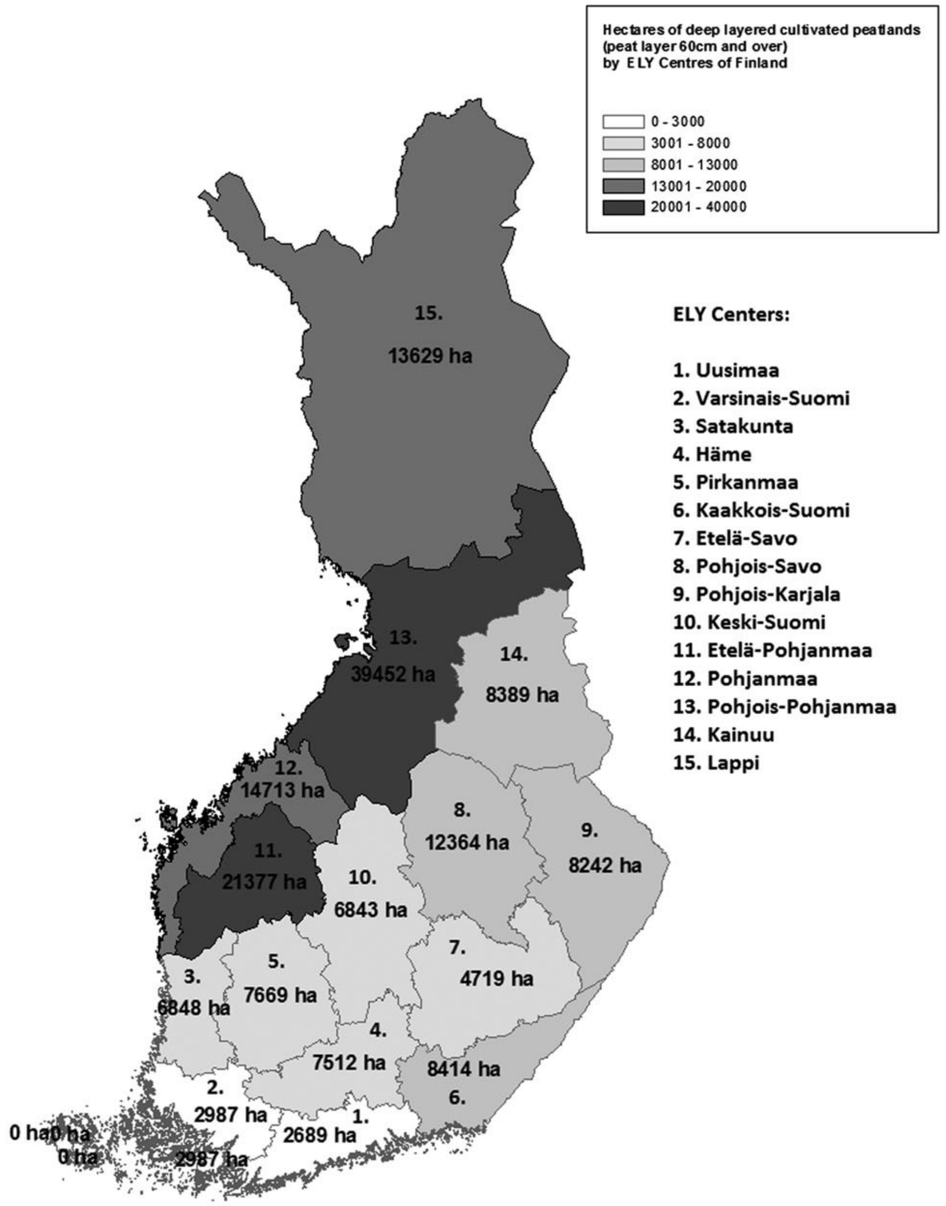

Figure 2. Distribution of deep layered (more than 60 cm of peat) cultivated peatlands in Finland by ELY Centers (Kekkonen et al., 2019).

From 166000 ha of cultivated deep layered peatlands, roughly 24 000 ha are in extensive use (in the year 2016). Extensive use includes, e.g., biodiversity objects, managed uncultivated and temporarily uncultivated fields, and perennial set-asides. Intensive cultivation areas are usually properties of active farms, including different types of annual and perennial grass cultivation, as well as essential food production sites. Feed production lands can be categorized as intensive cultivation areas but also as areas which are not under an active use. (Kekkonen et al., 2019)

2.6 Research gap

The basis for this study was the regional peatland analysis done by Kekkonen et al. (2019). They investigated the most promising fields that could be removed from production, and fields that have the longest mitigation impact on GHG emissions. They calculated the amount and distribution of organic soils in Finland, both on deep and shallow peat and divided them into intensively and extensively cultivated fields, but with less data than in this study. Their focus was on mitigating GHG emissions from organic soils, but they did not evaluate hydrological or topographical properties of the fields that could be suitable for raising the WTL. The information about the amount and distribution of organic soils that are considered for rewetting is not itself all the needed information that is required for fields to be rewetted. With proper topographical and hydrological analysis and wider and more exact data, it is expected that more accurate results of the areas suitable for the WTL management are achieved. The focus of this study is to take further the analysis by Kekkonen et al. (2019) with more precise data, especially hydrological, topographical and crop data. The aim of this study was to identify deep layered peatlands that would be especially suitable for rewetting.

The availability of data of specific locations can be an issue for methods used in this study. In Finland, the spatial and hydrological data cover almost the entire country, but if this methodology is used in some other country, the data may not be available and other methods must be used. In addition, crop data covers only field parcels that have been informed by the landowners, i.e. the owner had not applied for subsidies if fields are without crop code. This may raise some uncertainties, since some of the fields were left out of the datasets and, therefore, also of the analysis.

3 Site description and data

3.1 Study sites

The Pohjois-Pohjanmaa region is located approximately in the middle of Finland (65˚N, 26˚E), and it reaches from the west coast to the eastern border (Figure 3). Climate fluctuates between boreal continental and boreal cool due to the shape of the region (Lilja et al., 2017). Annual mean air temperature varies between 0 and 4°C (min ≈ -33, max ≈ 33°C), and annual mean rainfall between 450 and 700 mm (Finnish Meteorological Institute, 2019).

Two example catchments from Pohjois-Pohjanmaa were selected for detailed analysis. The area of the first catchment (C1, blue dot in Figure 3) is 3068 ha and the second catchment (C2, green dot in Figure 3) is 11505 ha. C1 is located approximately 120 km north from C2, thus, the climate is different in C1 than in C2. Annual mean air temperature in C1 is between 1 and 2 °C, and in C2 from 2 to 3 °C. Annual mean rainfall in C1 is between 550 and 600 mm, and in C2 from 550 to 650 mm. (Finnish Meteorological Institute, 2019)

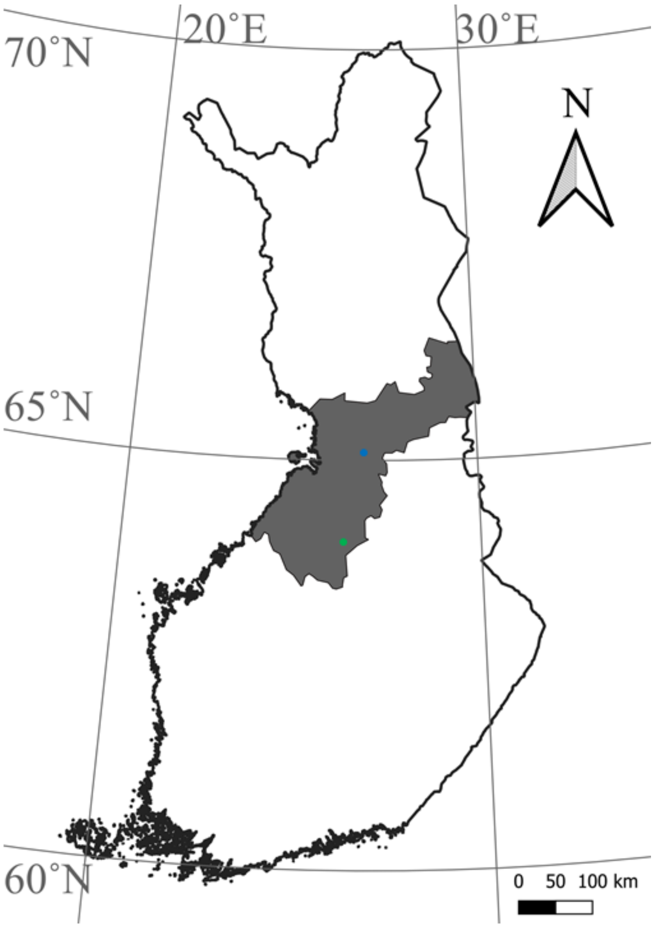

Figure 3. Location of the region of Pohjois-Pohjanmaa (grey area) and the example catchments C1 (blue dot) and C2 (green dot).

Most of the soil in Pohjois-Pohjanmaa is *Endogleyic Podzols* and *Dystric Histosols*, thus the parent material consists mostly of glacial deposits (ground moraine) and deep peat. The terrain in Pohjois-Pohjanmaa is classified as expanse and plain. (Lilja et al., 2017)

3.2 Spatial datasets

Spatial datasets used in this study are listed in Table 1. The coordinate system used in Finland was ETRS89 / ETRS-TM35FIN. All datasets covered almost the entire Finland, except DTW data, which was at the developing phase for Finland. In addition, all datasets were freely available and can be downloaded from the data provider. To be noted, hydrological modelling was only represented as an example method for how additional results could be completed with specified hydrological analysis. Thus, hydrological modelling was not fully implemented in practice. However, datasets required for the modelling were listed in order to be able to implement methods in the future.

Table 1. Spatial datasets used.

Dataset and year	Detailed data	Form	Scale/size	Usage in this study	Data provider
Administrative borders, 2017	Regional State Administrative Agency borders	ESRI Shapefile	1:10000	GIS analysis	National Land Survey of Finland
Field Plot Registry, 2016		ESRI Shapefile	1:5000 - 250000	GIS analysis	Agency for Rural Affairs in Finland
Deep layered peatlands		ESRI Shapefile		GIS analysis	Natural Resources Institute Finland
Soil database, 2009	Soilscapes, Soil regions	ESRI Shapefile	1:250000	GIS analysis, site description	Natural Resources Institute Finland
Catchment borders, 2017		ESRI Shapefile	1:10000	GIS analysis, hydrological modelling	Finnish Environment Institute
Digital elevation model, 2008-2019		Raster	2m*2m	GIS analysis, hydrological modelling	National Land Survey of Finland
Topographical wetness index, 2016		Raster	16m*16m	GIS analysis, hydrological modelling	Natural Resources Institute Finland
Depth to water, developing		Raster	2m*2m	GIS analysis	Natural Resources Institute Finland
Superficial deposits of Finland, 2002-2009	Topsoil data	ESRI Shapefile	1:200000	hydrological modelling	Geological Survey of Finland
Topographic database, 2018	Peatlands and waterbodies	ESRI Shapefile	1:5 000 - 1:10 000	hydrological modelling	National Land Survey of Finland
The Multi-Source National Forest Inventory, 2015	Biomasses of foliage for spruce, broad-leaved trees and pine, canopy cover, stand mean height and the growing stock volume	Raster	16m*16m	hydrological modelling	Natural Resources Institute Finland

Crop data of field parcels from 2008 to 2017 was intersected with data of deep layered peatlands in order to identify the amount and locations of different crop types.

3.3 Meteorological data

Meteorological data were provided by Finnish Meteorological Institute and LUKE at a scale of 10m x 10m. Data used to analyze the suitability of rewetting according to weather were monthly total values of P (mm) and E_p (mm), monthly average values of T (˚C) and snow depth (cm). For hydrological modelling (implemented mostly in theory as initial values and setup), the data used were daily P, daily mean T, relative humidity RH (%), global radiation R_g (Wm^{-2}), H_2O partial pressure (hPa) and wind speed U (m s^{1}).

4 Methods

4.1 Analysis steps

The development of the methods for mapping and analyzing the potential peatland areas was started with GIS analysis with the specific data presented in Section 3. Software used for spatial analysis was the open source QGIS Desktop 3.4.4 with GRASS 7.4.4. Simultaneously with GIS analysis, the effects of weather on suitable areas for rewetting were evaluated. The last step was to estimate how hydrological modelling can improve and specify the results from GIS and weather analysis. For that purpose, the example hydrological model *Spatial Forest Hydrology model (SpaFHy)* (Launiainen et al., 2019) was described and in the future, it can be implemented in open source Python 3.7. GIS data used in SpaFHy are presented in Section 3.2.

Analysis phases and data used in each phase are described in Figure 4.

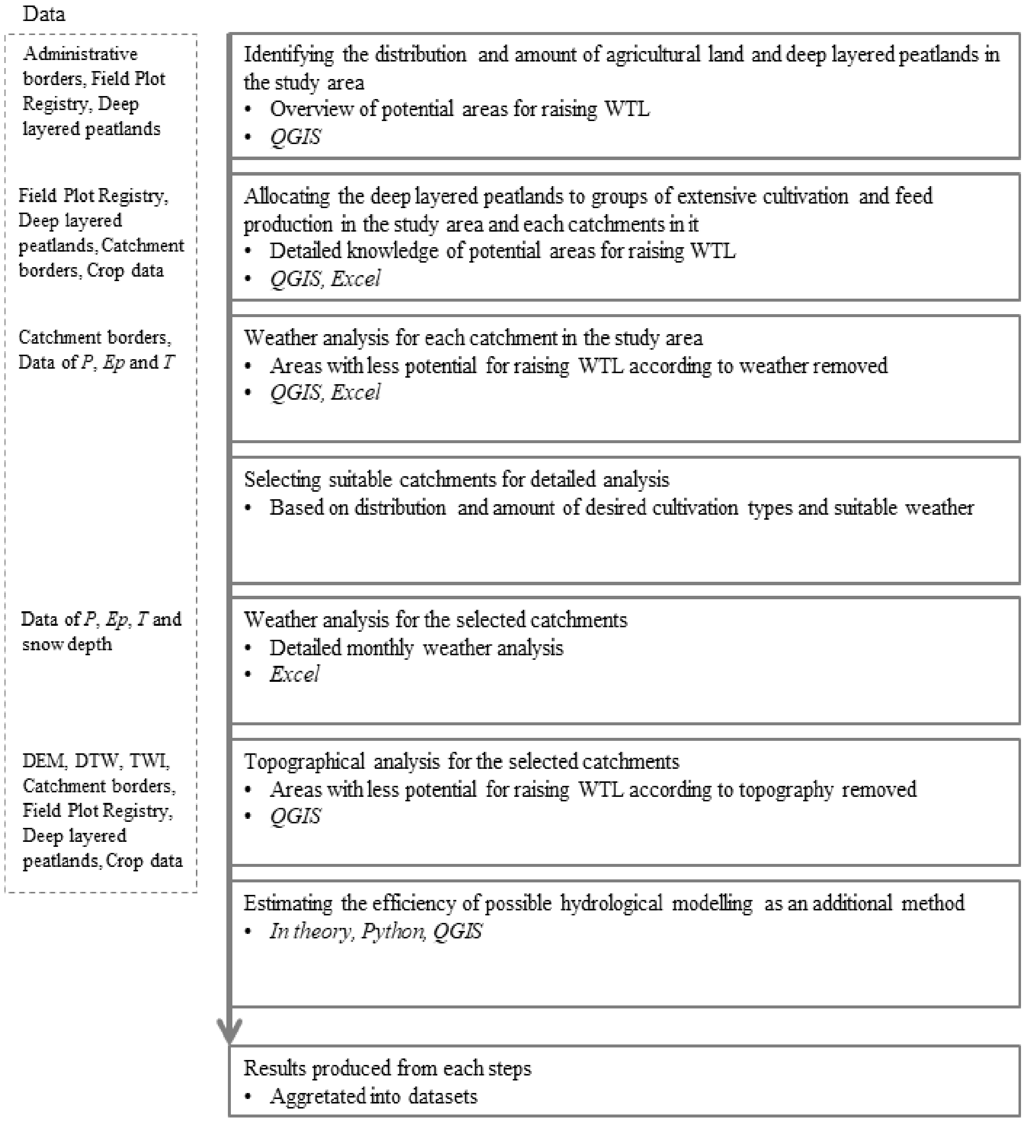

Figure 4. Methods and data used in this study.

4.2 Occurrence of cultivation types

The information about the cultivation type from 2008 to 2017 and the spatial data of deep layered peatlands and field parcels in Pohjois-Pohjanmaa were combined and analyzed. The occurrence of the same cultivation type (including temporarily and permanently uncultivated fields) was analyzed using a ten-year period. In general, a field parcel is assumed to have a specific cultivation type if the type is the same 80% of the time analyzed, i.e. eight out of 10 years the cultivation type is the same. The data of cultivation types was intersected in GIS software into all field parcels that contain fully or partly deep layered peat soil. This is due to the assumption, that even if only part of the field parcel is deep layered peatland, it is more efficient to rewet the whole field parcel instead of only the part where deep layered peatland exists. Figure 5 shows the methods of the analysis of the occurrence of cultivation types.

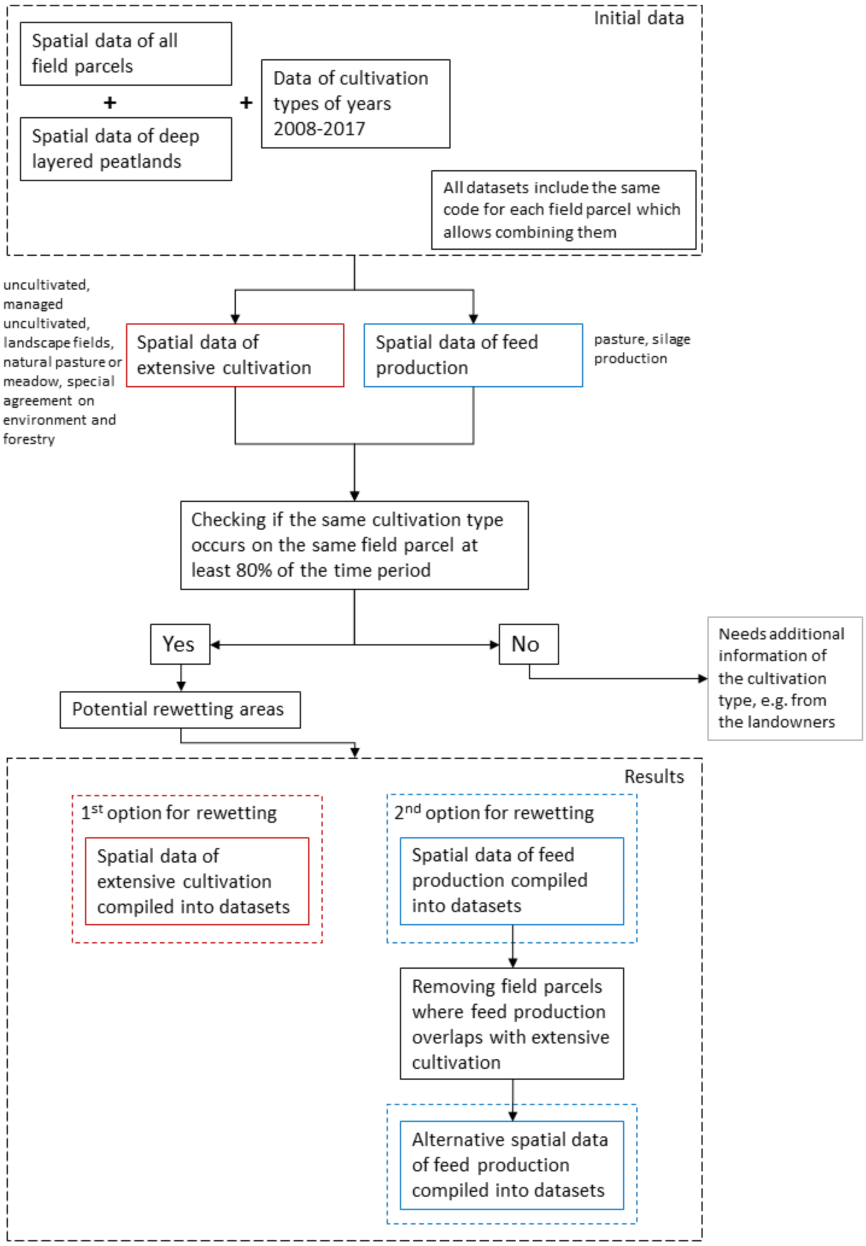

Figure 5. Methods of spatial analysis for identifying potential rewetting areas according to occurrence of the cultivation type in the entire region of Pohjois-Pohjanmaa and in each individual catchment in the region.

The primary option for areas which could be rewetted are fields in extensive cultivation (Figure 5). The secondary option, feed production fields, is considered when the first option is not available or desired. When the primary fields, i.e. extensive cultivation, have been selected for rewetting or already rewetted, and feed production fields are reserved to be rewetted, field parcels where feed production fields overlap with extensive cultivation fields are considered as extensive cultivation. That is, if only extensive cultivation fields are selected for rewetting, only the red box in the results box in Figure 5 needs to be considered. If only feed production fields are selected for rewetting, only the blue box in the results box in Figure 5 needs to be considered. If field parcels with both cultivation types are selected for rewetting, the red and the lower blue box in the results box in Figure 5 are both considered.

Field parcels with the occurrence of the same cultivation type less than 80% of the time period need further analysis and evaluation before they are considered for rewetting, e.g. specific information about cultivation types from landowners.

The total areas of both field parcels containing deep layered peat and extensive cultivation, and field parcels containing deep layered peat and feed production were calculated for the region of Pohjois-Pohjanmaa and for each catchment in the region. Two catchments, C1 and C2 (see Section 3.1), with the largest areas or sufficiently high fraction of field parcels containing deep layered peat and extensive cultivation, or field parcels containing deep layered peat and feed production were selected for detailed analyses.

4.3 Weather parameters

Weather parameters, P (mm), E_p (mm), snow depth (cm) and T (˚C) were taken from one weather station in each catchment in Pohjois-Pohjanmaa for analyzing possible rewetting areas according to weather. Stations located approximately in the middle of the catchments were selected. Comparing values of P, E_p, snow depth and T between the two selected catchments C1 and C2 and values of P and E_p within the whole region of Pohjois-Pohjanmaa for two years give an estimation of the suitability for rewetting at catchment level according to weather.

Monthly total values of P and E_p were used, while monthly averages of snow depth and T were used (Figure 6). The estimations of potential rewetting areas were done according to the difference in P and E_p. The most suitable areas for rewetting had higher P than E_p. Thus, potential catchments, in which suitable field parcels could be rewetted, was estimated by subtracting values of E_p from P (criterion of weather for rewetting). Besides an analysis of P and E_p, snow depth was evaluated in order to estimate the melting of snow during the spring, and therefore the hypothetical wetness of soil. The purpose of presenting monthly weather parameter values gives also information about seasonal demand for rewetting. Weather data were combined with the data of field parcels containing extensive cultivation and feed production in order to chose the suitable catchment according to weather data and then checked whether the catchment had desired cultivation type for managing the WTL, or vice versa. It must be noted that the weather parameters are not directly proportional to the catchment suitability for rewetting, but catchment suitability is rather dependent on the climate zones. However, evaluating meteorological values gives an estimation of the larger areas in which water reserves should be adequate for managing the WTL.

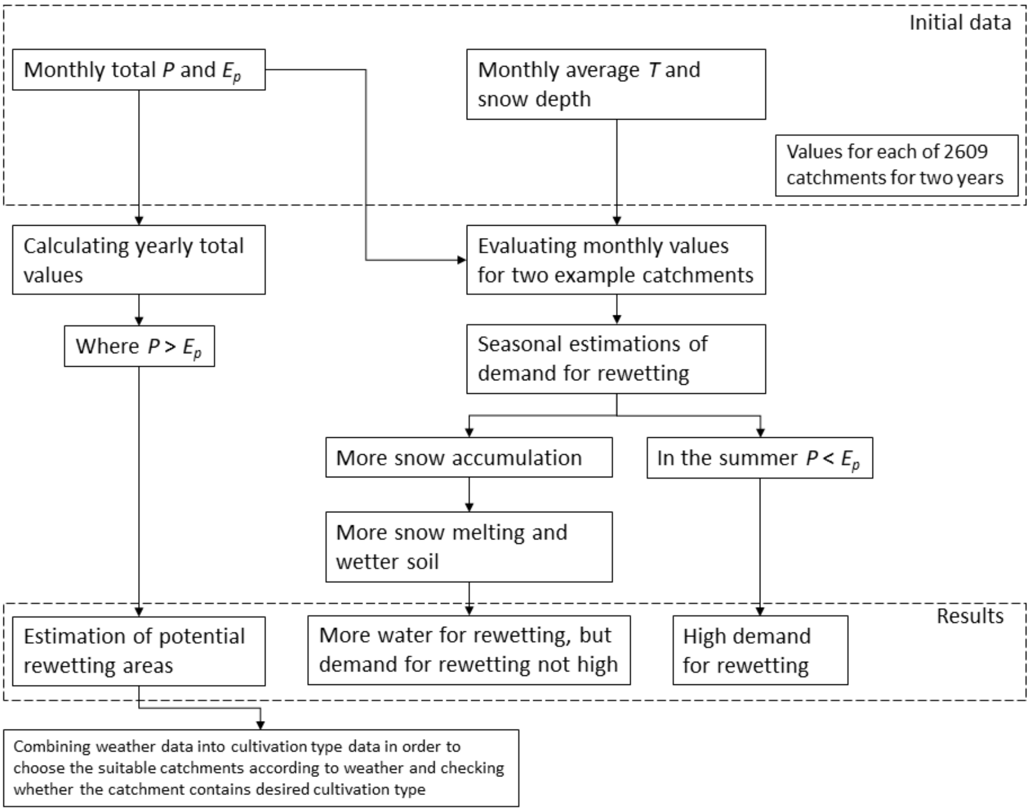

Figure 6. Methods of weather analysis for the entire region of Pohjois-Pohjanmaa and for the two example catchments.

4.4 Digital Elevation Model, Topographical Wetness Index and Depth to Water

Topography was analyzed in order to evaluate the effect of terrain elevation differences on finding the suitable peatlands to be rewetted. DEM, TWI and DTW data for selected catchments were used for spatial analysis (Figure 7). Comparison of elevation differences around field parcels that contain deep layered peat and extensive cultivation, or feed production was made. TWI is used for analyzing the possible accumulation of runoff, i.e. higher values are assumed to indicate flatter terrain and therefore wetter soils. For DTW, threshold areas of 4 ha and 1 ha for flow-channel were compared in order to analyze soil wetness in drier and wetter conditions, respectively. DTW values less than or equal to 1.5 m were selected for describing wet soil. Additionally, average slope of field parcels is needed when considering controlled drainage system for raising the WTL. The threshold value for the average slope of the field for rewetting by controlled drainage is ≤ 2%. The aim was to analyze the directions of water flows if certain field parcel is rewetted.

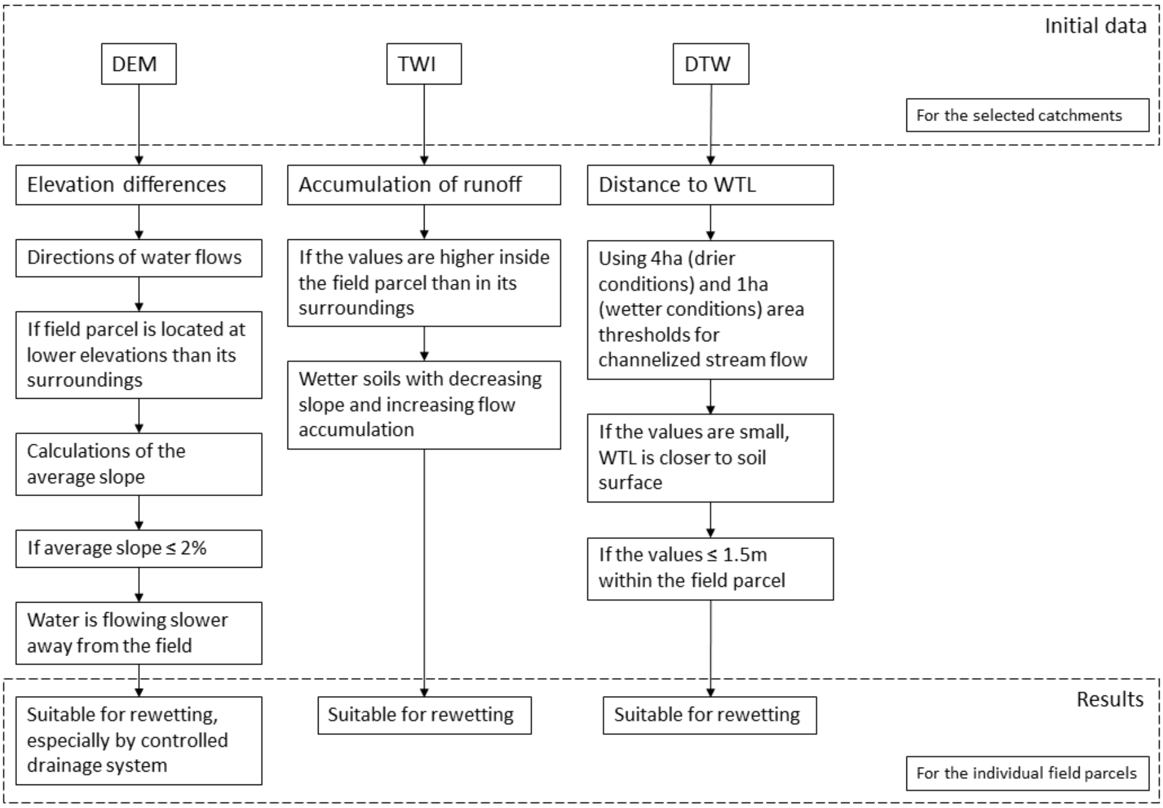

Figure 7. Methods of topographical analysis for the two example catchments.

4.5 Hydrological modelling

The aim of presenting hydrological modelling as an example method in this study is to demonstrate how results of cultivation type, topographical and weather data could be improved and specified by hydrological modelling. For this purpose, Spatial Forest Hydrology model (SpaFHy) (Launiainen et al., 2019) is briefly described.

SpaFHy integrates hillslope and catchment models, driven by topography, with a distributed representation of hydrology of topsoil and above-ground. The model is controlled by vegetation and soil characteristics. (Launiainen et al., 2019) SpaFHy contains three sub-models; Canopy model, Bucket model and Topmodel (Beven & Kirkby, 1979) (Figure 8). The model can be used either at catchment or grid scales. Models are run with Python 3.7. software, using Numpy-arrays operations. (Launiainen et al., 2019)

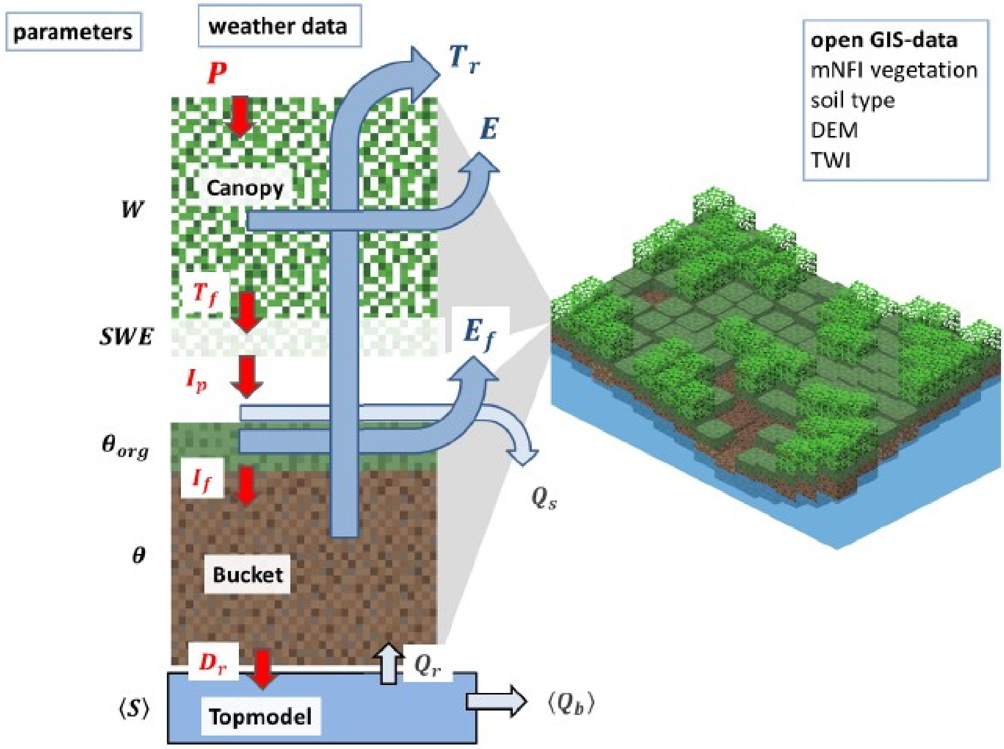

Figure 8. SpaFHy structure (Launiainen et al., 2019).

Meteorological parameters, presented in Section 3.3, are used for the model as forcing, and they can differ from grid cell to another or be spatially uniform. Besides meteorological inputs, several variables from GIS data as raster arrays are needed for providing inputs. Spatial data is listed in Table 1.

Parameters and their values for each sub-model at stand and catchment scale are used for initializing this hydrological model. These parameters include e.g. soil and vegetation characteristics, such as depth of soil layers, moisture content of soil, canopy storage for precipitation, stomatal parameters and transmissivity. (Launiainen et al., 2019)

User can define which results are produced by SpaFHy. The results include, for instance, snow water equivalent, components of evaporation, volume water content of different soil layers, water flows and saturation deficit. Results can be stored as NetCDF format.

5 Results and discussion

The results are firstly produced for the region of Pohjois-Pohjanmaa and secondly for the selected two example catchments. The analysis and the methods are designed to support implementation in any other area where the required data exists. The main results from GIS and weather analyses are collected into datasets as forms of shapefiles, text files and Excel sheets, which can be used in LUKE in the future.

5.1 Area and distribution of peatlands

According to the spatial analysis with the data of field parcels and deep layered peatlands, the total area of agricultural land in the region of Pohjois-Pohjanmaa is 264719 ha of which 41652 ha are deep layered peatlands. Their distribution in Pohjois-Pohjanmaa is presented in Figure 9, where it is shown that agricultural lands are mostly located in the southern part of the region, while deep layered peatlands are distributed more evenly. It should be noted that only deep layered peatlands are shown in Figure 9b instead of the whole field parcels that contain deep layered peat.

Figure 9. Distribution of total agricultural land (264719 ha) (a) and deep layered peatlands (41652 ha) (b) in the region of Pohjois-Pohjanmaa.

Table 2 presents the areas of different field parcel categories in Pohjois-Pohjanmaa. 80% occurrence refers to that at least eight out of 10 years the cultivation type stays unchanged on the same field parcel. Categories for which areas are considered first suitable rewetting lands are also listed in Table 2. Here the criterion for suitability for rewetting is selected only based on cultivation type, meaning that hydrological and topographical information are ignored at this point.

Categorizing in Table 2 is based on the full area of field parcels instead of only the area of deep layered peatlands. This is because it is more reasonable and practical to rewet the whole field parcel, albeit it is only partly deep peat soil.

The primary area considered for rewetting is field parcels containing deep layered peat and extensive cultivation, 1552 ha (category 1 in Table 2). These lands are mostly temporarily or permanently uncultivated, managed uncultivated, landscape fields, natural pasture or natural meadow. These can also be lands that have a special agreement on environment and forestry. The secondary area considered for rewetting is field parcels containing deep layered peat and feed production, 16915 ha (category 2 in Table 2). These lands are for annual or perennial pasture or silage production. Figure 10 illustrates the distribution of these field parcels in extensive cultivation and feed production. Comparing Figures 9 and 10 shows that there is a significant amount of potential cultivated lands that could be suitable for raising the WTL. This means ceasing the production in extensive cultivation sites, i.e. restoring these sites into their natural condition, and continuing cultivation in feed production sites in rewetted conditions, e.g. paludiculture.

It should be noted that most of the field parcels have both cultivation types; extensive cultivation and feed production. Generally, if a field parcel is partly in extensive use it is very probable that the whole field parcel will soon be in extensive use entirely. Therefore, when considering other cultivation types than extensive cultivation for rewetting, it is reasonable to ignore field parcels where extensive cultivation overlaps with the other cultivation type. Thus, categories 3 or 2 in Table 2 present the situations where the primary option (extensive cultivation, category 1) is already considered, i.e. field parcels containing both extensive cultivation and feed production are removed, and field parcels containing only feed production remain. Thus, it leaves an area of 16699 ha of feed production for rewetting.

The last row (category 4 in Table 2) illustrates the areas of extensive cultivation and feed production fields where the cultivation type is not completely certain. This means that in the same field parcel the cultivation type has not remained unchanged at least eight out of ten years. Less than 80% occurrence of the same cultivation type can also mean lack of available data, since not all farms and landowners inform their cultivation types. However, these lands presented as others in Table 2 can be considered for rewetting if the proper information about the cultivation type is received from the landowner.

Table 2. Areas of different field parcel categories and shares of different cultivation type from the field parcels partly or totally on deep layered peat (66594 ha) in the Pohjois-Pohjanmaa region. Category column refers to which areas are considered first for suitable rewetting lands.

Category	Land	Area (ha)	Share[4] (%)
	Total agricultural land	264719	
	Field parcels partly or totally on deep layered peat	66594	
	Total deep layered peatland[1]	41652	62.55
1	Extensive cultivation[2]	1552	2.33
2	Feed production[2]	16915	25.40
3 or 2	Feed production[2], overlaps with extensive cultivation removed	16699	25.08
4	Other[3]	41281	61.99

1 only the area of deep layered peatland, not the whole field parcels
2 field parcels containing partly or totally deep layered peat, occurrence of the same cultivation type more than 80%
3 field parcels containing partly or totally deep layered peat, occurrence of the same cultivation type less than 80%
4 from field parcels partly or totally on deep layered peat (66594 ha)

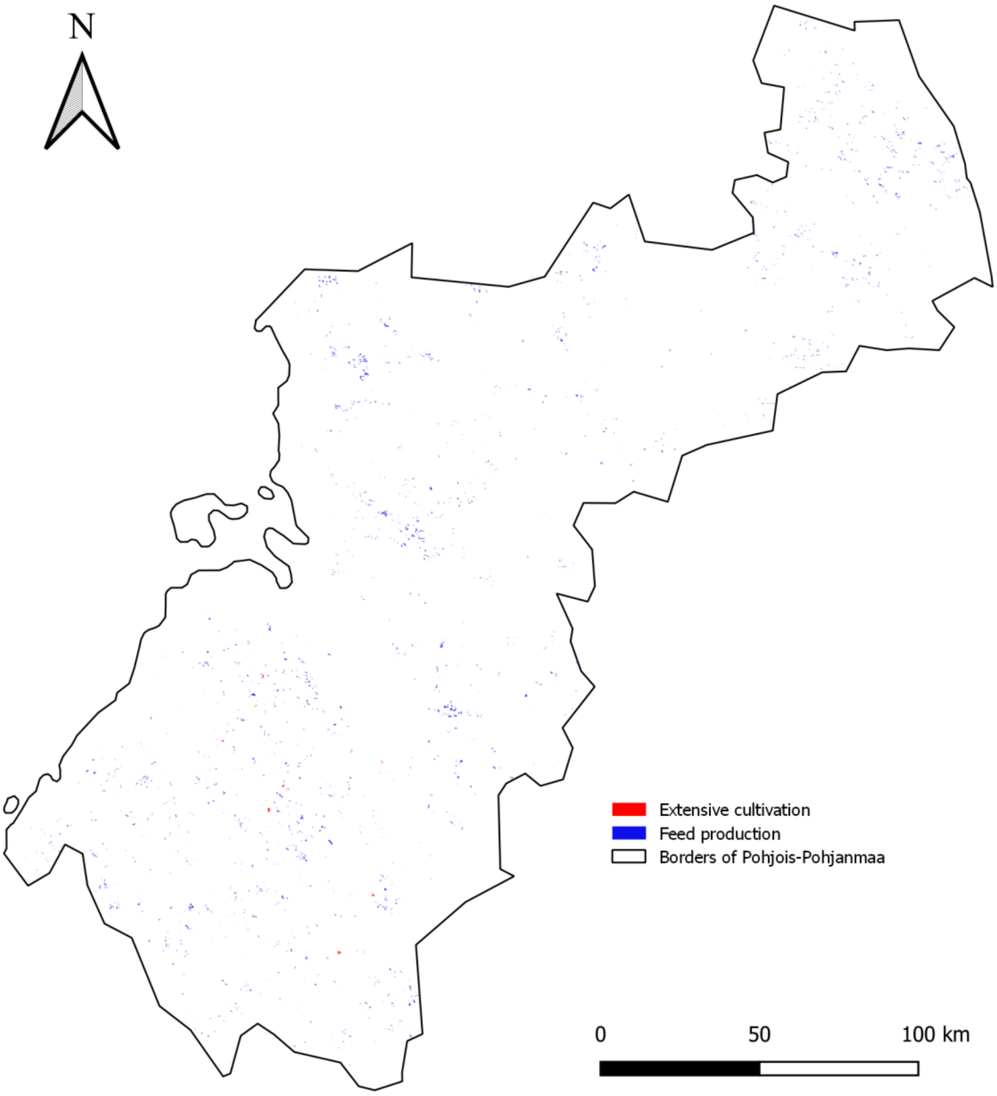

Figure 10. Field parcels containing extensive cultivation (1552 ha) and field parcels containing feed production (16915 ha) in the Pohjois-Pohjanmaa region.

The results in Table 2 differ from Kekkonen et al. (2019), since there were more data in this study. This is due to a different categorizing of cultivation types and a longer time period used for identifying the occurrence of the same cultivation type in the same field parcel. Kekkonen et al. (2019) categorized cultivation types only for intensive and extensive use on both shallow and deep peatlands, whereas this study excluded, e.g., all active annual food production lands as well as shallow peatlands, since they are not suitable for rewetting. For example, Kekkonen et al. (2019) found that in the region of Pohjois-Pohjanmaa there are approximately 5296 ha of extensive use on deep layered peatlands, while this study suggests that there are 1552 ha of extensive use on deep layered peatlands. Kekkonen et al. (2019) used information about cultivation types from only one year, while in this study the time period was 10 years and the same cultivation type in the same field parcel had to occur at least in eight years of the time period.

Based on the GHG emissions reductions in the study by Kekkonen et al. (2019), rewetting field parcels containing deep layered peat and extensive cultivation (category 1 in Table 2) and field parcels containing deep layered peat and feed production, where overlaps with extensive cultivation removed (category 3 or 2 in Table 2) would lead to approximately reduction of 0.44 Mt CO_2 eq. annually.

Table 3 presents five example catchments with the highest area of deep layered peatlands containing extensive cultivation and/or field parcels containing feed production in Pohjois-Pohjanmaa. The last one is a catchment containing the highest amount of both cultivation types. The idea of Table 3 is to show how desired catchments can be selected for rewetting according to catchment area and the amount of different cultivation types. After that or simultaneously, analyses of weather and topography can be implemented into the areas.

Table 3. Catchments with the largest area of deep layered peatlands containing extensive cultivation and feed production fields.

Catchment area (ha)	Area of deep layered peatlands (ha)
2187	63_1
3100	59_1
3008	195_2
1907	137_2
11505	39_1, 74_2

1 extensive cultivation
2 feed production

5.2 Weather as a criterion for rewettability

For the analysis of P and E_p, data from years 2017 and 2018 were selected. Combining weather data into catchments with a presence of field parcels containing deep layered peat and extensive cultivation and/or feed production resulted to datasets where cultivation types can be compared to weather data. Based on the comparison, the most potential catchments can be selected for possible rewetting according to cultivation type and area as well as weather. To be noted, yearly analyses in this study present static situations of the influence of weather parameters on potential areas where managing the WTL would be possible.

An example of the distribution of P and E_p in all catchments in 2017 and 2018 in Pohjois-Pohjanmaa is presented in Figures 11 and 12 with the locations of example catchments C1 (upper black dot) and C2 (lower black dot). The darker the shade of blue the higher the total yearly P is (Figures 11a and 12a), and the lighter the shade the lower the total yearly E_p is (Figures 11b and 12b). These areas where yearly total $E_p < P$ are generally more suitable for rewetting, since there are more water reserves in the catchment originated from weather parameters, than the areas where $E_p > P$.

Figures 11 and 12 show that the total P and E_p in 2017 and 2018 varies substantially. Taking the annual total values of P and E_p in all catchments in Pohjois-Pohjanmaa and calculating an average between them, resulted to P of 610.8 mm and E_p of 478.6 mm in 2017, and P of 482.7 mm and E_p of 640.3 mm in 2018. The difference in the values of E_p within the years can be partly explained by the higher average temperature during the summer of 2018. As a comparison, from 1981 to 2010 the total yearly average P has been 575 mm in Pohjois-Pohjanmaa (Finnish Meteorological Institute, 2019). The more reliable result would be achieved with longer time periods of weather data. However, at the moment the specific data is available only for the years 2017 and 2018.

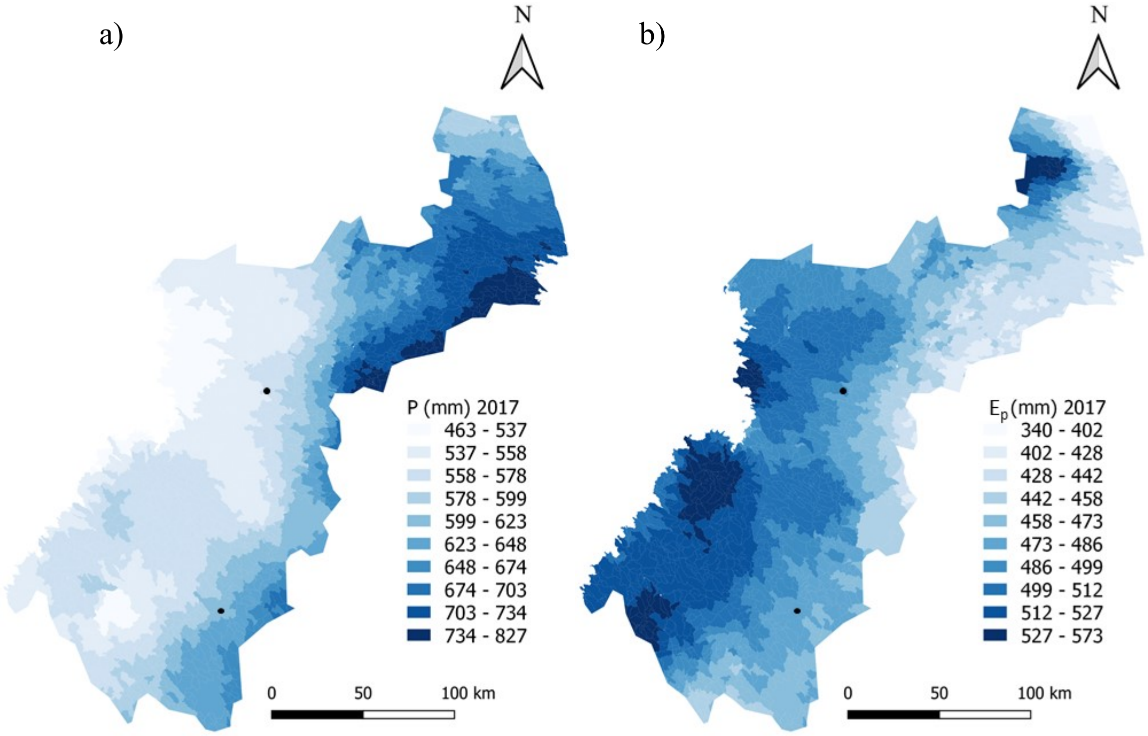

Figure 11. Distribution of the total values of P (mm) (a) and E_p (mm)(b) in the region of Pohjois-Pohjanmaa in 2017, and the locations of the example catchments C1(upper black dot) and C2 (lower black dot).

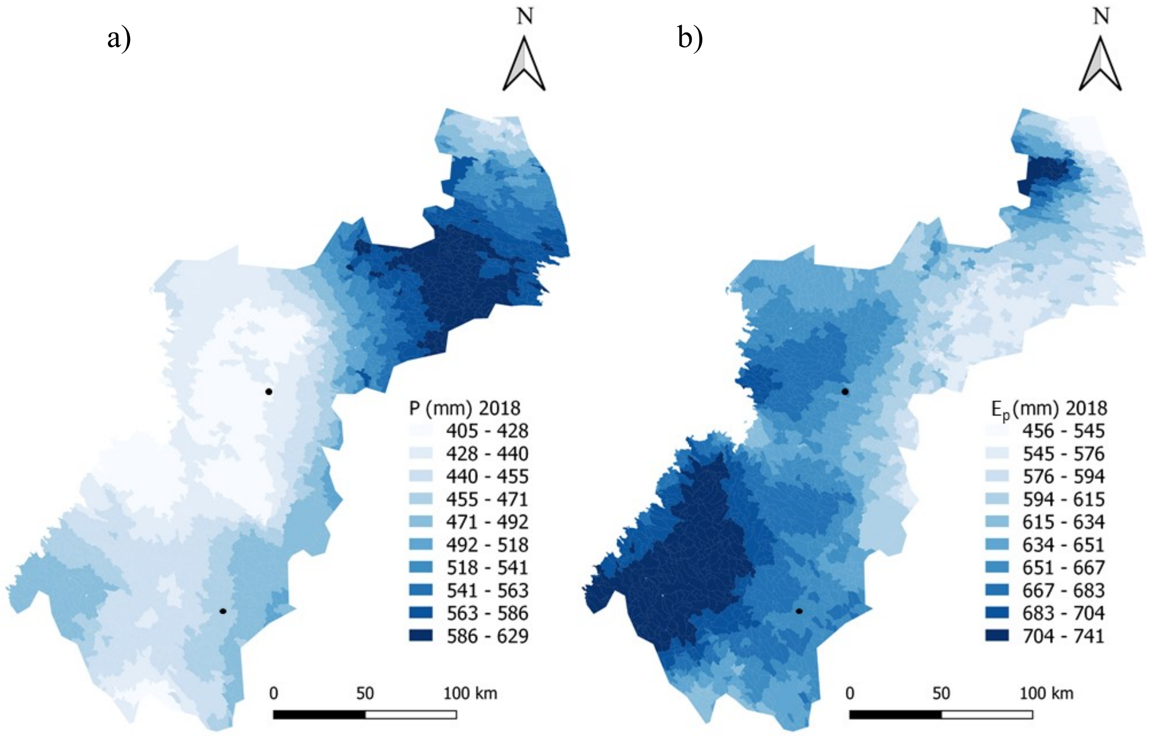

Figure 12. Distribution of the total values of P (mm) (a) and E_p (mm) (b) in the region of Pohjois-Pohjanmaa in 2018, and the locations of the example catchments C1(upper black dot) and C2 (lower black dot).

The maps in Figures 11 and 12 and the data produced from them can be used for choosing the most potential areas for rewetting according to weather, and then check whether the catchment contains the wanted cultivation type (or vice versa). However, it must be noted that even if a catchment is not located at the most promising weather areas, the field parcels can still be rewetted if more detailed sub grid scale analyses are made. For example, smaller scale topographical and hydrological analyses.

Subtraction of E_p from P as a weather criterion for potential field parcels in Table 2, eliminates poorly suitable parcels for rewetting according to weather. Table 4 presents the same results of the field parcels containing deep layered peat and either extensive use or feed production as in Table 2, but according to the weather in 2017 and 2018. The remained area indicates all field parcels inside the catchments where yearly E_p is greater than yearly P.

Table 4. The areas of different field parcel categories, their remained area after removing field parcels in catchments where yearly total $P < E_p$ in 2017 and 2018, and the shares of remained areas from the field parcels partly or totally on deep layered peat (66594 ha) in the Pohjois-Pohjanmaa region.

Land	Area (ha)	Remained area (ha) according to weather in 2017	Share_3 (%) according to weather in 2017	Remained area (ha) according to weather in 2018	Share_3 (%) according to weather in 2018
Total agricultural land	264 719				
Field parcels partly or totally on deep layered peat	66 594				
Total deep layered peatland_1	41 652				
Extensive cultivation_2	1 552	1 539	2.31	4	0.01
Feed production_2	16 915	16 852	25.31	566	0.85
Feed production_2, overlaps with extensive cultivation removed	16 699	16 643	25.00	566	0.85

1 only the area of deep layered peatland, not the whole field parcels
2 field parcels containing partly or totally deep layered peat, occurrence of the same cultivation type more than 80%
3 from field parcels partly or totally on deep layered peat (66594 ha)

Table 4 illustrates the difference in weather between the compared years. According to weather in 2017, almost the same results of the areas of field parcels are obtained than by the analysis of only cultivation types. Evaluating weather in 2018, a radical decrease in the areas of field parcels suitable for rewetting is observed. The removed areas of field parcels according to 2018 are located in the northern part of the region of Pohjois-Pohjanmaa.

A longer time period would have led to more accurate results, since more data would have been analysed and the yearly values could have been compared to each other. However, the results in Table 4 show how more precise results can be achieved by evaluating the weather, compared to the earlier study by Kekkonen et al. (2019).

Category of field parcels in which the occurrence of the same cultivation type is less than 80% (see Table 2) were left out from the further analysis, since the information about this category is not relevant at this point. This is because the cultivation type on these fields is not certain, and one cannot be sure whether they are suitable for rewetting or not.

Two example catchments, C1 and C2, were selected for closer weather analysis. They were selected according to their proper amount and distribution of extensive cultivation and feed production lands. Monthly total values of P and E_p and average values of T were compared between two catchments (Figures 13 and 14). These catchments selected for detailed weather and topographical analysis fulfilled the weather criterion (as discussed according to Figures 11 and 12 and Table 4) of year 2017, i.e. there are higher yearly P than Ep, but not in 2018.

In Figures 13-16, the weather in C1 and C2 is simply analyzed and the catchment suitability for managing the WTL is estimated. Considering only the year 2017 and the difference of total P and E_p, the catchment 2 (C2) seems to be a better choice for rewetting than catchment 1 (C1), since total P is relatively higher and E_p lower. During the year 2018, P was significantly lower within the whole region of Pohjois-Pohjanmaa, and E_p higher, assumed due to higher T in the summer and lower T during the winter (and more snow). However, also in 2018 C2 seems to be a reasonable choice for rewetting according to weather. Additionally, considering the sum of the total values of P from 2017 and 2018 and the sum of the total values of E_p from 2017 and 2018, C2 is again a better choice than C1 with a smaller difference between P and E_p. It must be noted, that there are other factors, such as terrain topography and snow melting, influencing soil wetness than only the relation of P and E_p.

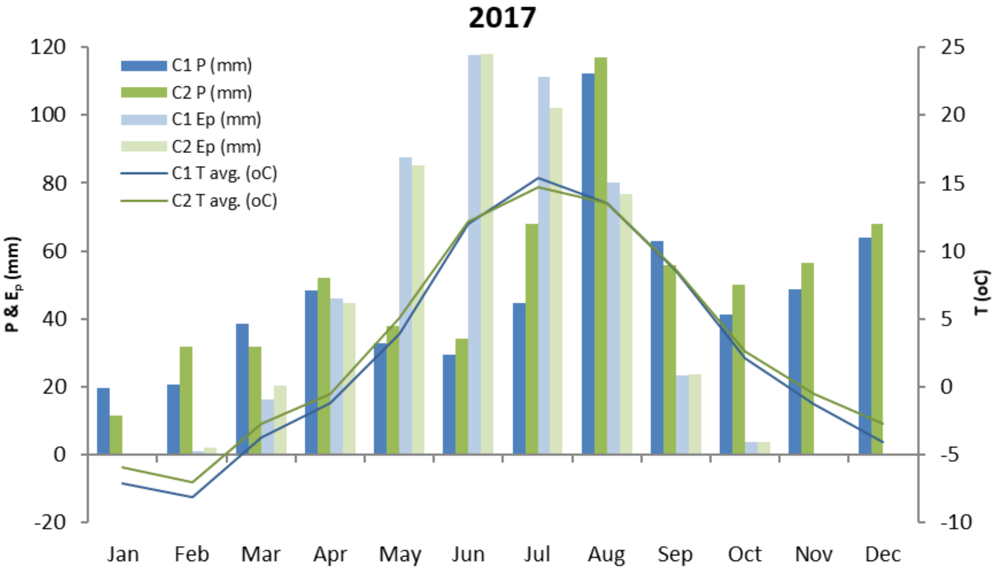

Figure 13. Monthly total values of P and E_p (mm) and average monthly values of T (˚C) in the two example catchments C1 and C2 in 2017.

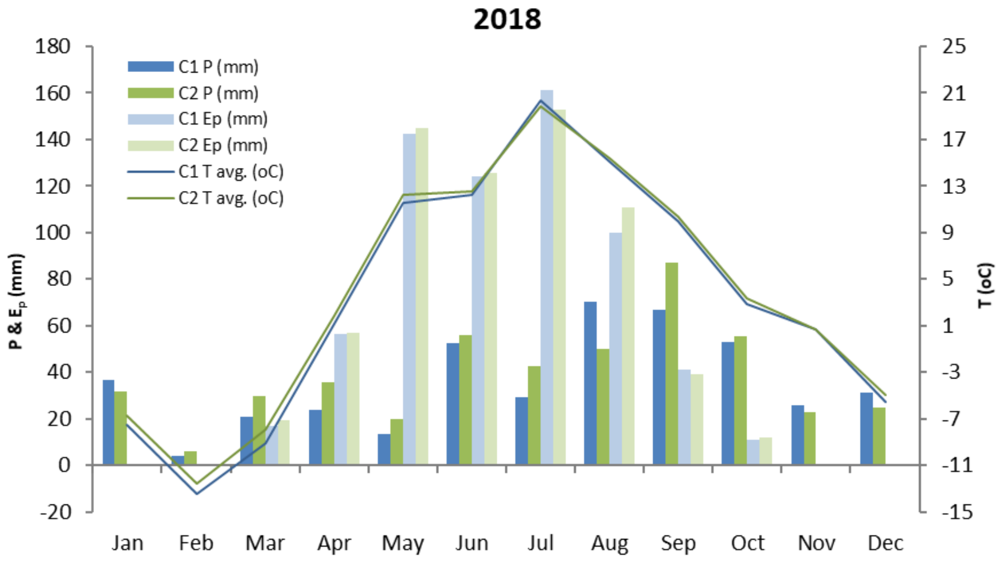

Figure 14. Monthly total values of P and E_p (mm) and average monthly values of T (˚C) in the two example catchments C1 and C2 in 2018.

Figures 15 and 16 show monthly average snow depth in catchments C1 and C2 in 2017 and 2018. Due to the amount of snow, in C1 there was more melting of snow during the spring. Thus, it can be assumed, that the greater snow melting leads to wetter soil in the area and more water for rewetting, but in contrast, the wetter the soil is, the higher the WTL is assumed to be and the need of rewetting is not urgent. Again, water flows according to terrain elevations, therefore, whether the selected field parcels for rewetting are located at lower elevations than the surroundings should be analyzed.

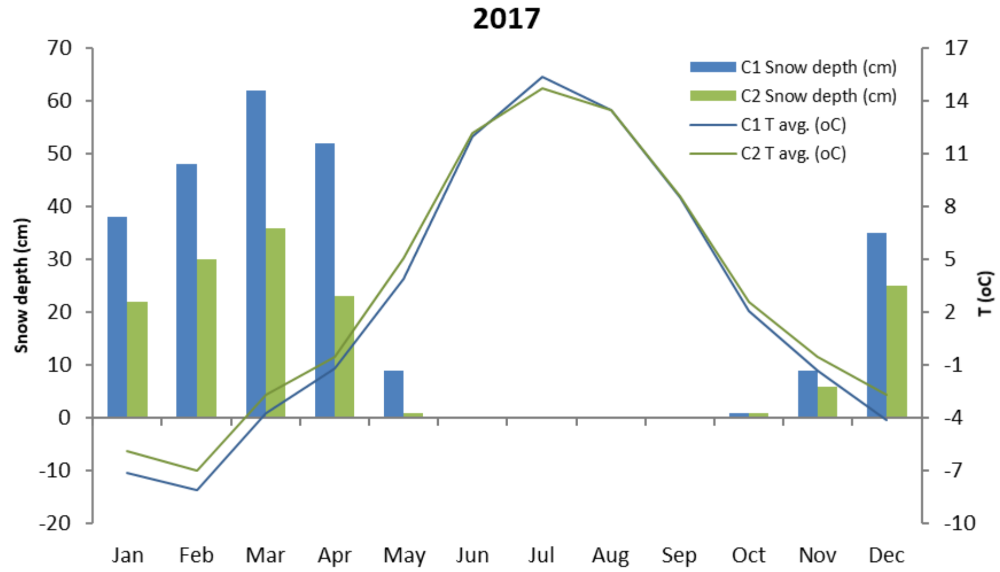

Figure 15. Monthly average snow depth (cm) and T (˚C) in the two example catchments C1 and C2 in 2017.

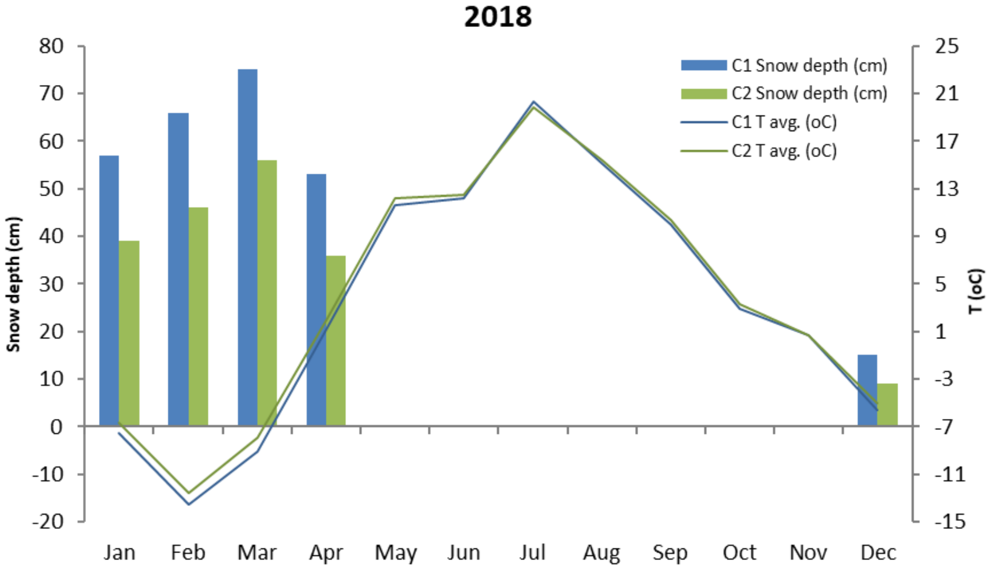

Figure 16. Monthly average snow depth (cm) and T (˚C) in the two example catchments C1 and C2 in 2018.

Figures 13-16 can be compared to Figure 1 presented in Section 2.4.3. They show the period when E_p is higher than P (approximately May till August) and when there is snow on the ground, and snow melting, indicating the need for the WTL managing by controlled drainage. In contrast, E_p is one factor causing lowered WTL, and E_p is generally high during the period when rewetting would be needed the most. This leads to the high possibility that there are not adequate water reserves during rewetting period. Thus, rewetting would be the most effective to implement before and after the driest period of the year, which is usually from June till August in Finland. It is very probable that there exists a period during the year when areas in need of rewetting remain dry. Additionally, the calculation of the variable E_p has not been considered in this study. There are several parameters affecting on E_p, such as vegetation and meteorological parameters. This caused some uncertainties within the weather analysis in this study.

5.3 Topography as a criterion for rewettability

The example catchments C1 and C2 were used for topographical analysis. In addition to the selection methods of the example catchments presented in Section 4, the selection was based on the distribution of field parcels in the catchments (i.e. field parcels distributed evenly) in order to make simple visualizations. As stated before, they fulfill the weather criteria in 2017, i.e. there were higher yearly P than E_p, but not in 2018.

Figures 17-20 present DEM, Figures 21-23 DTW and Figures 24-27 TWI in the catchments with field parcels containing deep layered peat and extensive cultivation, and field parcels containing deep layered peat and feed production. The idea is to visualize the effect of topography on hydrology, i.e. to see if the field parcels are suitable for rewetting based on elevation differences. The lowest DEM value (m) in the catchments have been subtracted from all DEM values in order to make the visualization clearer, i.e. in order to make the lowest point starting from zero. DTW is only implemented for the second catchment due to the availability of the data.

Figure 17 shows how field parcels are generally located at lower elevations than their surroundings. Therefore, according to DEM, these field parcels should be suitable for rewetting. As stated in Section 2.4.3, field parcels with average slope less than 2% are generally suitable for controlled drainage systems, and thus they should also be suitable for permanent rewetting. Controlled drainage system allows raising the WTL periodically if permanent rewetting is not possible. Smaller average slope indicates smaller elevation differences within the field parcel. This means that if the field parcel will be rewetted and more water is generated at the surface and subsurface, water movements are not so radical, and water is likely to slowly flow away from the field parcel.

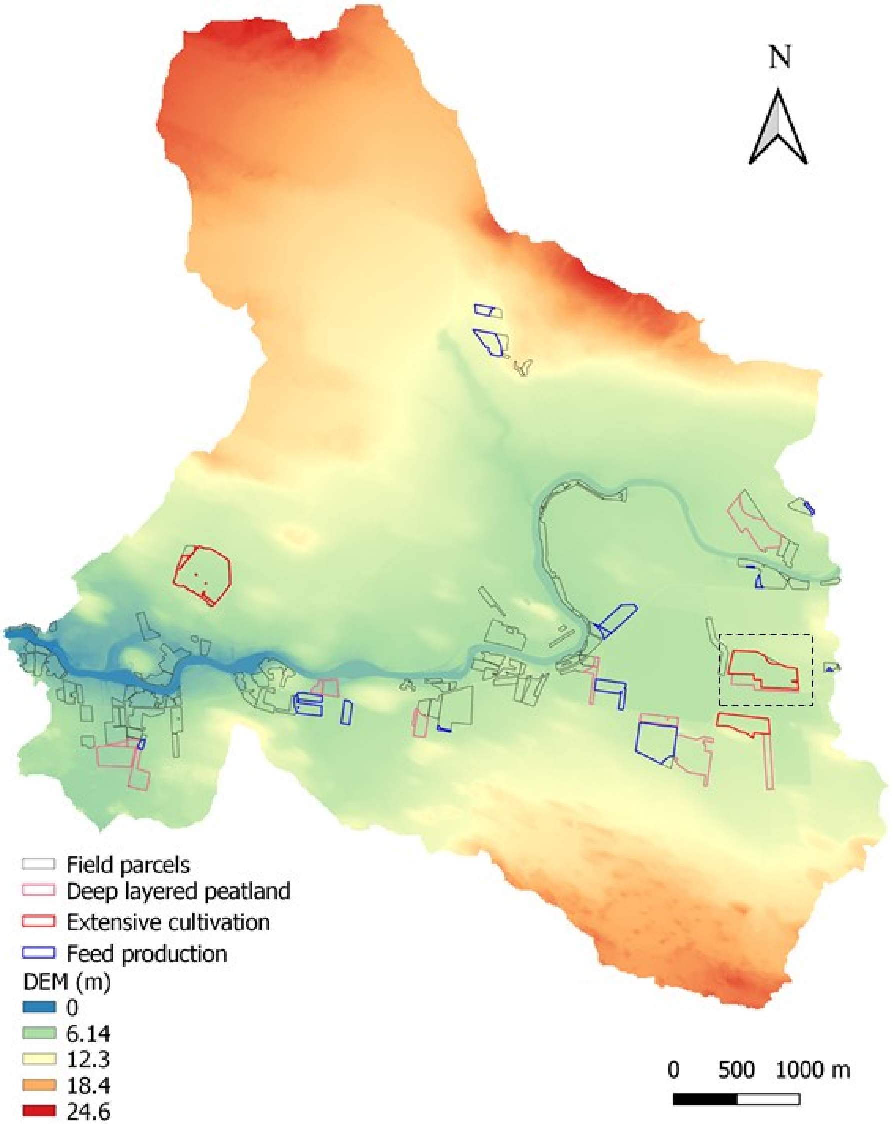

Figure 17. DEM and all agricultural field parcels, deep layered peatlands and field parcels containing deep layered peat and either extensive cultivation or feed production in C1. The box with dashed lines indicates a field parcel containing deep layered peat and extensive cultivation analyzed in detail in Figure 18.

Figure 18 presents a detailed example of a field parcel from C1 containing deep layered peat and extensive cultivation with elevation differences shown. Figure 18 shows that example field parcel in C1 is located at lower elevations than its surroundings. According to DEM, this field parcel is suitable for rewetting and it can be assumed that water would be slowly flowing topographically away from the field. However, as seen from Figure 18 there are elevation differences inside the field parcel as well. The minimum elevation is approximately 7.52 m while the maximum is 8.50 m. However, average slope of the field is less than 2%, thus controlled drainage system can be applied and, therefore, also rewetting. Topographically water is flowing from higher WTL to lower WTL, and usually terrain elevations correlate with the WTL. Thus, when practical rewetting is applied, an evaluation of the beginning point is needed.

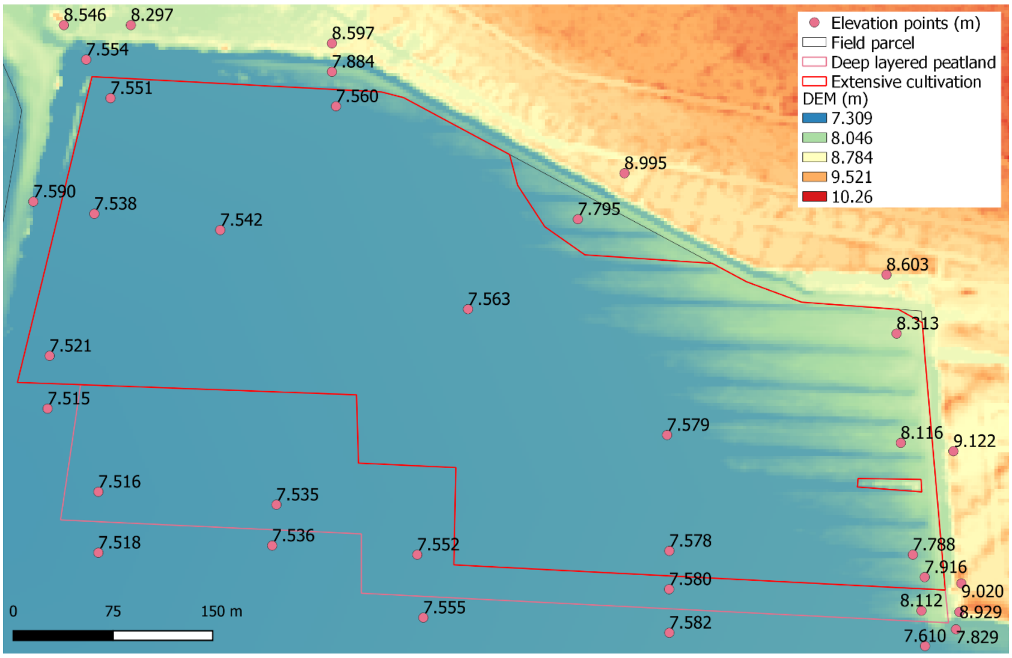

Figure 18. Detailed DEM analysis with elevation points and a field parcel in extensive use in C1.

Figure 19 shows that in the second catchment the field parcels containing desired cultivation type are located at lower elevation that their surroundings (in the similar manner as in Figure 17).

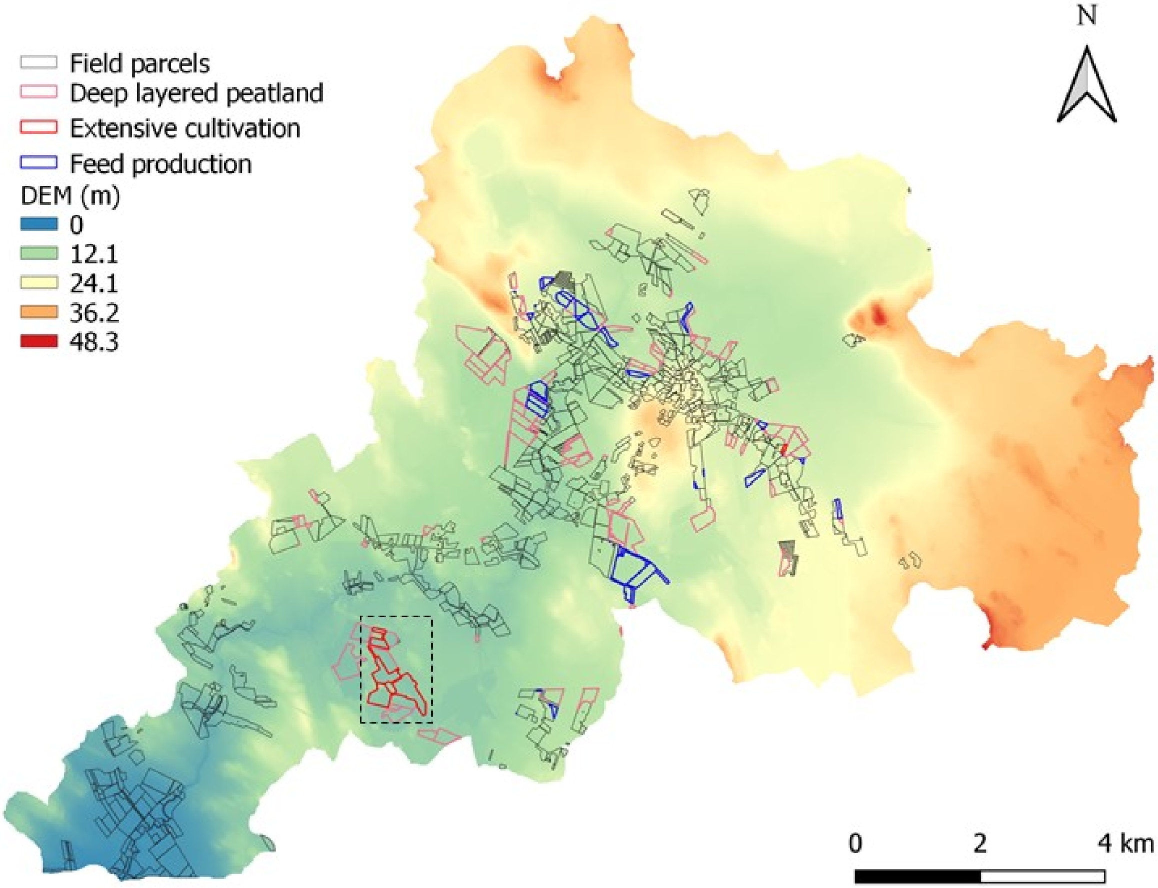

Figure 19. DEM and all agricultural field parcels, deep layered peatlands and field parcels containing deep layered peat and either extensive cultivation or feed production in C2. The box with dashed lines indicates field parcels containing deep layered peat and extensive cultivation analyzed in detail in Figure 20.

Figure 20 illustrates the same situation as in Figure 18 in the field parcels located in C2. There are more clearly shown the elevation differences between field parcels and the surrounding area than in Figure 18. In contrast, there are fields with other cultivation types near the field parcels containing deep layered peat and extensive use, which makes topographical analysis a bit complex. Thus, it cannot be stated that each field parcel in extensive use in Figure 20 is surrounded by higher elevations. However, Figure 20 supports the fact that cultivated peatlands are usually located at lower elevations than their surroundings.

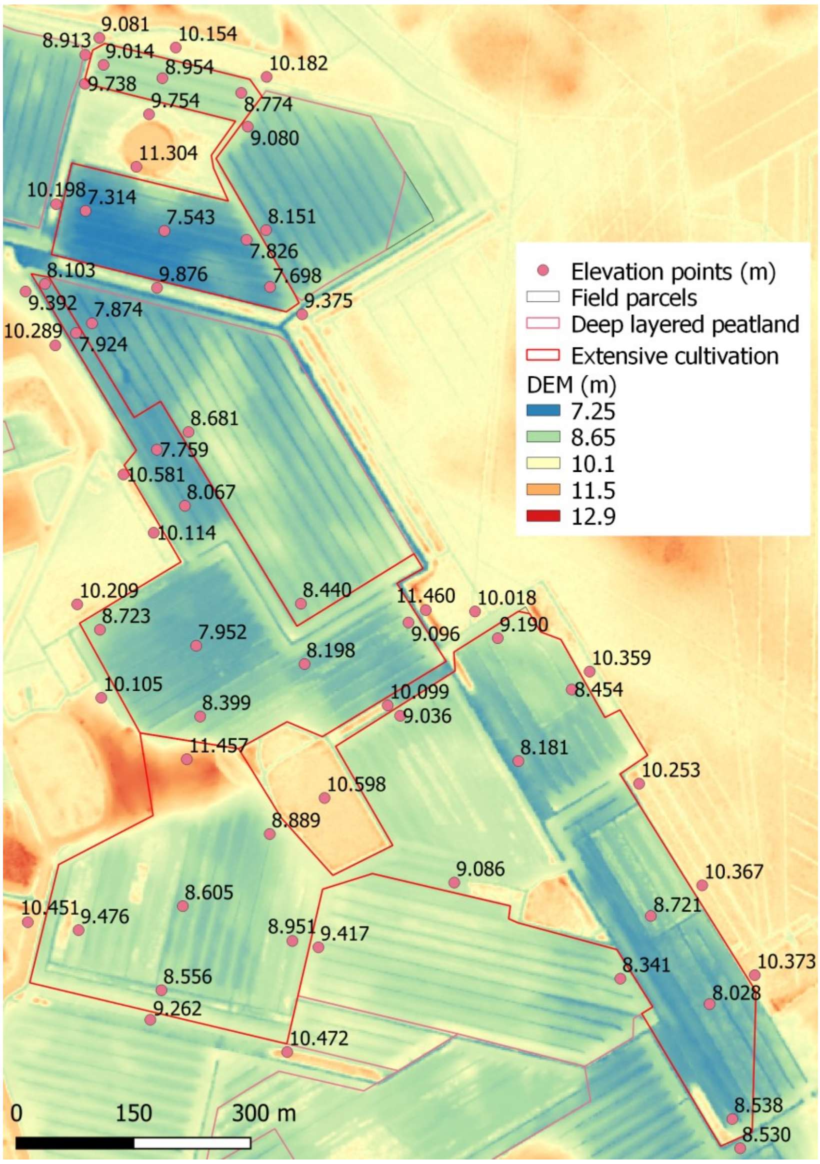

Figure 20. Detailed DEM analysis with elevation points and field parcels in extensive use in C2.

There are three field parcels containing extensive cultivation in Figure 20. Two of them (two located in the upper part) have average slopes less than 2%. These are the only field parcels suitable for raising the WTL according to the average slope of the field.

Tables 5 and 6 represent the same variables as in Table 2, but at a catchment level, and the remained area of field parcels according to average slope of field parcel is inserted. Tables 5 and 6 demonstrate how inclusion of topographical evaluations into cultivation type analysis leads to a more accurate identification of rewetting areas, since the steeper field parcels are left out of the possible rewetting areas. It must be noted that these results are only produced for two catchments in the study area, and in order to evaluate the effect of topography for each field parcel in Pohjois-Pohjanmaa, DEM model has to be applied for the whole area. Thus, these results presented in Tables 5 and 6 are examples of the analysis, since it remained to be out of scope to apply DEM to significantly large area.

Table 5. The areas of different field parcel categories, their remained area after removing field parcels with slope > 2%, and the shares of the areas and remained areas from the field parcels partly or totally on deep layered peat (128 ha) in C1.

Land	Area (ha)	Share[3] (%)	Area (ha) when slope ≤ 2%	Share[3] (%) when slope ≤ 2%
Total agricultural land	204			
Field parcels partly or totally on deep layered peat	128			
Total deep layered peatland[1]	93	72.66		
Extensive cultivation[2]	30	23.44	11	8.60
Feed production[2]	67	52.34	28	21.88
Feed production[2], overlaps with extensive cultivation removed	53	41.40	0	-

[1] only the area of deep layered peatland, not the whole field parcels

[2] field parcels containing partly or totally deep layered peat, occurrence of the same cultivation type more than 80%

[3] from field parcels partly or totally on deep layered peat (128 ha)

Table 6. The areas of different field parcel categories, their remained area after removing field parcels with slope > 2%, and the shares of the areas and remained areas from the field parcels partly or totally on deep layered peat (725 ha) in C2.

Land	Area (ha)	Share[3] (%)	Area (ha) when slope ≤ 2%	Share[3] (%) when slope ≤ 2%
Total agricultural land	1 740			
Field parcels partly or totally on deep layered peat	725			
Total deep layered peatland[1]	413	56.97		
Extensive cultivation[2]	39	5.38	14	1.93
Feed production[2]	182	25.10	53	7.31
Feed production[2], overlaps with extensive cultivation removed	0	-	-	-

[1] only the area of deep layered peatland, not the whole field parcels

[2] field parcels containing partly or totally deep layered peat, occurrence of the same cultivation type more than 80%

[3] from field parcels partly or totally on deep layered peat (725 ha)

These results calculated from DEM can be implemented for any new area with the required data. They are used for estimating whether the field parcel for rewetting is located at lower elevation than its surroundings and how fast water would be flowing away from the field parcel if it will be rewetted.

DTW with 1 ha and 4 ha thresholds for flow-channel in C2 are shown in Figures 21 and 22. All of the deep layered peatlands as well as fields in extensive cultivation and feed production in the catchment have mostly DTW smaller than 1.5 m, when using 4 ha area threshold for flow-channel (Figure 21), even though 4 ha area threshold indicates to drier situation than 1 ha area threshold. This indicates that in these areas it is easier to raise the WTL than in the areas with higher DTW. Areas with small values of DTW refers to that they remain wet for a significant time of the year.

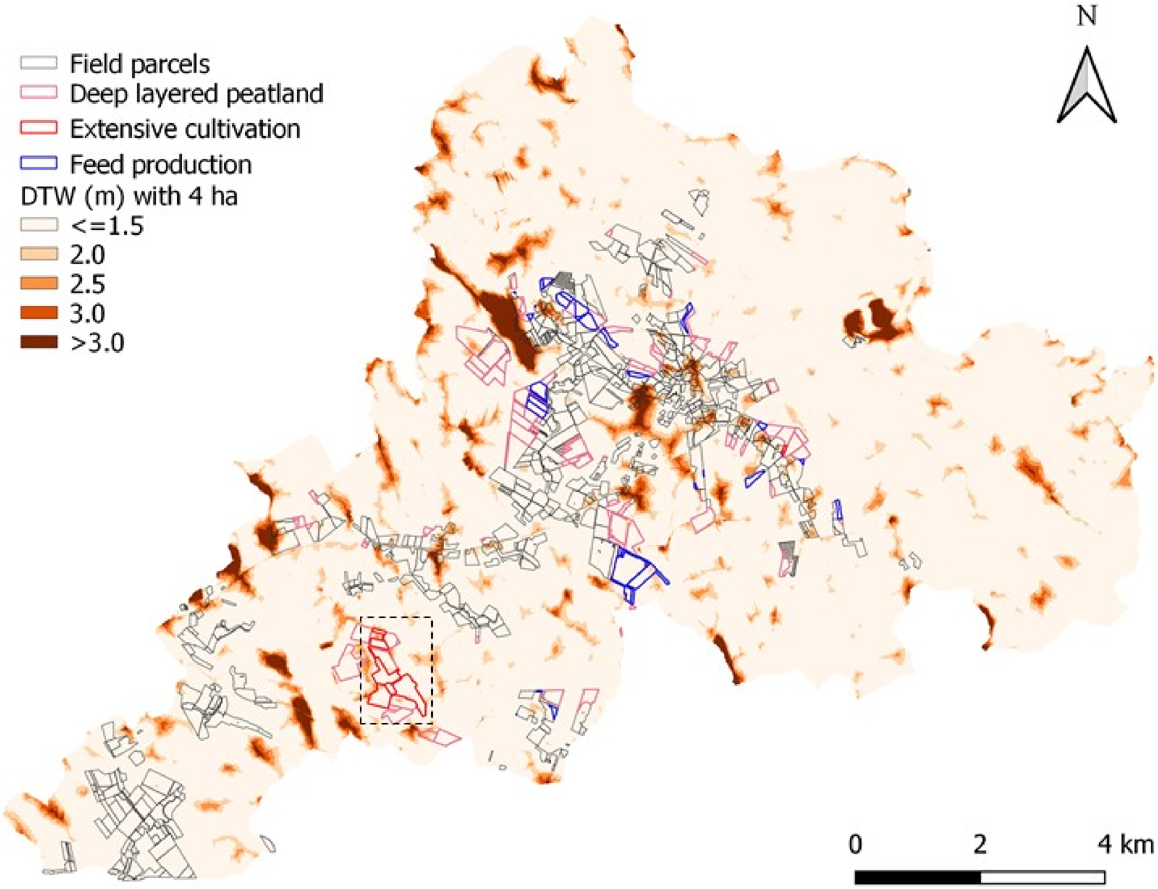

Figure 21. DTW with 4 ha area threshold for flow-channel and all agricultural field parcels, deep layered peatlands and field parcels containing deep layered peat and either extensive cultivation or feed production in C2. The box with dashed lines indicates field parcels containing deep layered peat and extensive cultivation analyzed in detail in Figure 23a.

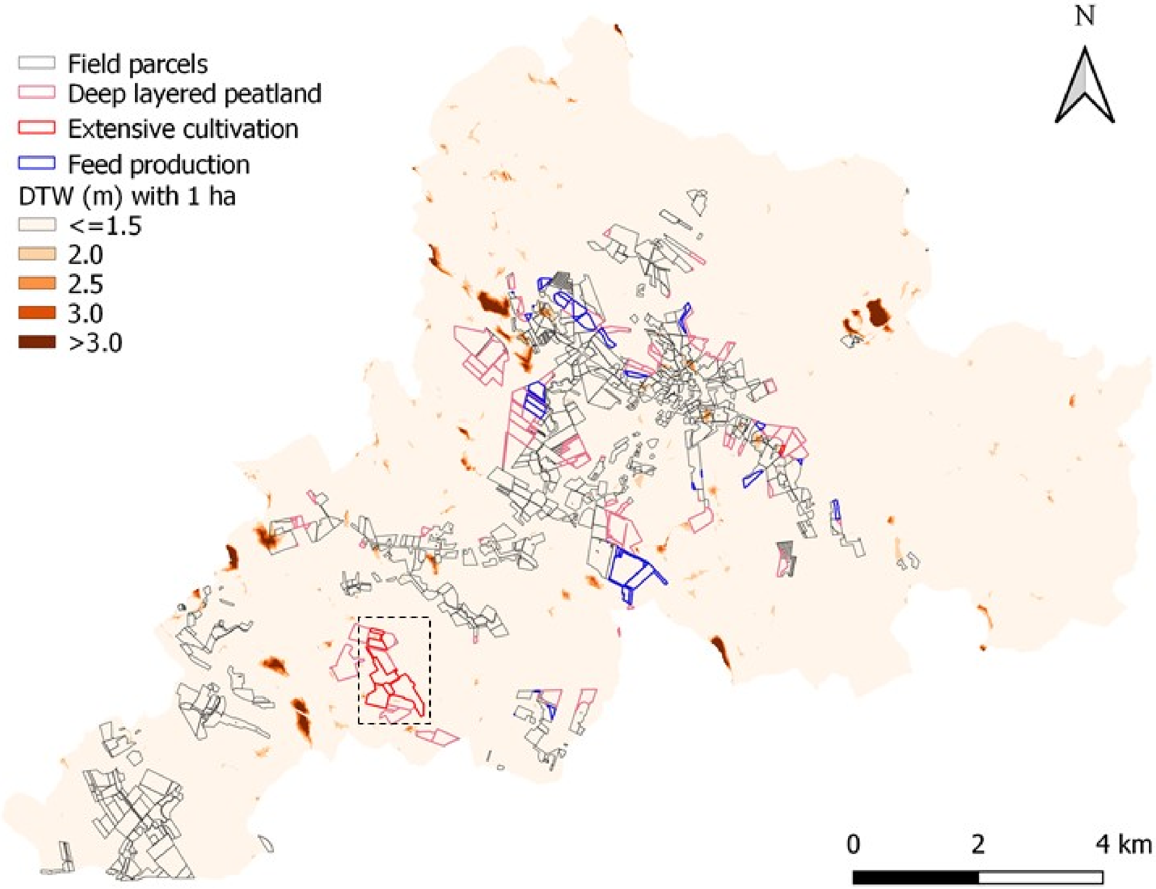

Figure 22. DTW with 1 ha area threshold for flow-channel and all agricultural field parcels, deep layered peatlands and field parcels containing deep layered peat and either extensive cultivation or feed production in C2. The box with dashed lines indicates field parcels containing deep layered peat and extensive cultivation analyzed in detail in Figure 23b.

Comparing DTW with 1 ha and 4 ha area thresholds for flow-channel, it clearly shows that DTW decreases within the entire catchment with 1 ha. This means that the WTL is closer to the soil surface and larger area would become wetter and, therefore, more water is available for rewetting. This, however, is due to the increased *P* or snow melting and, thus, is temporary. Nevertheless, this could be used for estimating the amount of water reserves available for rewetting.

Detailed DTW within a few field parcels in extensive use in C2 are shown in Figure 23. The extensive cultivation fields in Figure 23 should be suitable for rewetting, if areas where DTW is smaller than 1.5 m are considered. Areas with DTW smaller than 1.5 m are expected to be wet enough.

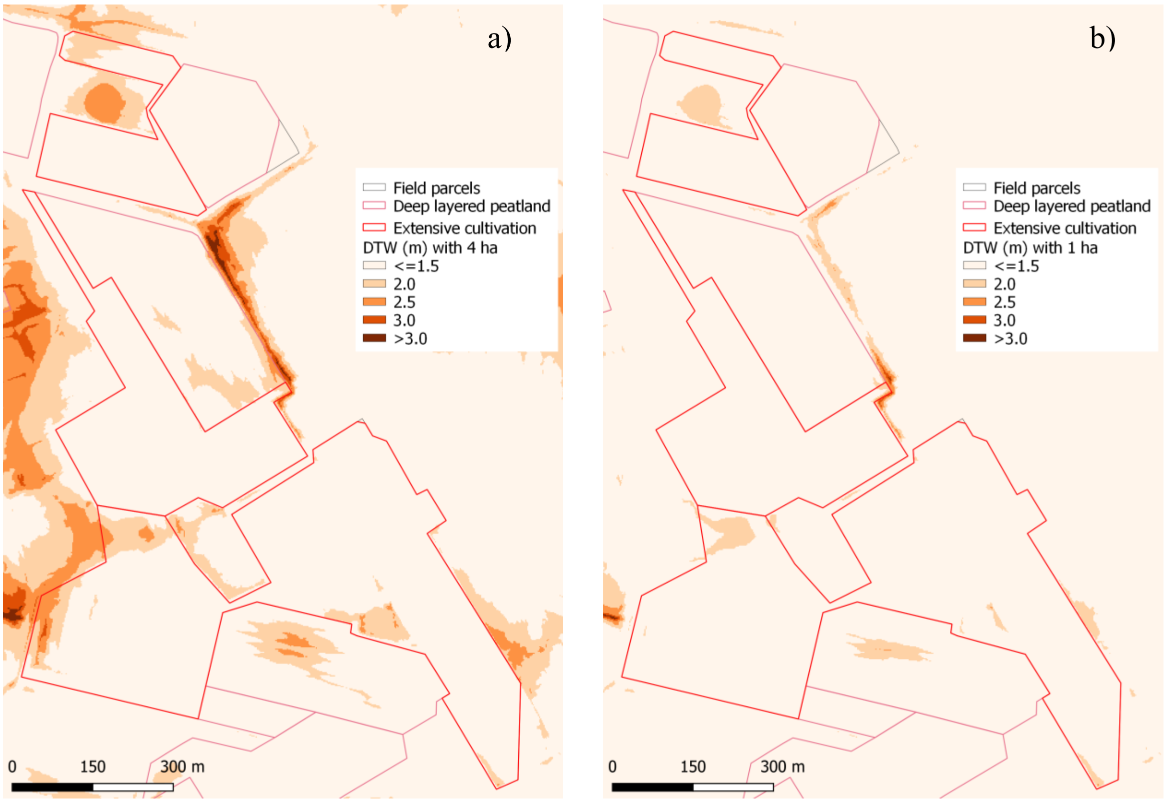

Figure 23. Detailed DTW analysis with 4 ha (a) and 1 ha (b) area thresholds for flow-channel and field parcels in extensive use in C2.

These results calculated from DTW can be implemented for any other area with the required data. They are used for estimating larger wet areas that would be potential for rewetting.

Figures 24 and 26 illustrate TWI within the whole two catchments, and Figures 25 and 27 the individual field parcels in extensive cultivation of the catchments. Lower values of TWI indicate terrains with steep slopes, and the accumulation of runoff is not likely to be generated. High values of TWI represent the wettest areas, usually streams, but also flatter areas where water flows could be accumulated and therefore creating wet soils. It can be assumed, that areas where TWI is higher are probably more suitable for rewetting than areas where TWI is low, since the availability of water in soil is greater. However, TWI is a better indicator for showing the locations of streams instead of the wider wet areas, as also seen in Figures 24-27. (Murphy, et al., 2011)

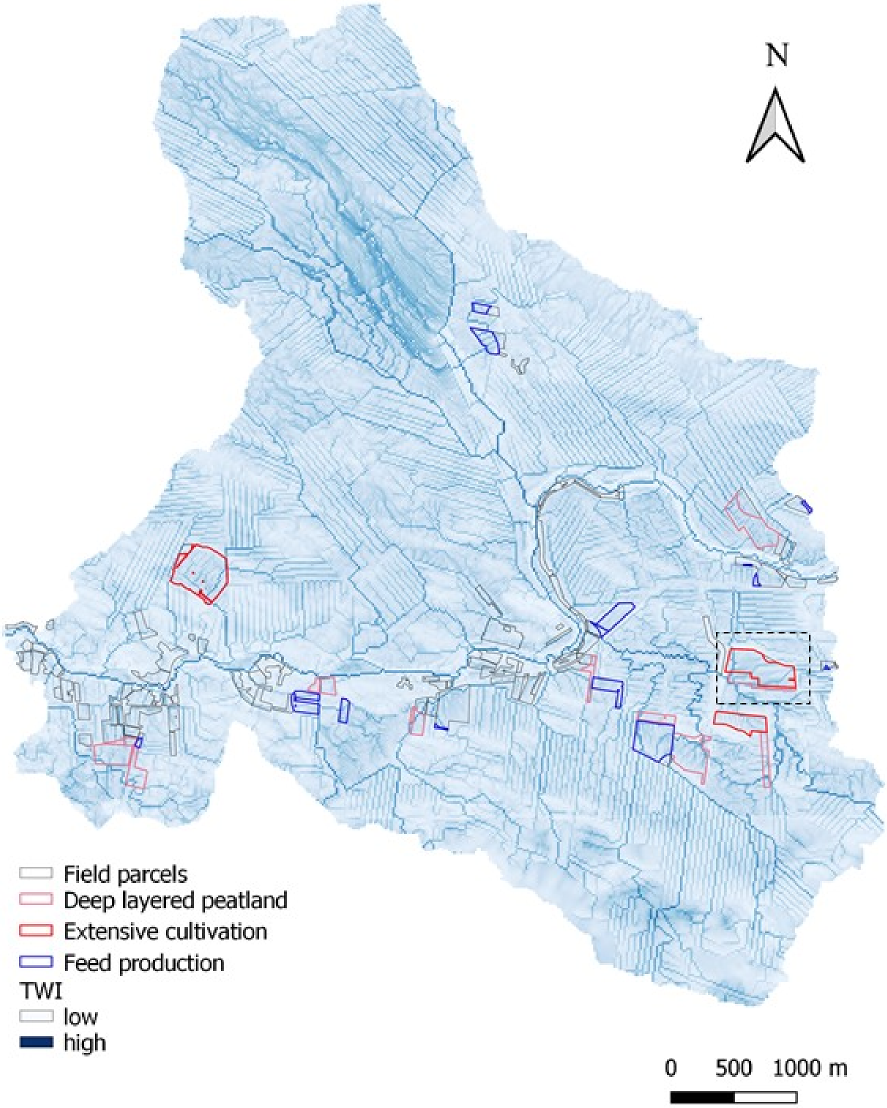

Figure 24. TWI and all agricultural field parcels, deep layered peatlands and field parcels containing deep layered peat and either extensive cultivation or feed production in C1. The box with dashed lines indicates a field parcel containing deep layered peat and extensive cultivation analyzed in detail in Figure 25.

A closer look for individual field parcels and TWI was needed in order to analyze the distribution of TWI in the catchment and its surroundings (Figures 25 and 27). Figure 25 shows that overall the borders (and nearby the borders) of a field parcel in extensive use have lower TWI than in the field parcels. This signifies that water flows are likely to accumulate inside the field, if rewetting is conducted by blocking the ditches.

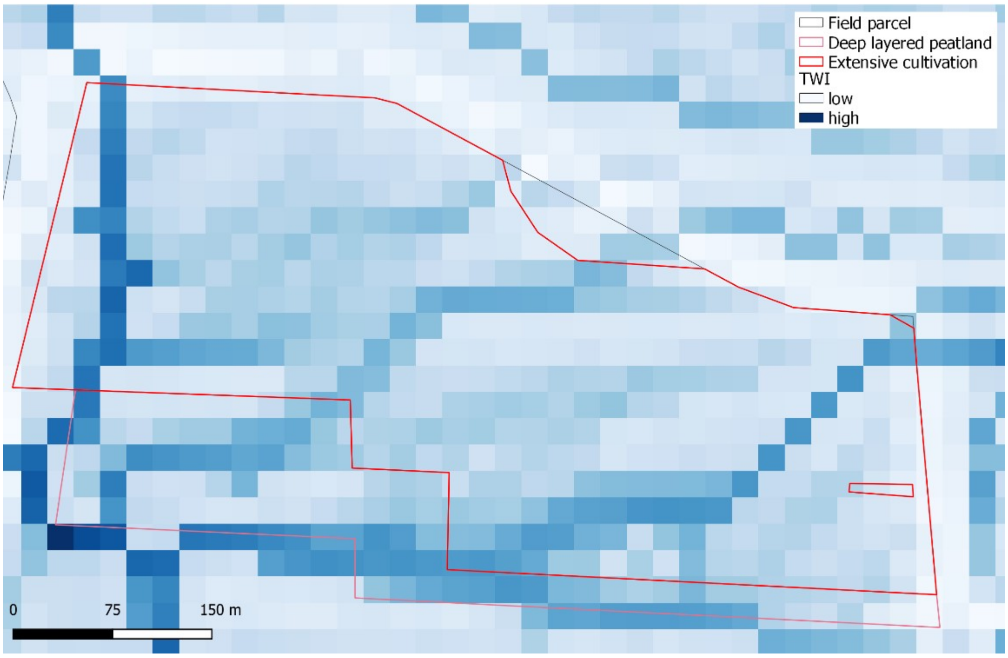

Figure 25. Detailed TWI analysis and a field parcel in extensive use in C1.

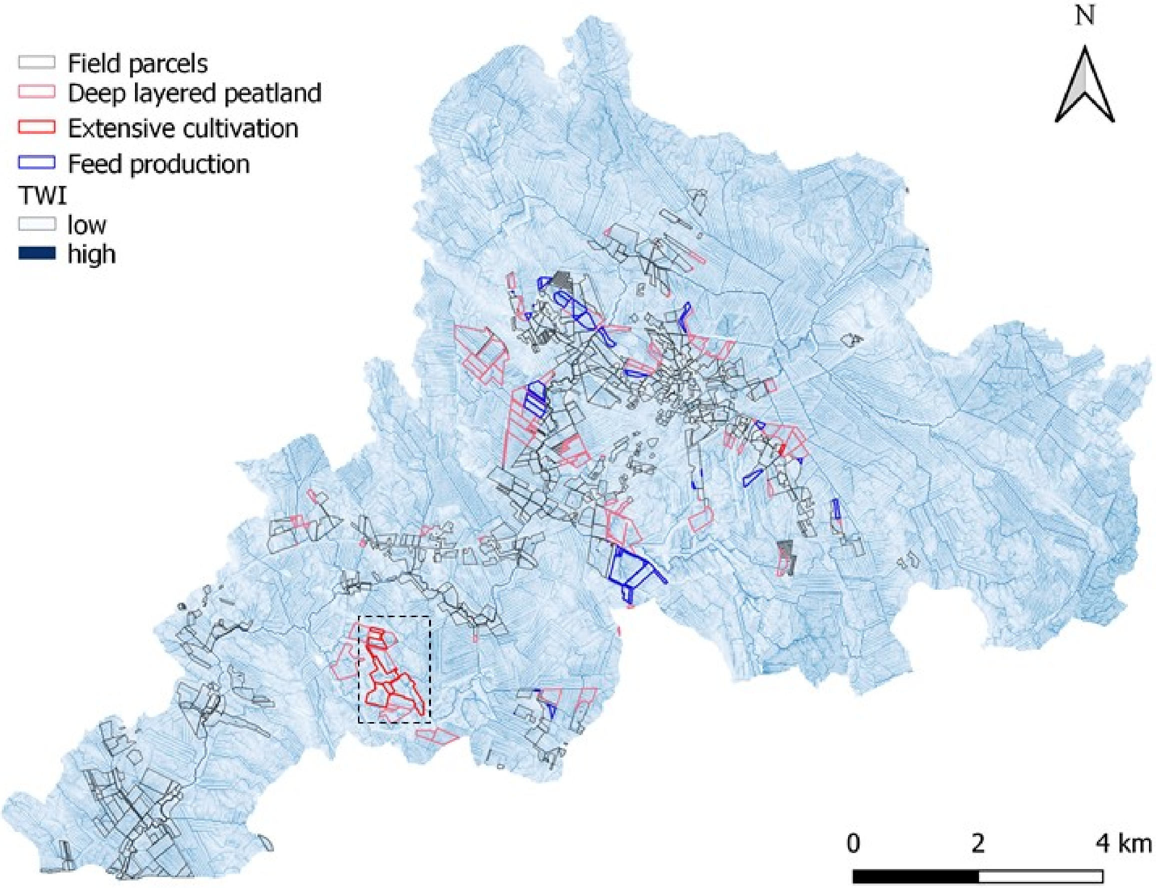

Figure 26. TWI and all agricultural field parcels, deep layered peatlands and field parcels containing deep layered peat and either extensive cultivation or feed production in C2. The box with dashed lines indicates field parcels containing deep layered peat and extensive cultivation analyzed in detail in Figure 27.

The borders (and nearby the borders) of field parcels in extensive use in C2 as well have mostly lower TWI than the field parcels (Figure 27). Again, this indicates that water flows generated from rewetting are accumulated inside the fields creating wetter soil.

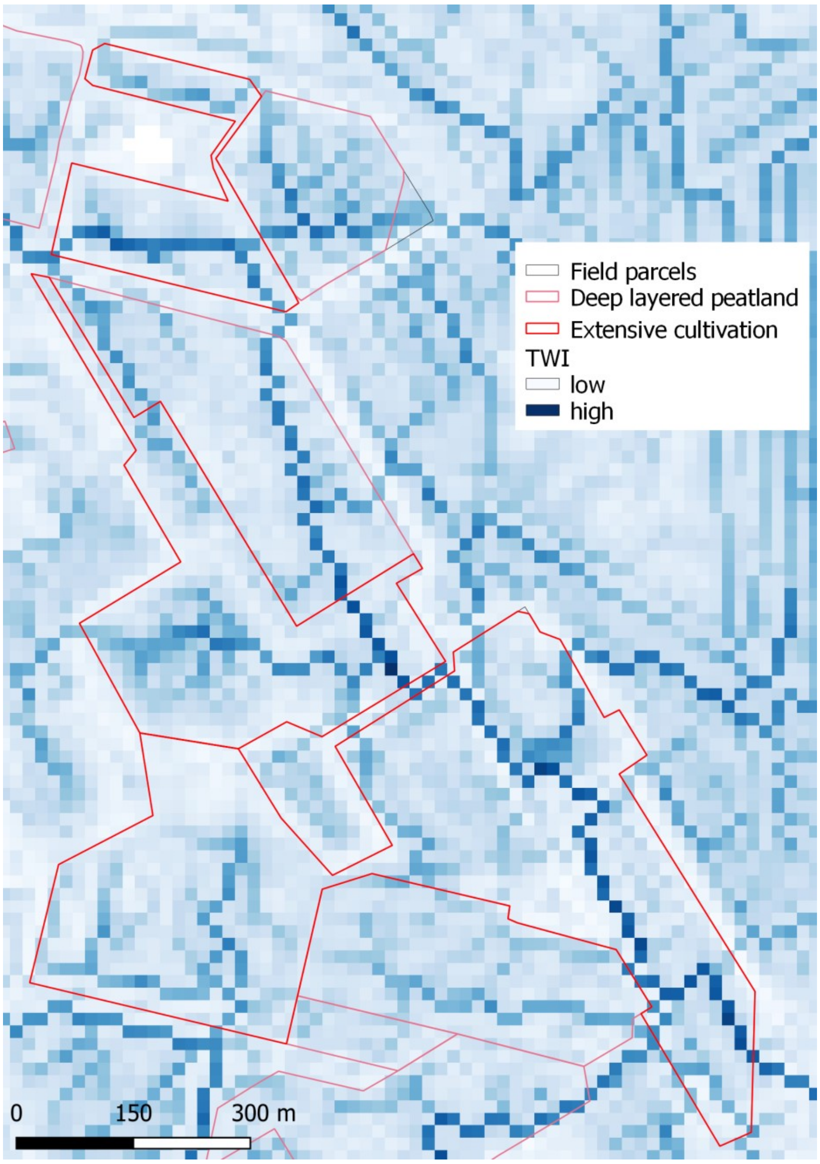

Figure 27. Detailed TWI analysis and field parcels in extensive use in C2.

The results and methods of TWI can be implemented for any other area with the required data. TWI is mainly used for detecting areas where accumulation of runoff would happen, i.e. the areas with high TWI, and, therefore, wet areas.

Figures 17-27 are examples of topographical analysis that can be used for theoretical and simple evaluation of directions of water flows when only terrain elevations are considered, and spatial differences of wet conditions. As stated in Section 2.2, most of the cultivated fields in Finland have drainage network and, thus, rewetting can be conducted by blocking all or some of the drains within the field parcels. This creates more surface and subsurface water flows that flow from higher to lower elevation, and therefore topographical analysis represented is relevant to implement. For this study, only two catchments were analyzed topographically due to the size and availability of data.

Topographical analyses are an essential part of evaluating water movements in soils and, therefore, also important for mapping possible areas where the WTL could be raised. Haahti et al. (2012) stated that surface elevation is one of the most important factors affecting the WTL, and Murphy et al. (2009) stated that water flows and accumulation happen as a result of gravitational potential energy. These support the importance of topographical analyses.

5.4 Discussion on hydrological modelling as an additional analysis tool for detecting peatlands for rewetting

The output variables of hydrological modelling obtained from SpaFHy model are demonstrated and discussed here. The idea was to illustrate how much more specified results can be obtained according to hydrology of field parcels. As a summary, all results that can be produced by SpaFHy are listed in Table 7.

Table 7. Results produced by SpaFHy model.

Parameter	Unit	Parameter	Unit
canopy storage	mm	drainage	mm
snow water equivalent	mm	streamflow	m
throughfall	mm	baseflow	m
interception	mm	returnflow	m
potential infiltration	mm	surface runoff	m
dry-canopy evapotranspiration	mm	average recharge	m
transpiration	mm	average saturation deficit	m
forest floor evaporation	mm	saturated area fraction	-
interception evaporation	mm	local saturation. deficit	m
mass-balance error	mm	root zone volume water content	m^3 m^{-3}
pond storage	mm	organic layer volume water content	m^3 m^{-3}
infiltration	mm		

By SpaFHy modelling, overall catchment water balance can be predicted. For instance, for the catchments C1 and C2 in this study, the analysis after topographical evaluations could be continued to predict seasonal water balances. Daily simulation of catchment hydrological behavior would produce more accurate estimations of water reserves within the areas than only estimating them by long-term (e.g. annual) P and E_p.

For this specific study, the most relevant results obtained from SpaFHy model are soil moisture characteristics. For instance, with saturation deficit, the distribution of soil wetness within a catchment can be analyzed. Therefore, observations of the suitability of potential rewetting field parcels in the catchment can be made according to seasonal variations of the wetness of soil. However, saturation deficit is directly related to TWI implicating that areas with high values of TWI are more probable to become saturated. This effect can also be observed by only analyzing TWI, as explained in the previous section.

There exist a variety of other models intended for analyzing the hydrology of areas containing peatlands. The presentation of SpaFHy model was chosen since it is an integrated hydrological model, thus very accurate results can be achieved by it. SpaFHy can be implemented at a catchment as well as at a grid scale.

By hydrological modelling, on top of other results produced in this study, detailed information about hydrological behavior of the area for rewetting can be achieved. Considering the objectives and specific aims of this study, the spatial weather and topographical analyses without extension to hydrological modelling were found to provide usable and sufficient results about the most promising rewetting. If the methods of this study are to be taken further, then it is recommended also to conduct a detailed hydrological analysis considering the desired results.

6 Conclusions

The aim of this study was mapping and locating possible agricultural fields suitable for rewetting or for cultivation with controlled WTL. The idea was to extend the earlier analysis of these areas presented in the study by Kekkonen et al. (2019), which acted as a basis for this thesis. Overall, the results of possible deep layered peatlands suitable for rewetting are more accurately and precisely achieved by the methods presented in this study than the results from the study by Kekkonen et al. (2019). There are several reasons for this. First, the occurrence of the cultivation types was categorized differently in this study than in Kekkonen et al. (2019). Here the categorizing was based on extensively used field parcels including temporarily or permanently uncultivated, managed uncultivated, landscape fields, natural pasture or natural meadow, or lands that have a special agreement on environment and forestry, and on feed production sites, that are annual or perennial pasture or silage production. In Kekkonen et al. (2019) they divided cultivation types into extensive and intensive use, which is a bit less accurate than the division of cultivation types made in this study. Secondly, this study used a method of 80% occurrence of the same cultivation type on the same field parcel containing deep layered peat, i.e. the specific cultivation type is assumed to occur on the field parcel if it was reported at least in eight out of 10 years. This gives more accurate results of possible rewetting areas than information about the cultivation type from only one year, which was used in Kekkonen et al. (2019). Lastly, analyses according to weather and topography eliminated field parcels, that were suitable for rewetting based only on their cultivation types, and thus did not fulfil the requirements of weather and topography. These requirements were roughly based on the difference in yearly P and E_p at catchment level, and on the average slope of a field parcel (for controlled drainage: slope $\leq 2\%$), as well as the distribution of DTW, i.e. estimating the wettest areas. For instance, based on the yearly difference between P and E_p (2017) in all catchments in the region of Pohjois-Pohjanmaa, the results of field parcels containing deep layered peat and extensive cultivation reduced from 1552 ha to 1539 ha, and feed production from 16915 ha to 16852 ha. Additionally, in C2, the share of total area of field parcels which could be rewetted (including extensive cultivation and feed production) from field parcels partly of totally on deep layered peat dropped from approx. 30.5% to 9.2% after removing fields where the average slope is more than 2%.

The methods presented in this study were implemented for the region of Pohjois-Pohjanmaa in Finland (land area 3681843 ha; land area of Finland 30392109 ha (National Land Survey of Finland, 2019)), and for two catchments within the region in detail. In practice, methods for calculating and categorizing deep layered peatlands with desired cultivation types suitable for the WTL raise can be implemented for the entire Finland. Spatial data needed for this is available (mostly without costs) from providers listed in Table 1. Weather analysis is as well simple to implement for the entire Finland but requires quite large meteorological data. This data is available from Finnish Meteorological Institute. Topographical analysis is a bit more complex to implement for a larger area, because the size of DEM data is remarkably large. Therefore, for this study, it was deemed reasonable to implement topographical analysis only at a smaller scale. However, it is possible to execute topographical analysis to any other area as well with rational time effort.

The available datasets and methods developed allowed for detecting field parcels with adequate water reserves for the WTL raise. Weather analysis gives a rough estimation of water reserves within the area to be rewetted but however it is a useful and practical starting point. Topographical analysis of DEM gives an overview of the elevation differences in the area, which is directly proportional to the distribution of the WTL and, thus, can be used for estimating possible wetter areas as well as directions of water flows. TWI, in turn, shows the locations of streams and sinks, which is not only useful information for detecting rewetting areas but also it indicates the wet soil areas, and therefore, it can be used for evaluating the potential accumulation of water flows. DTW is a good indicator for modelling larger wet areas and the distribution of soil wetness. The most promising topographical analysis, especially concerning controlled drainage system, is evaluating the average slope of the field parcel. This is the most accurate method for indicating whether the water stays in the rewetted field parcel or not, i.e. the efficiency of rewetting. When all the analysis steps presented in Section 4 are implemented together, adequate results of possible areas for raising the WTL are achieved with reasonable time and work effort. This indicates that hydrological modelling is not required unless more accurate hydrological analysis of the area is desired. By hydrological modelling, estimations of, e.g., more precise seasonal water flows and soil water content can be accomplished, if hydrological behavior of the study area is more complex or unsure. Additionally, hydrological modelling requires significantly more working time, which might not be reasonable to add on top of other results. This is also due to that actual rewetting results are only obtained when practical rewetting for the field parcel is done. Therefore, the methods presented in this study are sufficient enough for locating the field parcels on deep layered peat with desired cultivation type that are suitable for rewetting or cultivation in wet conditions.

This study aimed at developing tools to implement the climate plan, since raising the WTL is one of the GHG emissions mitigation measures in the Government Report on Medium-term Climate Change Plan for 2030 (Ministry of the Environment, 2017). Therefore, methods of this study could be useful also for politicians improving mitigation methods from climate change issues. However, the results of the areas and distribution of field parcels on deep layered peat with desired cultivation type, and distribution of yearly difference in P and E_p are as such applicable, if the results are only wanted from Pohjois-Pohjanmaa. In contrast, topographical analysis results can only be applied as examples, since they represent the results from two example catchments. Nevertheless, the results of the topographical analysis can also be implemented as themselves if C1 and C2 are the desired rewetting areas.

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