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Soil moisture in process-based modeling in cold environments

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Tiivistelmä/Referat – Abstract

Maaperän kosteus vaikuttaa lukuisiin ympäristöprosesseihin ja ilmastollisiin tekijöihin. Se on tärkeä osa hydrologista kiertoa, mutta sen alueelliseen ja ajalliseen vaihteluun vaikuttavat tekijät ovat monimutkaisia ja toisiinsa kytkeytyneitä. Maaperän kosteus vaikuttaa usein myös itse sitä säätelevien prosessien voimakkuuteen. Nämä tekijät vaikeuttavat maaperän kosteuden havainnointia ja ennustamista. Kylmissä ympäristöissä kosteuden ennustaminen on erityisen hankalaa, sillä sen on osoitettu vaihtelevan hyvin pienillä mittakaavatasoilla sekä vaikuttavan olennaisesti moniin ekosysteemiprosesseihin. Näiden vaihteluiden ja prosessien vaikutusten tarkasteluun on kehitetty lukuisia hydrologisia prosessimalleja, jotka käsittelevät maaperän kosteutta eri tavoin. Mallien erojen ja lähestymistapojen ymmärtäminen on tärkeää, jotta niitä voidaan käyttää oikein.

Tätä tutkimusta varten valittiin kolme prosessimallia, jotka kuvailevat maaperän kosteutta eri tavoin ja jotka on kehitetty erilaisia tutkimuskysymyksiä varten. Näillä malleilla simuloitiin maaperän kosteuden alueellista ja ajallista vaihtelua pienellä tutkimusalueella Luoteis-Lapissa. Näistä JSBACH on globaali maanpinnan geofysikaalisia ja -kemiallisia prosesseja kuvaava malli, jota käytetään mallintamaan maanpinnan ja ilmakehän välisen rajapinnan olosuhteita. SpaFHy on hydrologinen valuma-aluemalli, joka on kehitetty kuvaamaan boreaalisten metsien vesitasetta ja haihduntaa. Ecohydrotools puolestaan on hienon spatiaalisen skaalan vaihteluun keskittyvä hydrologinen malli.

Mallitulokset osoittavat selkeitä yhteneväisyyksiä sekä eroja verrattuna toisiinsa ja kentällä tehtyihin kosteusmittauksiin. Mallit kykenivät hahmottamaan kosteiden ja kuivien alueiden laajan skaalan sijoittumisen alueella, vaikkakin kosteuden suuruus vaihteli mallien välillä merkittävästi. Kaikilla malleilla oli ongelmia hienon resoluution alueellisen vaihtelun kanssa, erityisesti kuivemmilla alueilla. Ajallinen vaihtelu osoitti enemmän yhteneväisyyksiä mallien välillä, mutta mittausten ja mallien välillä oli myös selkeitä eroja.

Nämä tulokset osoittavat, että monet tekijät vaikuttavat mallin kykyyn mallintaa maaperän kosteuden vaihtelua. Vaaditut ympäristömuuttujat, mallien sisältämät kuvailut prosesseista sekä mallien rakenne ja käyttötarkoitus vaikuttavat kaikki lopputuloksiin ja johtavat vaihteleviin arvioihin maaperän kosteudesta. Mallitulosten kehittäminen kylmillä alueilla vaatii parempaa ymmärrystä maaperän kosteuteen vaikuttavista prosesseista sekä yksityiskohtaisempaa tietoa olennaisista ympäristömuuttujista.

Avainsanat – Nyckelord – Keywords
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Tiivistelmä/Referat – Abstract

Soil moisture influences various environmental and climatological processes and is an important part of the hydrological cycle. The processes influencing its spatial and temporal variation are complex and linked with each other as well as influenced by soil moisture itself which makes observing them challenging. This is especially true in cold regions where soil moisture has shown strong fine scale variation and influences numerous ecosystem processes. To test different hypotheses related to soil moisture and to simulate its variation, several hydrological process-based models have been developed. Understanding how these models differ from each other and how they describe soil moisture is crucial in order to use them effectively.

For this study, three process-based models representing varying model approaches and answering different research questions were chosen and used to simulate the spatial and temporal variation of soil moisture in a small study area in northwestern Finland. JSBACH is a global-scale land surface model that simulates various geophysical and geochemical processes over land and in the boundary layer between land surface and the atmosphere. SpaFHy is a catchment scale hydrological model developed to simulate water balance and evapotranspiration in boreal forests. Ecohydrotools is a hydrological model used to study fine scale spatial variation in soil hydrology.

The model results show clear similarities as well as differences when compared with each other and with field measurements of soil moisture. The strongest similarities are in distinguishing wetter and drier areas in the study area, although the actual moisture content estimations vary between the models. All models show difficulties in simulating finer scale spatial variation, particularly in drier areas. Temporal variation shows more similarities between the models, although there are also clear discrepancies with measurements and the models.

These simulations show that there are several things influencing a model's capability to simulate soil moisture variation. Varying data requirements, included processes as well as model design and purpose all influence the results, leading to varying estimations of soil moisture. Improving model predictions in cold environments requires better understanding of the underlying processes as well as more detailed information on the environmental variables influencing soil moisture.

Avainsanat – Nyckelord – Keywords
soil moisture – process models – spatial modeling – arctic regions – hydrological modeling – mechanistic models

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1 Introduction

Soil moisture is a small but crucial part of the hydrological cycle. It is strongly linked with processes interacting between land surface and the atmosphere, influencing for example temperature and precipitation patterns from local to global scales (Koster et al. 2004; Seneviratne et al. 2010). It controls surface runoff processes and flood formation but also mitigates drought conditions (Robock et al. 2000; Berthet et al. 2009; Hagemann and Stacke 2015). It is strongly linked with plant functionality, making it an important part of ecological and agricultural studies (Western et al. 2002; Maclean et al. 2012; Roux et al. 2013; Winkler et al. 2016). The processes and interactions related to soil moisture and its role in the environment are complex and intertwined, forming feedback loops and patterns that can be difficult to observe (Seneviratne et al. 2010; Legates et al. 2011).

In high latitudes, the importance of soil moisture is highlighted in its connection with fine scale vegetation patterns as well as its contribution to geomorphological processes (Legates et al. 2011; J. Aalto et al. 2013; Winkler et al. 2016). Soil moisture shows great spatial and temporal variation in high latitudes but the impact of this variability and the processes related to it are not yet fully understood (Penna et al. 2009; Roux et al. 2013; Winkler et al. 2016; Kemppinen et al. 2018). Soil moisture studies are further complicated by the lack of spatially detailed data and due to the difficulty of observing processes operating below the land surface (Guswa et al. 2002; Z. Zhang et al. 2016).

Hydrological process models are used to simulate complex processes and feedback loops to study the aspects of hydrological cycle that would otherwise be difficult to observe. Soil moisture modeling has been used in various applications such as estimating global wetland areas, improving catchment scale flood forecasts and simulating fine scale species distribution patterns (Berthet et al. 2009; Maclean et al. 2012; Zhao et al. 2013). There are a vast number of models capable of simulating soil moisture on coarser and finer spatial scales, developed to function in varying geographical areas and answering different research questions. Each model emphasizes the processes and characteristics relevant to its purpose, meaning that the outcomes may vary greatly.

In this study, three distinctive process-based models were chosen to simulate the spatio-temporal variation of soil moisture in a small study area located in Northern Finland. The study aims to answer two research questions:

1. How do process-based models predict soil moisture and describe the processes and variables related to it?
2. What features do the three chosen models show in simulating the spatial and temporal variation of soil moisture in a high latitude study area and how do the results fit with measured soil moisture values?

2 Theoretical background

2.1 Soil moisture

Soil moisture is an important hydrological variable in many ecosystem processes and is therefore related to many different research fields from hydraulics to agriculture and from meteorology to ecology (Seneviratne et al. 2010; Legates et al. 2011). This interdisciplinarity means that the precise definition and how it is measured varies. The basic definition of soil moisture defines it as water held in between soil particles in the unsaturated zone above groundwater. However, stricter definitions on which part of the unsaturated zone is meant and what units are used, vary depending on the purpose.

The definition of soil moisture can include the whole unsaturated soil layer or specific layers. Moisture content of the whole soil column is often of interest in studies which focus on understanding the whole hydrological cycle or estimating ground water dynamics (Maxwell et al. 2007). While soil moisture at different depths does correlate strongly with other layers (Tromp-van Meerveld and McDonnell 2006), it is sometimes beneficial to focus on specific layers. Root zone, defined as the layer from which transpiration may occur, is particularly important for vegetation as it can limit plant growth as well as evapotranspiration (ET) which in turn influences many climatological processes (Laio et al. 2001; Kurc and Small 2004). However, in certain regions and studies, surface layer soil moisture can be more useful as it regulates bare soil evaporation as well as rainfall partition to infiltration and runoff (Kurc and Small 2004; Dorigo et al. 2011). The depth of these layers is not constant but varies spatially as well as temporally (Seneviratne et al. 2010).

Regardless of the soil layer, there are different metrics to describe the amount of water held between soil particles (figure 1). Soil moisture can be described as the absolute amount of water (in mm or kg) or as a fraction of the total soil volume (volumetric water content, VWC). However, these are often insufficient as they don't relate moisture content to soil properties or vegetation. Ratio of saturation on the other hand measures moisture as a fraction of the available space between soil particles and is therefore dependent on soil porosity. Soil moisture index varies between wilting point and field capacity and tells how much water is available to plants. Below wilting point, suction forces caused by soil particles are stronger than the force by which roots extract water while above field capacity gravitation causes an upper limit to the plant available water. Soil moisture potential considers the forces influencing movement of water in more detail and describe how tightly water is held in soil. It rises with increasing moisture content as gravitation causes water to move downwards. The less water there is, the stronger it is tied to the soil by plants and soil particles, causing less moisture to drain to lower levels and moisture potential to decrease.

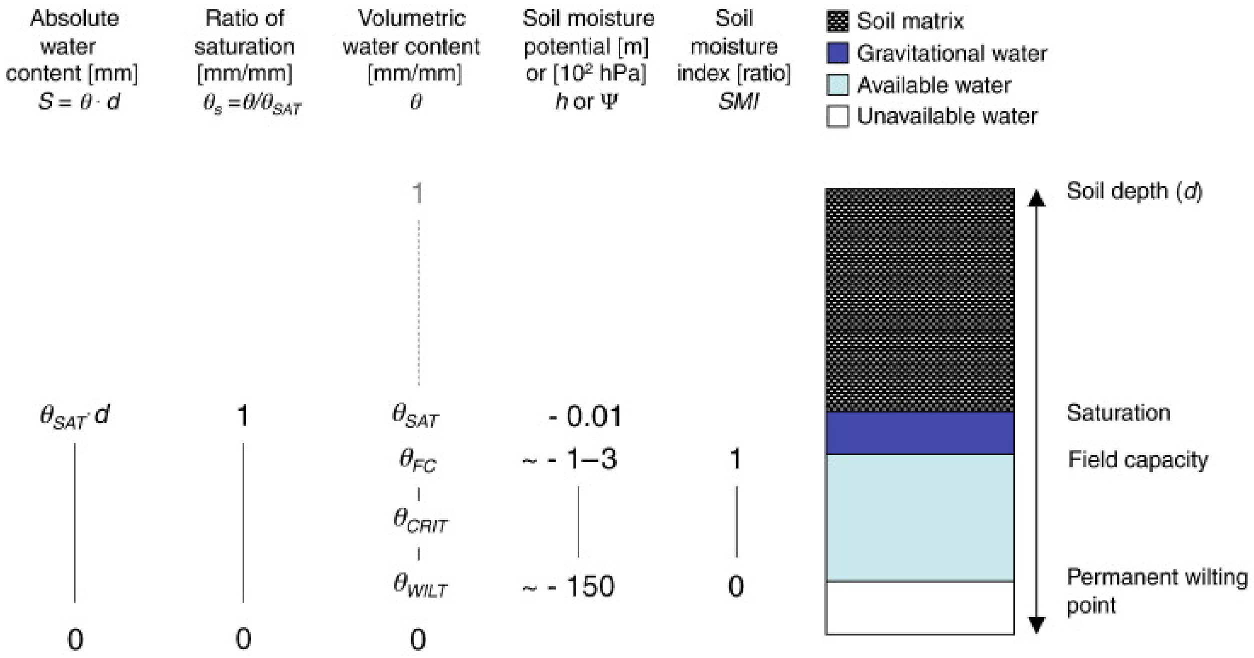


Figure 1: Units and metrics to describe soil moisture. θ refers to volumetric water content (VWC). Permanent wilting point (θ_{WILT}) is reached when plants can no longer subtract water from soil. At saturation level (θ_{SAT}) all pores are filled with water. At that point, which can be reached during a precipitation event, water is pulled down until the moisture content reaches field capacity (θ_{FC}). θ_{CRIT} refers to the level of soil moisture which regulates whether soil moisture or energy is the limiting factor in evapotranspiration. Figure from Seneviratne et al. 2010.

2.1.1 Processes controlling soil moisture

Interaction with atmosphere

Large scale variation of soil moisture is mainly controlled by climate, especially precipitation and solar radiation controlled ET (figure 2). Precipitation is the main source of incoming water to soils and thus controls a large portion of soil moisture variation temporally and spatially. However, the relationship between soil moisture and precipitation is nonlinear and linked (Seneviratne et al. 2010). The amount of precipitation entering a soil column depends on the prior soil moisture content as well as the intensity of rain (Dunne 1978). The faster the rain falls, the less water infiltrates and the more partitions into surface runoff. A similar processes is caused by saturation of soil. In certain conditions soil moisture and precipitation may form a positive feedback loop where higher soil moisture content leads to more precipitation (D. B. Clark et al. 2004; Koster et al. 2009).

Soil moisture is strongly controlled by water leaving soil through evapotranspiration although this relationship is also intertwined an nonlinear. While the direct influence of ET is to decrease soil moisture, it can lead to higher precipitation (Koster et al. 2004; Teuling et al. 2009). Land surface ET consists of bare ground evaporation as well as transpiration through vegetation. These in turn are strongly coupled with soil moisture. This coupling is often represented by a division to moisture limited and energy limited regimes. In energy

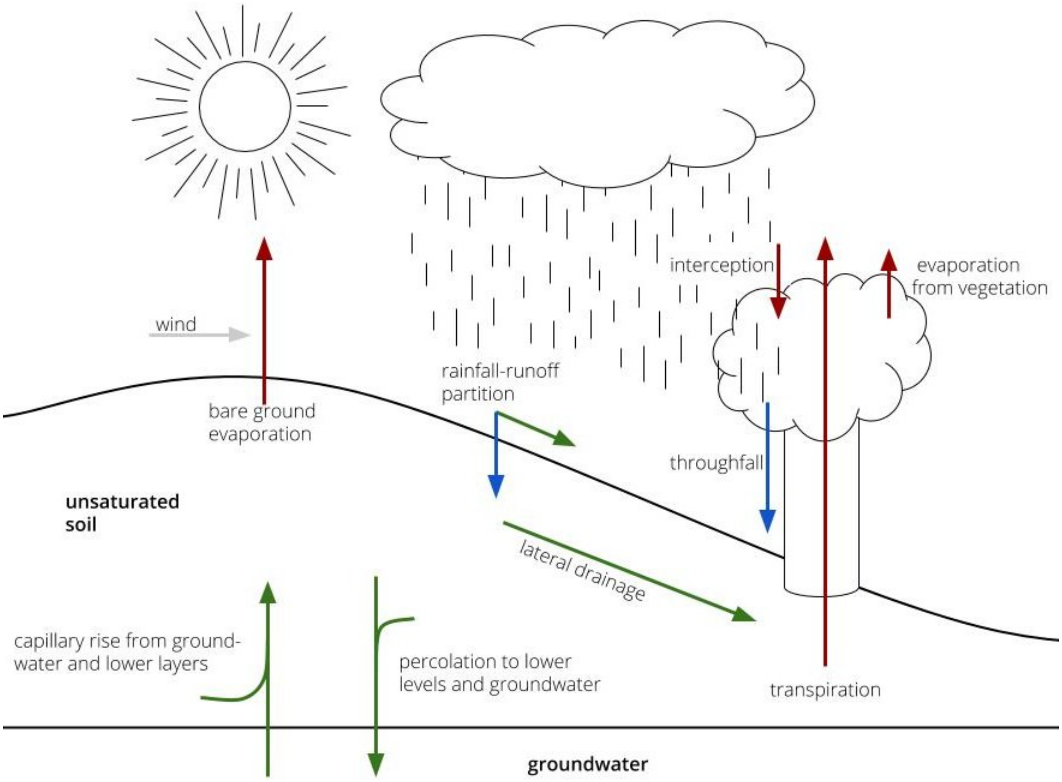


Figure 2: Main components of the hydrological cycle influencing soil moisture. Water enters the soil through precipitation, throughfall from vegetation and infiltration from upstream runoff. It leaves soil through evapotranspiration either from the bare ground or through plant roots. In the soil, water moves downwards due to gravitation, upwards due to capillary rise and sometimes laterally in hillslopes.

limited systems, soil moisture is high enough to not limit ET and available energy becomes more important whereas in moisture limited systems the lack of soil moisture limits ET (Seneviratne et al. 2010). ET is also influenced by wind and vertical mixing of air. As with infiltration to soil, moisture can only enter an air column if the air is not saturated and that level of saturation close to the surface depends strongly on the movement of air. If air is still, the saturation point is reached faster which leads to a decrease in ET (McVicar et al. 2012). In windier conditions, unsaturated air is constantly brought in contact with the surface layer, providing more space for moisture in the air.

Processes in the land surface layer

In meso- and microscales, the impact of land surface properties such as vegetation and topography become important factors in soil moisture dynamics (figure 2). The relationship between soil moisture and vegetation cover is complex, including feedback loops and non-linear relationships (D'Odorico et al. 2007; Roux et al. 2013; J. Aalto et al. 2013). In densely vegetated regions, ET consists mainly of transpiration, contributing greatly to soil moisture depletion and local climatic processes (Western et al. 2002). Canopy layer intercepts part of precipitation causing vegetated patches to receive less water than patches with no vegetation cover. However, moisture in a vegetated area tends to evaporate at a slower rate due to vegetation shading the ground from direct radiation. Vegetation close to the surface can also shield the soil from wind and therefore decrease bare ground evaporation (Wilson 1959). Part of the intercepted water can enter the ground as throughfall if it hasn't evaporated from the canopy layer (Launiainen et al. 2019). Therefore, the overall influence of vegetation on soil moisture tends to be positive, although the correlation between vegetation and higher soil moisture seems to become weaker in wetter areas, highlighting the nonlinear characteristic of this relationship (Dorigo et al. 2011).

Topographic variation plays an important role in distributing soil moisture on catchment scale. Rainfall partition into surface runoff and infiltration is largely controlled by slope steepness - the steeper the slope, the more surface runoff there is (K. J. Beven and M. J. Kirkby 1979; Dunne et al. 1991; Western et al. 2002). Through surface runoff, topographic variation then distributes soil moisture to lower and flatter areas and to local depressions. Slope aspect on the other hand controls incident solar radiation that reaches the ground and can therefore increase or decrease evaporation. This effect can be visible on very fine spatial scales if topographical variation is large. Vegetation cover is also linked to infiltration-runoff processes. Vegetation decreases surface runoff velocity, thus allowing more time for infiltration to happen (Dunne et al. 1991). Under the surface, plant roots and other organic material influence soil properties such as hydraulic conductivity and soil porosity and increase infiltration rates (Leung et al. 2015).

Soil properties and below-ground processes

Processes operating below the surface influence how much water fits to the soil and how it moves there (Dunne et al. 1991; Western et al. 2002). Inside the soil, water moves in different directions due to different forces. Percolation to lower layers is caused by gravitation and happens only in layers where soil moisture is above field capacity (Seneviratne et al. 2010; Hagemann and Stacke 2015). In deeper layers, soil moisture drains to groundwater. Suction caused by water holding on to soil particles is an opposing force to gravitation and keeps water in upper layers. It can cause water to rise from lower layers under certain conditions to replenish depleted root zone and provide water to plants during dry seasons (Western et al. 2002). Soil can also move laterally in hillslopes which in turn can contribute to soil moisture depletion in locally higher areas as well as to an increase in downslope areas (Dunne et al. 1991). All of these processes depend on the existing moisture content and are mostly slower when there is less moisture as the influence of suction is stronger.

Movement of water is also controlled by soil properties (Clapp and Hornberger 1978; Western et al. 2002; Legates et al. 2011). Soil porosity influences how much water can fit in the soil. Soil hydraulic conductivity describes the speed at which moisture can move in the soil and depends on the existing moisture. Field capacity and wilting point also depend on the soil properties (Seneviratne et al. 2010). These properties depend mainly on soil texture which describes the percentages of different particle types in a soil type (Cosby et al. 1984). Soils with larger particle sizes tend to have larger porosity as well as higher hydraulic conductivity whereas very clay soils tend to fit much less water and the movement of water inside the soil is slower. In clay soils under dry conditions, cracking of the soil can also cause variations in surface runoff and move water to deeper soil layers (Maclean et al. 2012).

2.1.2 Soil moisture in cold environments

Processes and feedback loops related to soil moisture dynamics are often strongly dependent on the region and certain processes are only applicable in specific regions. Cold regions contain several such processes. These, in addition to the importance of soil moisture on ecosystem processes make soil moisture studies vital in order to better understand high latitude regions and their environment (J. Aalto et al. 2013; Roux et al. 2013).

Stark seasonal differences in climatological variables are important factors influencing soil moisture dynamics in high latitudes. Radiation varies from non-existent in winter to weak but constant during the short summer. Precipitation arrives as snow throughout most of the year. These cause water to stay fairly immobile over and below ground for a large part of the year. Wind on the other hand distributes snow according to local topography, causing it to accumulate in depressions and be depleted from hilltops (Mott and Lehning 2010). This influences soil moisture during spring and summer when snow melts. The effect of wind on evaporation may also be more pronounced in arctic-alpine regions where vegetation has a lesser effect on wind speed and the finescale variation of topography causes parts of the landscape to be more sheltered from the wind than others (Wilson 1959).

Snow cover influences the spatial distribution of soil moisture. During winter it acts as a reservoir, keeping water from draining to streams or infiltrating to the ground. It also acts as an insulating layer, affecting the rate of frost formation in the ground (Nyberg et al. 2001). During spring and early summer, snowmelt causes a peak in runoff and brings higher soil moisture content to especially local depressions and lowlands. Nivations act as a reservoir and keep downslope areas wetter than they would otherwise be. Frost processes acting below ground surface also influence soil moisture. Snowmelt often occurs over frozen ground which increases runoff although it doesn't prevent infiltration completely (Stähli et al. 1999). During winter, frost retains soil moisture which can delay lateral flow below ground and can cause suction from lower layers (Nyberg et al. 2001).

Patchy peatland areas are typical for cold regions due to slower decomposition rates (Whalen and Reeburgh 1988). The high concentration of organic material causes them to have distinctive soil properties compared to mineral soils which in turn influence soil moisture patterns (Legates et al. 2011; J. Aalto et al. 2013; Hagemann and Stacke 2015). Soil porosity for example is considerably higher than in mineral soils, causing peatlands to have more space for soil water. Peatland areas in high latitudes tend to be patchy and occur on local depressions and downslope from snow nivations which also increases their moisture content (Woo et al. 2006).

Finally, another distinct feature of soil moisture in high latitudes is its high fine-scale spatial variation (J. Aalto et al. 2013; Roux et al. 2013; Kemppinen et al. 2018). The variability is influenced by many of the variables mentioned previously but it is also a key variable in itself controlling many ecosystem processes such as vegetation, microclimate and geomorfological processes.

2.2 Hydrological models

Models are always a simplified representation of reality (Abbott and Refsgaard 1996; Jajarmizadeh et al. 2012). They are used in scientific research as well as in society, leading to two fundamentally opposing ways to view them (Savenije 2009). On one hand, models can be considered a representation (albeit a simplified one) of reality and they can be used as a tool to solve a more complex problem. In this case, a model is viewed as state-of-the-art. On the other hand, models can be considered as hypotheses which represent our understanding of a system. They are seen as imperfect and the focus is on trying to find out where their imperfections arise from and how they can be improved. The latter view provides an opportunity to improve the understanding of a system as well as to observe complex features which can be very useful in doing hydrological research.

There are many ways to construct a model (Abbott and Refsgaard 1996). They can be physical representations such as miniature models or analogical models which simplify a complex system to one more easily observable. Perhaps the most commonly used in scientific research are mathematical models that represent the system through equations that can either be based on statistical properties of the variables, empirical studies such as field measurements or on the theoretical understanding of the system's underlying processes.

In hydrology, modelling has been used increasingly from early 20th century onwards (Jajarmizadeh et al. 2012; Fatichi et al. 2016). The first models were developed to simulate rainfall-runoff curve, i.e. how much precipitation in a rainfall event partitions to runoff instead of infiltration (Abbott et al. 1986; Todini 1988). These were mainly used for practical problems and a typical approach was to find links and relationships between variables. However, they were simple in design and relied on long meteorological datasets for model calibration. When knowledge of hydrological processes and computing technology developed, the focus shifted towards more theory-based models that considered the holistic nature of catchment-scale hydrological modeling (Todini 1988; Silberstein 2006).

From then on, the number of hydrological models has increased rapidly and they have been used in a wide range of applications (K. J. Beven 1996; Buytaert et al. 2008; Jajarmizadeh et al. 2012; Fatichi et al. 2016). In the meanwhile, hydrology has developed towards an indisposable part of many other disciplines such as climatology, ecology and hydroengineering while sementing its position as its own field of research (Savenije 2009; Fatichi et al. 2016). However, in spite of the advances in modeling and computation, the complex nature of hydrology means that there is still work to do in model development. Hydrological processes, particularly ones in the unsaturated soil, are difficult to observe or simulate and depend on variables that are heterogenic on even very small scales which makes simplifying or averaging them tricky (K. J. Beven 1996; Savenije 2009). The relevant processes are also highly scale-dependent and for example large-scale hydrological models, vital for global scale climate simulations, require simplification of processes that still contain the relevant characteristics of the hydrological cycle (Bierkens et al. 2015). Additionally, hydrology is a very regional science, with many processes and their influence varying under different conditions (K. J. Beven 2000; Fatichi et al. 2016).

2.2.1 Process-based models in hydrology

Over the last decades, process models (also mechanistic or physically-based models) have been developed to answer the increasingly complex questions in hydrology (Sivapalan et al. 2003; Fatichi et al. 2016). They are also called bottom-up or reductionist models which refers to the idea that they first try to understand the underlying processes influencing a hydrological system and then deduce larger-scale responses of that system (figure 3). These models represent hydrological processes inside a system in a distributed way through physically-based partial-differential equations considering the laws of conservation of mass, energy and momentum (Abbott and Refsgaard 1996; Fatichi et al. 2016). They are typically spatially distributed and use spatial input data to describe the environmental conditions (Abbott et al. 1986). In an ideal physically-based model and with sufficient input data, every process influencing the hydrological cycle should be simulated in a physically meaningful way. However, often it's not possible or practical to have fully distributed physically-based equations describing all hydrological processes and most models include simplifications, lumping of parameters or conceptualisation of equations (Savenije 2009).

Process models have been widely used to provide insight to the processes and interactions operating inside hydrological systems. They can be used to observe feedback loops and relationships that would be difficult to observe through field studies or more simple models (Abbott et al. 1986). They are particularly useful with advancing climate change to simulate previously uncommon conditions (K. Beven et al. 1980). However, process-based models have received considerable critique over several issues. Due to their distributed nature, they require spatially distributed input data which can be difficult to obtain (Abbott et al. 1986;

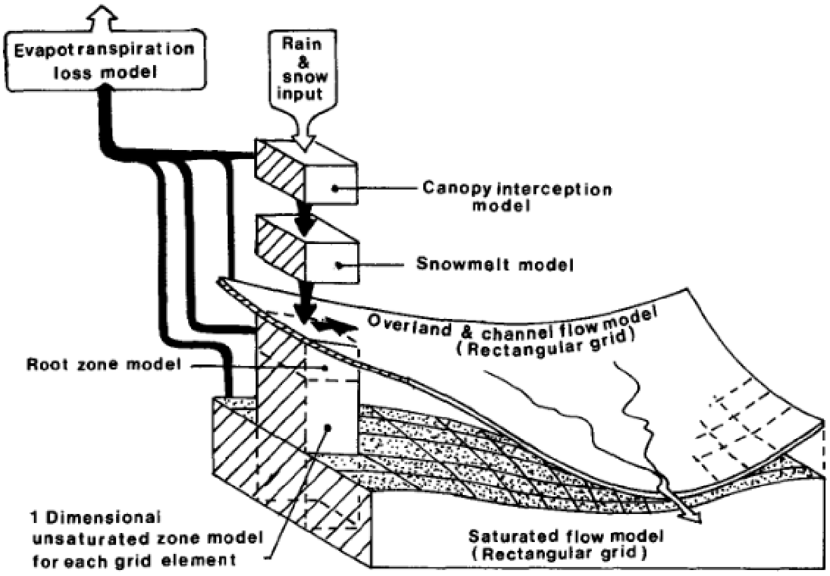


Figure 3: An example of an early physically-based model, SHE (Système Hydrologique Européen) (Abbott et al. 1986). The model includes different submodels that describe parts of the hydrological cycle inside a grid cell as well as a distributed aspect of the model that distributes water in the catchement scale. Figure from Abbott et al. 1986.

Oreskes et al. 1994; Sivapalan 2003; K. J. Beven 2006; M. P. Clark et al. 2011; Fatichi et al. 2016). This can cause great uncertainty in the model results which needs to be taken into account when analysing model results. Recent advances in GIS and remote sensing databases has however improved this (Daniel et al. 2011; Launiainen et al. 2019).

Process-based models are often be computationally heavy and mathematically complex which can limit their usability (Fatichi et al. 2016). In an overly complex model, it may be difficult to observe the relevant processes and sources of uncertainty. There are also ongoing discussions of how well certain processes can be scaled or transferred to regions outside the model's original area as hydrological processes and their importance can depend on spatial scale and region (K. J. Beven 2000). In spite of these issues, process-models are widely used in hydrological research to test hypotheses and to study complex systems with little prior measurements or simulating past or future systems (Fatichi et al. 2016).

2.2.2 Soil moisture in hydrological models

Soil moisture modelling requires description of below ground conditions and processes, many of which are not completely understood (Guswa et al. 2002; Starks et al. 2003). This often leads to simplifications of some or all of the aspects governing soil moisture variation. The approaches and processes described here do not represent an exhaustive list of the available options but rather give an overview of some of the often used processes and options in approaching them.

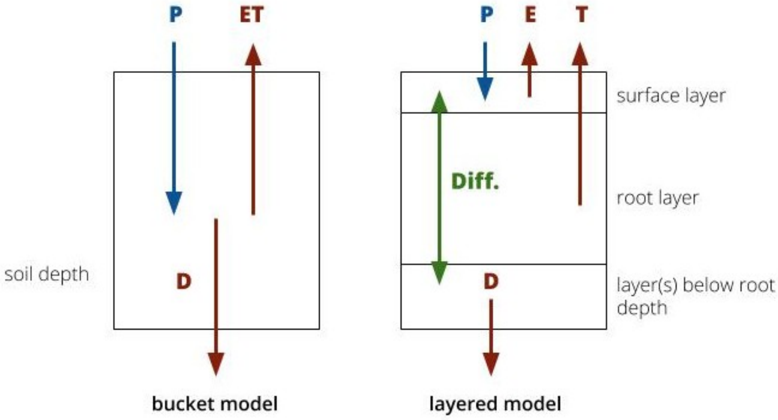


Figure 4: Soil moisture models view soil columns as either buckets or as consisting of several layers. In a bucket model, all changes in moisture content happen to the entire soil column and moisture content is uniform throughout the column. In a layered version, moisture content may vary depending on the layer and different processes affect directly only some of the layers. P = precipitation, ET = evapotranspiration and D = drainage.

A typical division of soil moisture models is based on how the soil column is described (figure 4). Simple models view the soil column as a single bucket into which water enters through certain processes and leaves through others (Guswa et al. 2002; Hagemann and Stacke 2015). In more complex models, the soil is divided into 2 or more layers and processes influence moisture content of the relevant layers. Moisture and soil properties can vary from layer to layer and moisture can be moved between layers. This allows for a more realistic representation of the soil column but requires also more complex parametrisation and model description.

Input data regarding soil hydraulic properties also varies from model to model. Generally at least some information on the hydraulic conductivity and soil water retention is required (Starks et al. 2003). However, these are difficult and time consuming to measure directly and so models often take other parameters such as soil porosity or texture class as input parameters and use transfer functions to estimate the necessary hydraulic properties.

Vertical movement of water inside the soil column can be solved using the one-dimensional Richards' equation that describes movement of water in unsaturated soil (Starks et al. 2003; Zeng and Decker 2009; Hagemann and Stacke 2015). However, as the equation is a non-linear partial differential equation, finding an exact solution in closed-form is difficult (Barry et al. 1993; Zeng and Decker 2009). Numerical solutions have been developed and are used widely in different land and hydrological models although they require some estimations of boundary conditions which may cause uncertainty in the results (Zeng and Decker 2009). In simpler models, movement inside the simulated soil column can either be ignored or represented through more empirical equations (Guswa et al. 2002).

In simpler models, infiltration to the soil is typically set to happen until saturation level, i.e. porosity is reached and no more water can fit into the soil (Guswa et al. 2002; Starks et al.

2003). However, in many models infiltration from precipitation or overland flow depends on the infiltration rate which also defines the formation of surface runoff (Guswa et al. 2002; Starks et al. 2003). There are two main causes for surface runoff. Hortonian runoff forms when precipitation rate is faster than infiltration rate (K. Beven 2004; Loague et al. 2010). In this case soil might not be saturated in lower layers but water doesn't infiltrate fast enough and some of it turns to surface runoff. In Dunne runoff on the other hand, precipitation rate is slower than infiltration rate which allows the whole soil column to become saturated. These two aspects are not mutually exclusive and in reality they tend to be intertwined (Loague et al. 2010).

An important part of any soil moisture model is the representation of evapotranspiration. Simulating the different parts of ET is often difficult and data regarding the exact properties of plants is seldom available (Launiainen et al. 2019). Therefore, many different approaches have been developed. Zhao et al. (2013) classify these methods into two groups: first group of methods calculates the different sources of ET (bare ground evaporation, canopy evaporation and transpiration) separately and then sums them to form an estimation of the total ET. The second group calculates potential ET and then scales it down using a function depending on plant available soil moisture.

There are also some commonly used methods that aim to simplify some aspects of hydrological cycle. One common method is TOPMODEL which is used in catchment scale modeling to distribute water inside the catchment so that areas with steeper slopes and which are situated higher up in the catchment receive less water than areas in flatter and lower parts (K. J. Beven and M. J. Kirkby 1979; Ambroise et al. 1996; M. Kirkby 1997). Its original idea was to simplify catchment scale models and make them more physically-based (Ambroise et al. 1996). It ties together instant runoff at points throughout the catchment and runoff out of the catchment downstream which then allows for an estimation of the total water budget inside the catchment. It then uses the Topographic Wetness Index (TWI) to distribute the water budget based on topographic variation. TWI is calculated as the ratio of the upslope contributing area (a) and the local slope (β) (eq. 1).

$$TWI = ln(\frac{a}{tan\beta}) \tag{1}$$

It can be used in TOPMODEL in its original form or as modified to include information about soil properties. While TOPMODEL is a very simplified representation of catchment-scale hydrology, it has been used rather successfully in comparison to more complex models (Buytaert et al. 2008).

3 Study area

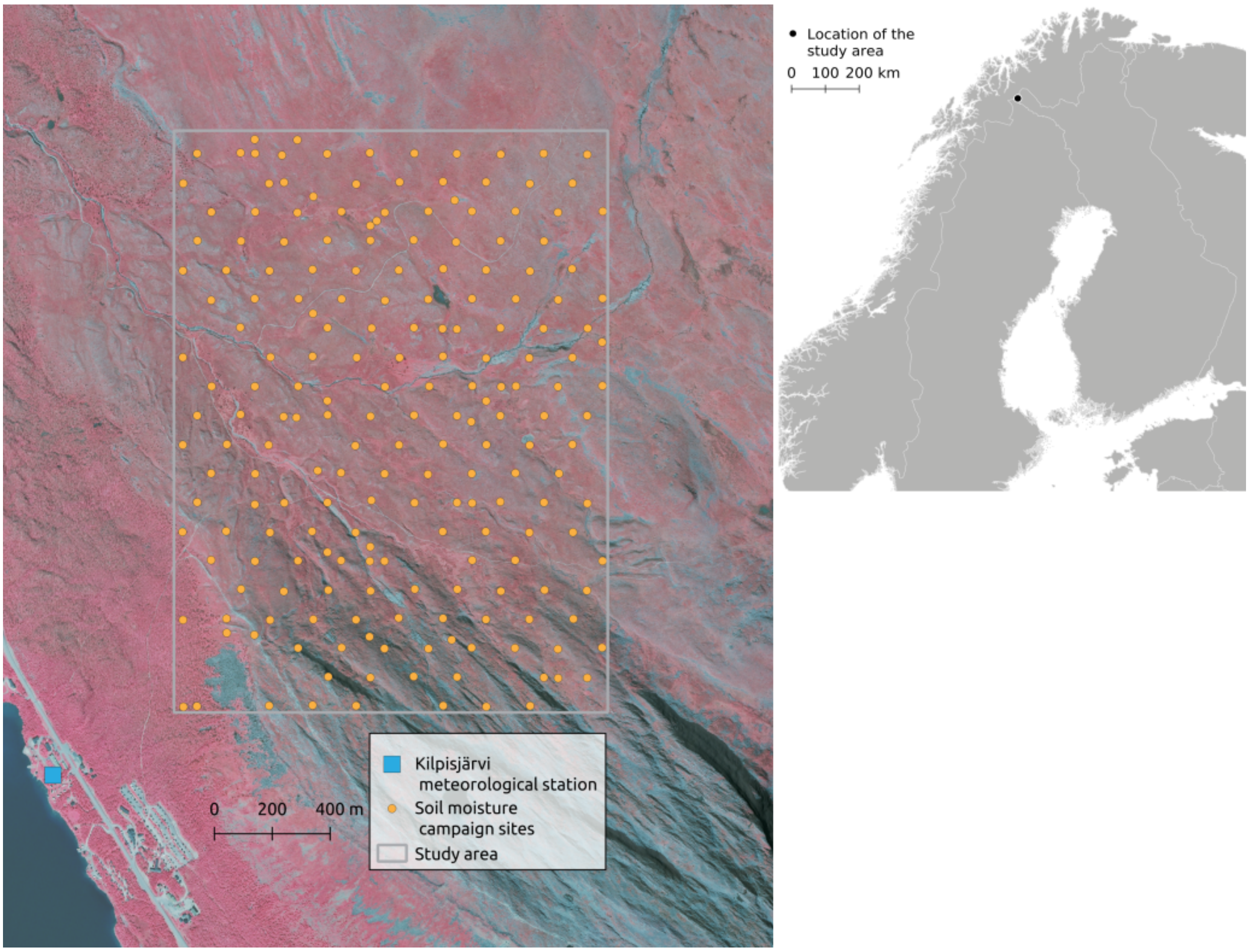


Figure 5: Map of the study area with soil moisture campaign sites and the location of the Kilpisjärvi kyläkeskus meteorological station.

The study area is located near the border between Finland, Norway and Sweden, in northwestern Finland (69°03'N 20°51'E) (figure 5). It covers and area of approximately 3 km^2 between two fells, mount Saana and mount Jehkas and contains several environmental gradients.

Climatologically the region belongs to the subarctic climate and is strongly influenced by the nearby Scandes mountainrange as well as proximity to the Arctic Ocean and the warm North Atlantic current (J. Aalto and Luoto 2014; Kemppinen et al. 2018) (figure 6).

The landscape is dominated by a mosaic of varying vegetation, soil type and topography (Riihimäki et al. 2019). Vegetation consists mainly of dwarf-shrub dominated mountain heath with small meadow patches as well as mountain birch tundra below the treeline in the southwestern corner of the area (Kemppinen et al. 2018; Riihimäki et al. 2019). Soil layer consists mainly of a thin layer of mineral soil covered by an organic layer of varying depth with patches of boulders and rock outcrops scattered around (figure 9). Much of the environmental variation is driven by finescale variation of topography with relative elevation difference reaching almost 250 meters.

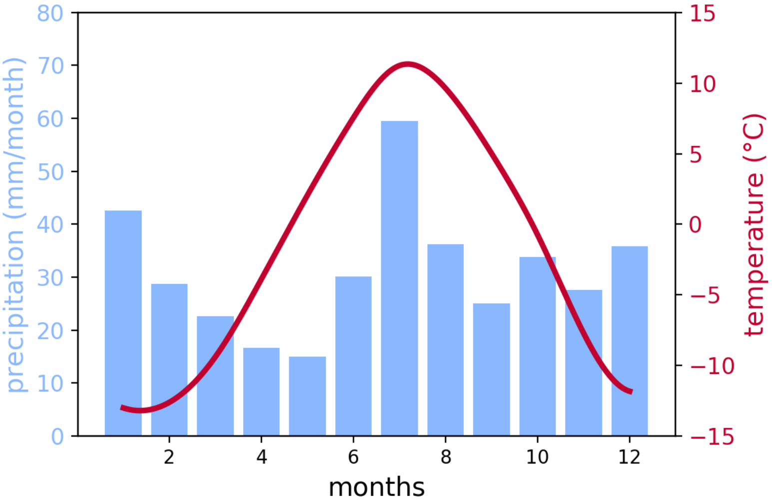


Figure 6: 30 year average (1980 - 2010) of monthly average temperatures and precipitation in the Kilpisjärvi meteorological station.

4 Data

4.1 Field measurements

Soil moisture was measured as VWC (%) on the field using hand-held time-domain reflectometry sensors (FieldScout TDR 300; Spectrum Technologies Inc., Plainfield, IL, USA) (figure 7) which were calibrated as adviced (Kemppinen et al. 2018). The measurements were done in six campaigns, each lasting 2-3 days, in the summer 2017. Soil moisture was measured from 220 sites (figure 5 of which 204 were situated inside this study's area of interest and were used in further analyses. One site consists of five 1 m^2 plots situated at the centre of the site and five meters from the centre to cardinal directions. 3 measurements were taken from each plot from the depth of 7.5 cm, trying to account for topographic microscale variation inside the plot. The results where then averaged over each plot and in this study further over each site. Plots that had too shallow soil depth or that were under water or snow were not included in further analyses.

Soil classes, their spatial distribution and soil depth were taken from the study done by Kemppinen et al. (2018). Soil classification was done through field surveys and high resolution aerial images provided by the National Land Survey of Finland and included five surficial deposit classes: peat, fluvial, glacial till, boulders and rock outcrops (figure 9). Spatial resolution of the soil map is 0.5 meters. Soil depths were measured on the field using a thin metal rod.

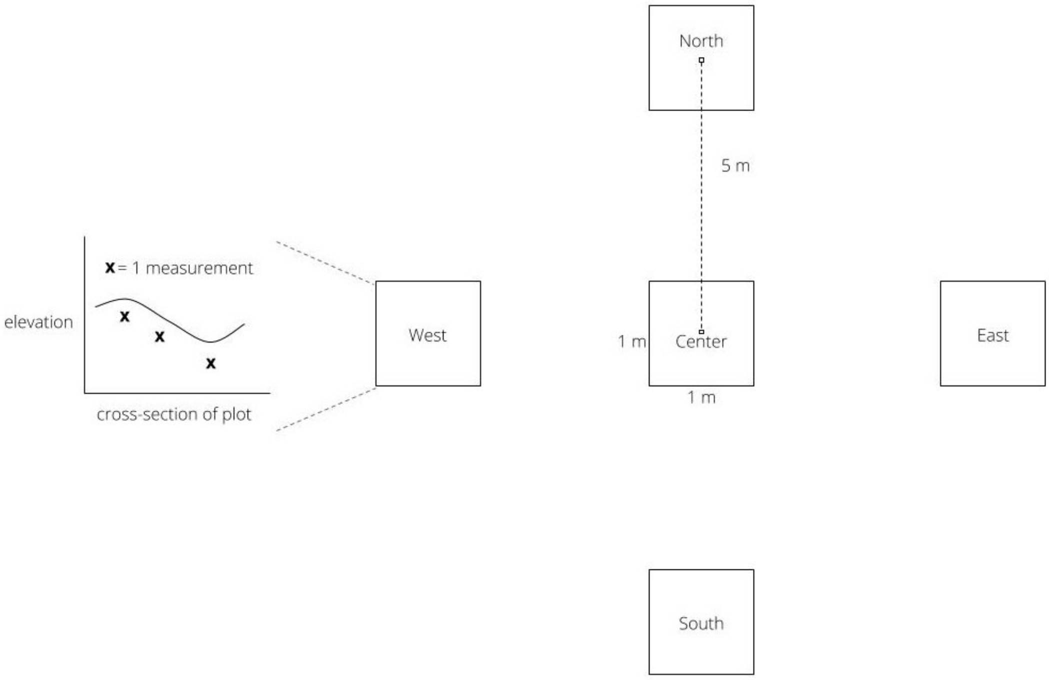


Figure 7: The figure shows an example site of the soil moisture measurements. On the left is a cross-section of one plot inside one site, demonstrating how single soil moisture measurements were collected. These measurements were repeated inside all 1 m^2 plots.

4.2 Meteorological data

Main source of meteorological data was the Finnish Meteorological Institute's Kilpisjärvi kyläkeskus meteorological station (figure 5). The variables used were air temperature (°C), precipitation (mm/h), relative humidity (%), wind speed (m/s) and direction (°) and air pressure (hPa). Temporal resolution for all measurements was 1 hour. Due to long gaps in the measurements, data from the surrounding meteorological stations in Norway and Sweden was also used (figure 8). Global radiation data for Kilpisjärvi area, i.e. total shortwave radiation including both direct and diffuse radiation, was extracted from Finnish Meteorological Insitute (2018) that contains an estimation of global radiation for the whole Finland. The spatial resolution of the dataset is 10 km, the temporal resolution is 1 day and the dataset covers years 1961-2018.

4.3 GIS datasets

The digital elevation model (DEM) from the National Land Survey of Finland was used for elevation and other topography related variables (figure 9) (National Land Survey of Finland 2017). It was created in 2017 and its spatial resolution is 2 meters. National Land Survey of Finland also provides fine-scale (0.5 m resolution) aerial images that were used to estimate vegetation cover. Several datasets describing forest attributes were downloaded from

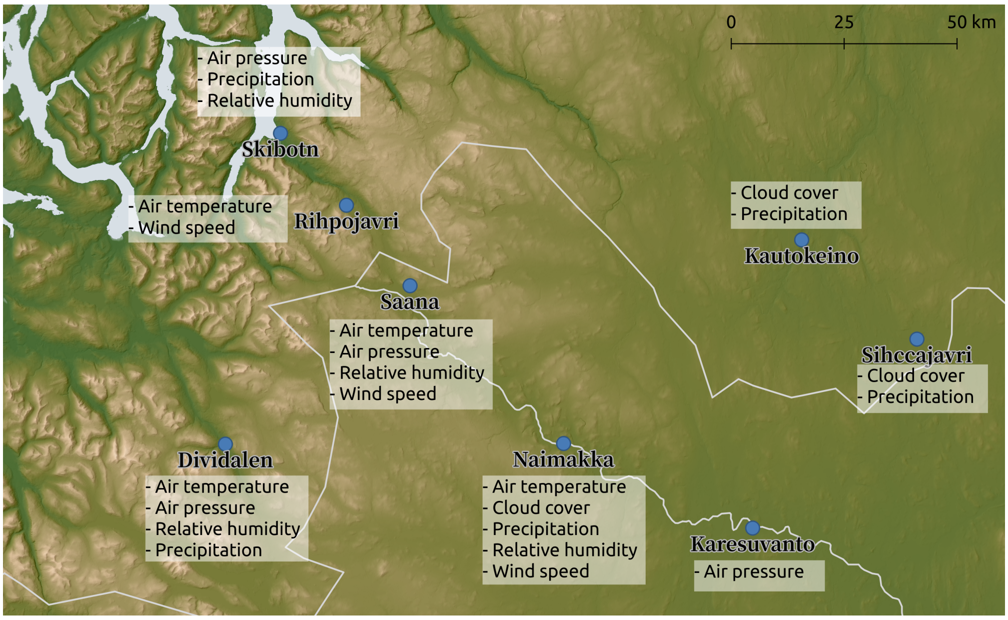


Figure 8: Meteorological data used to fill the gaps in the Kilpisjärvi measurements. Several stations were used because different stations measure different variables.

the multi-source National Forest Inventory (mNFI, Mäkisara et al. 2016). These datasets included raster maps of stand age, stand basal area, biomass of leaves and needles, canopy height and canopy cover (%) of trees and their resolution was 16 meters. The datasets were collected in 2015.

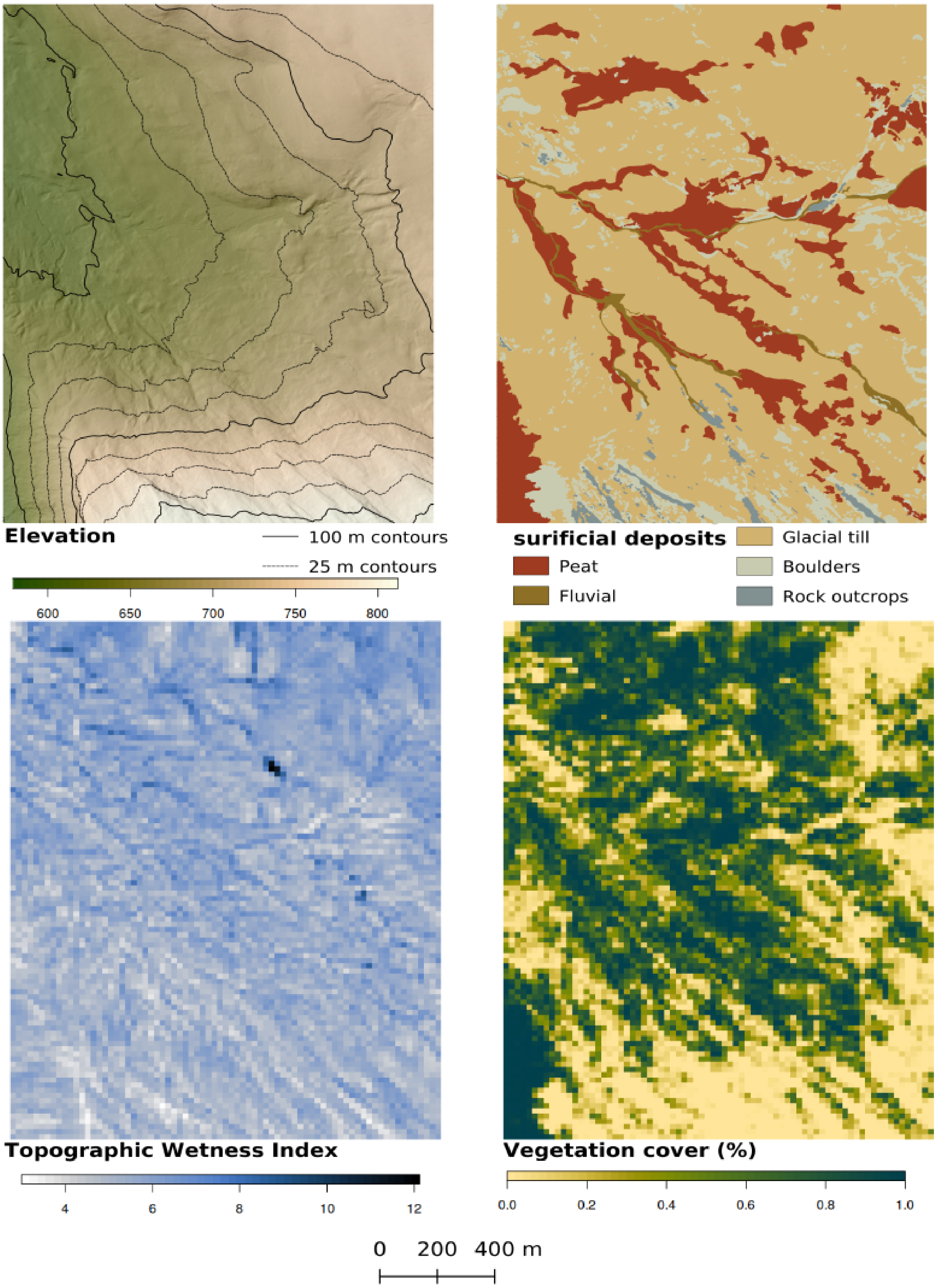


Figure 9: Environmental data used for the input data in models.

5 Models

The three models represent varying modelling approaches and are used for different purposes (table 1). The descriptions given here are not complete representations of the models or their internal structure as these are provided in more detail in literature.

Table 1: Basic characteristics of the models

	JSBACH	**SpaFHy**	**Ecohydrotools**
Developed by:	Max Planck Institute, Germany	Finnish National Resources Institute	microclimate research group, University of Exeter
Developed for:	large-scale land surface modelling	modelling hydrology in boreal forests	fine-scale hydrological modelling
internal structure:	several separate modules for different land surface processes	3 submodules for canopy, soil and cathcment distribution	separate microcale models for microclimate variables and soil hydrology
spatial distribution:	point scale model, no interaction between grid cells	point and catchment scale versions	point scale and catchment scale versions

5.1 JSBACH

JSBACH is a land surface model developed by Max Planck Institute (MPI). It was originally part of ECHAM, the atmospheric model of MPI-ESM (MPI's Earth System Model) but was later changed into its own model by collecting together processes involved in the interactions between lower layer of atmosphere and land surface processes (Roeckner et al. 2003; Groner et al. 2018; Heidkamp et al. 2018). JSBACH can be run as its own model as an offline version without having to connect it to a General Circulation Model (GCM) or as part of one. It has been used in various studies simulating different biogeophysical and -chemical processes and many studies have also investigated the performance of the different processes included in JSBACH (Heidkamp et al. 2018).

Structurally JSBACH consists of several submodules, each focusing on a separate aspect of land surface processes (Thum et al. 2011; Gao et al. 2016; Hagemann and Stacke 2015; Groner et al. 2018; Heidkamp et al. 2018). These modules describe terrestrial energy balance, heat transfer and water budget, vegetation dynamics and phenology, carbon cycle over land, land cover change (natural and anthropogenic) and surface albedo. Because JSBACH is intended for large-scale modeling, there are formulations that take into consideration land surface variability inside grid cells. Vegetation types, described as plant functional types (PFTs), are added to each grid cell as tiles, i.e. each tile represents a different PFT and its fraction of the total vegetated grid cell area. Topographical variation inside the grid cell is described through standard deviation of topography.

Soil moisture is depicted in JSBACH as 5 layers increasing in depth and going down to approximately 10 meters (figure 10). The actual depth of the layers is restricted by a separate soil depth parameter. Root zone depth defines the depth from which transpiration can occur and is also defined separately. However, moisture can exist in all layers also below the root zones and can be moved upwards if there is too little moisture in the upper layers (Hagemann and Stacke 2015).

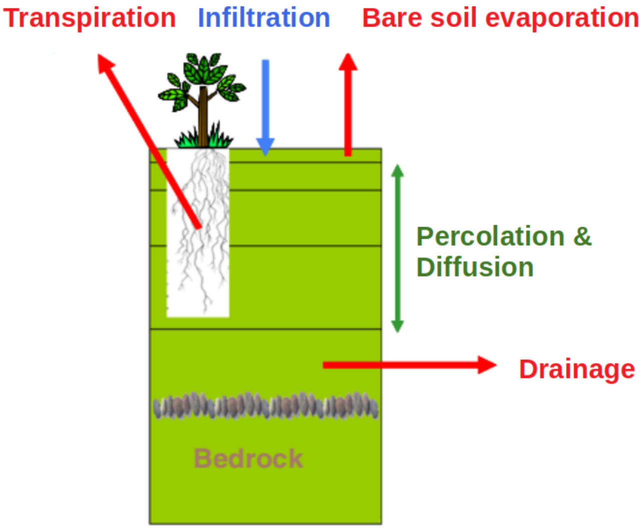


Figure 10: Conceptual representation of JSBACH's soil hydrology scheme. There are five layers with increasing depth. Bare ground evaporation is only dependent on the top layer while transpiration can happen from the whole root zone. Lateral drainage removes water from all layers. Figure modified from Hagemann and Stacke (2015).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}(D \cdot \frac{\partial \theta}{\partial z}) + \frac{\partial K}{\partial z} + S \tag{2}$$

Vertical movement of moisture is described through Richards' equation (eq. 2). First term on the right side describes vertical diffusion which distributes soil moisture among different layers depending on soil properties. The second term refers to percolation. These two terms are described as separate processes in the scheme (Hagemann and Stacke 2015). S includes infiltration to the soil, bare ground evaporation from the top layer and transpiration from the root zone.

5.2 SpaFHy

Spatial Forest Hydrology Model (SpaFHy) is a spatially distributed hydrological model developed in the Finnish Natural Resources Institute to simulate evapotranspiration and water balance in boreal forests (Launiainen et al. 2019). Its focus is on the spatial variation of vegetation and soil properties and how they influence hydrological processes above and below ground. It has so far been tested at stand scale (model results representing single point) and at catchment level in various test sites in Finland and it can be a useful tool in for example simulating future changes induced by climate change in forest hydrology and forest management.

SpaFHy consists of three submodules that can be run together, separately or be joined with other models (figure 11). The canopy module includes forest canopy, ground surface and snow pack and it calculates the water balance above ground. It calculates ET as the sum of evaporation from the ground and from vegetation and transpiration. The snow description includes accumulation and melting of the snowpack.

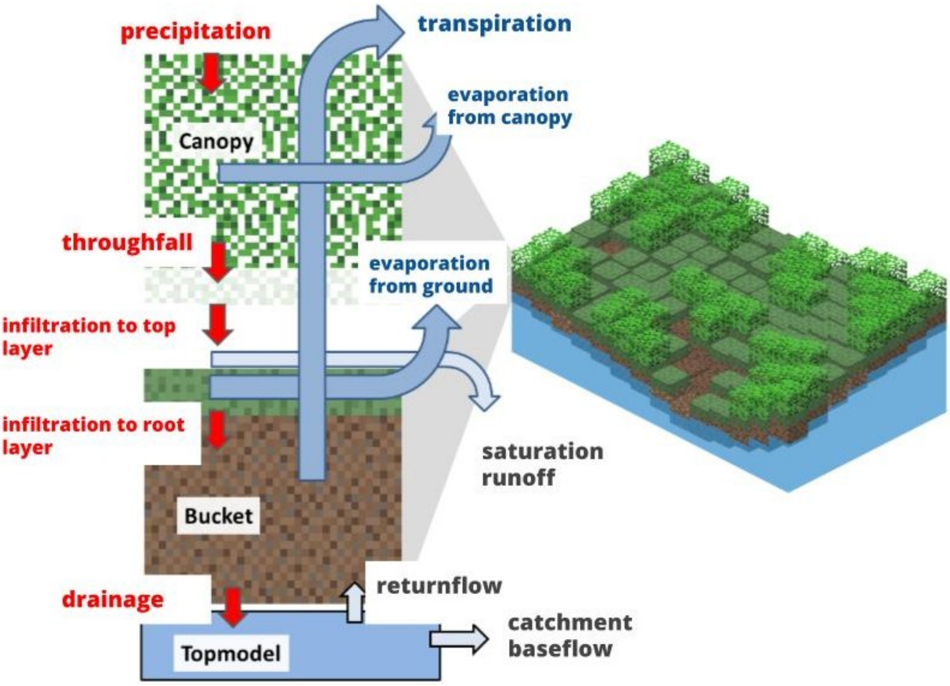


Figure 11: Conceptual representation of SpaFHy's submodules. Canopy and bucket modules are used to calculate water balance at point scael after which TOPMODEL is used to distribute water in the saturated zone according to the local TWI and the average TWI of the catchment area. On the right is a representation of the catchment area. Water balance in each grid cell is calculated on its own and in the bottom TOPMODEL links the cells to a distributed catchment area. Modified from Launiainen et al. (2019).

The bucket model describes soil as two layers - organic surface layer and root layer. Soil moisture in the upper organic layer (θ_{org}) is controlled by throughfall from the canopy and snowmelt from above (I_{org}), evaporation from the ground (E_f) and upward flow from root layer coming from upstream areas ($Q_{r,ex}$) (eq. 3).

$$\frac{\Delta\theta_{org}}{\Delta t} = \frac{I_{org} - E_f + Qr, ex}{z_{org}} \tag{3}$$

Root layer moisture content on the other hand changes due to infiltration from the organic layer (I_f), transpiration (T_r), drainage to the bottom layer (D_r) and returnflow from the bottom layer (Q_r) (eq. 4).

$$\frac{\Delta\theta}{\Delta t} = \frac{I_f - T_r - D_r + Qr}{z_s} \tag{4}$$

Last of the submodels is TOPMODEL which simulates the saturated layer below root layer and connects grid cells to the catchment scale water balance. In case of saturation excess in the bottom layer, water is rooted first to the root layer and from there to the organic layer. Saturation deficit (S) in the whole basin (i.e. the amount of water required to bring the layer to saturation) depends on drainage to the bottom layer (D_r), catchment baseflow in the lowest layer (Q_b) and returnflow to the root layer (Q_r) (eq. 5). It is tied to each grid cell's saturation deficit through the topographic wetness index (eq. 6).

$$\frac{\Delta S}{\Delta t} = -D_r + Q_b + Q_r \tag{5}$$

$$S_{cell} = S_{avg} + m(TWI_{avg} - TWI_{cell}) \tag{6}$$

5.3 Ecohydrotools & microclima

The third model is a combination of two models specialised in fine scale microclimatic and hydrological modeling (Maclean et al. 2018; Maclean 2019). They are currently under development by the microclimate research group led by Dr Ilya Maclean in the University of Exeter. The purpose is to provide detailed microclimatic information that can be used in fine scale environmental research such as species distribution modeling. The hydrological model, Ecohydrotools (EHT), uses a simple two-layer soil hydrological model developed originally by Mahrt and Pan (1984) (figure 12). The thin upper layer receives precipitation and stores water for bare ground evaporation. Hydraulic diffusivity and conductivity control water movement between the upper and lower layers and evapotranspiration can happen from both layers given that there is vegetation to cause transpiration. If the top layer is saturated, precipitation is changed to surface runoff. There are two versions of the model: temporal point model and a spatio-temporal version. In the spatial version, basins are calculated from a DEM that can be given by the user or downloaded by the model. Soil moisture is distributed inside each basin according to TWI. In addition to the two soil layers, the model also calculates the depth of still surface water, i.e. the area of inundation. This is also distributed across the basins based on TWI.

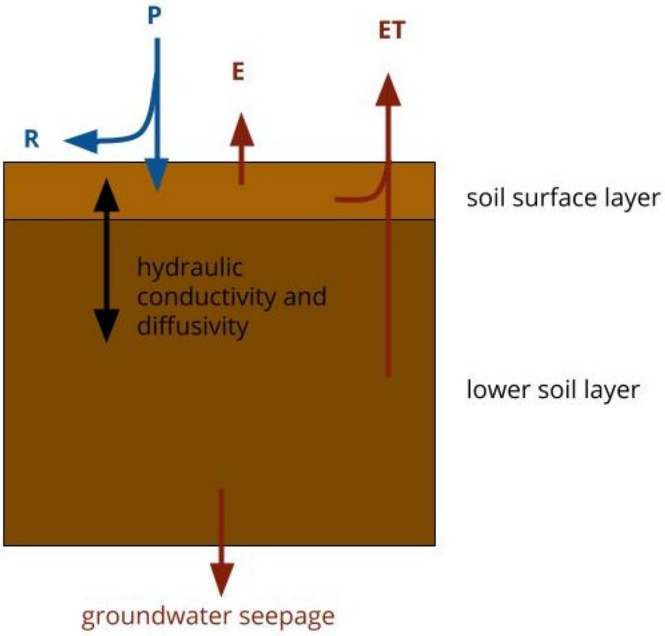


Figure 12: Conceptual representation of the soil column in Ecohydrotools. Water comes in to the upper layer through precipitation, is distributed inside the soil according to soil parameters and leaves through evapotranspiration. Excess precipitation is changed into runoff and there is an option to allow for groundwater seepage.

EHT uses precipitation and evapotranspiration as meteorological input data. In this version, evapotranspiration across the study area is calculated with microclima calibrated by another microclimate model, NicheMapR (Kearney and Maino 2018; Maclean et al. 2018). The combination of the two models, still under development, downloads global meteorological and radiation data at 2 °resolution from NCEP-DOE Atmospheric Model Intercomparison Project (Kanamitsu et al. 2002). It then estimates microclimatic variation of temperature and evapotranspiration based on topographic and meteorological variation.

6 Preparation of input data and simulations

6.1 Input data

Most of the input data is given in raster format. For JSBACH, the resolution was set to 50 meters to keep simulation times reasonable. To allow for finer scale variation between grid cells in JSBACH, all variables were calculated in the finer resolution datasets and then an average in 50 m resolution was calculated. For SpaFHy, the highest possible resolution is currently 16 meters due to the resolution of the mNFI database. However, to keep the exact study area similar in all models, the resolution of the mNFI datasets as well as other raster layers required by SpaFHy were changed to 20 meters. For EHT the resolution was also set to 20 meters for simplicity.

6.1.1 Meteorological data

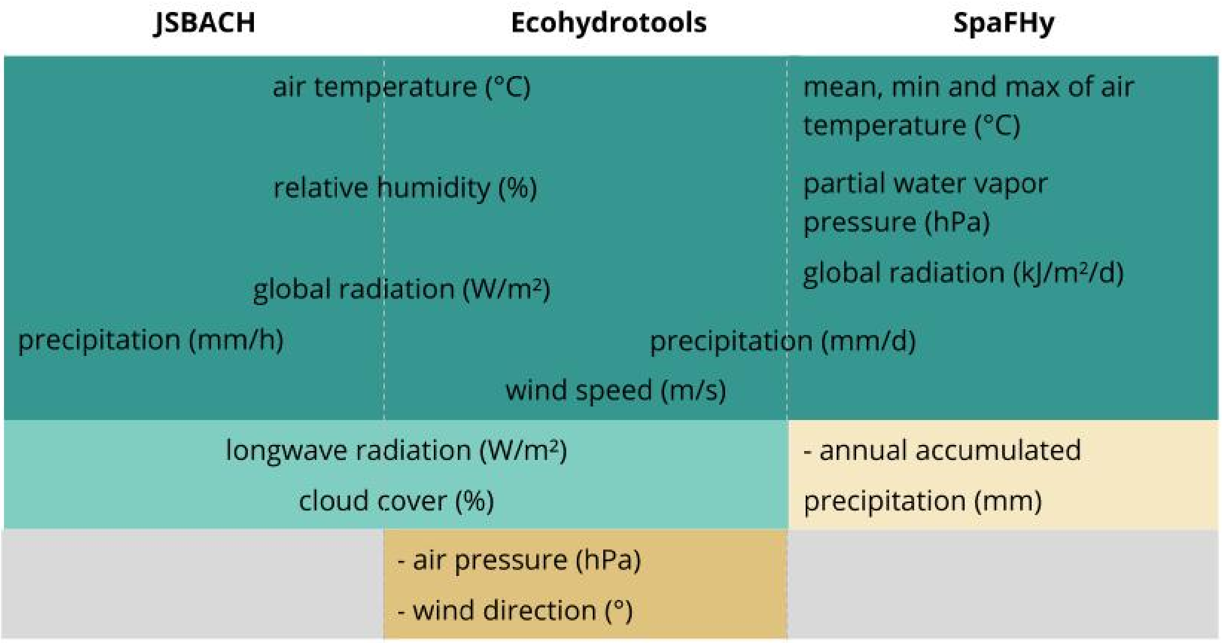


Figure 13: Meteorological data and their units in each model. The width of the boxes indicate which models use the variables inside the box, for example both JSBACH and Ecohydrotools require data about longwave radiation but SpaFHy doesn't. In case there is only a slight difference in a variable (such as difference in units), the units are mentioned separately but the variable is seen as common to several models, for example air humidity is expressed as relative humidity in JSBACH and EHT and as partial vapor pressure in SpaFHy. In general, JSBACH and EHT require input data in hourly format (except for precipitation for EHT) while SpaFHy uses daily input data.

While the meteorological data from Kilpisjärvi station was generally comprehensive, there were some longer gaps in the measurements lasting from a few days to two to three weeks. To fill these gaps, multiple imputation method was used to calculate an estimate of the weather conditions in Kilpisjärvi based on meteorological data from nearby stations in Norway, Sweden and Finland (figure 8) (Yozgatligil et al. 2013). Multiple imputation method was developed by Rubin (1987) and calculates several possible estimates for missing data values using Monte Carlo techniques, i.e. random sampling of the data to account for uncertainty in the estimates. The R package "mice" was used to run the imputations with the default settings of 5 imputated datasets (i.e. 5 estimations for the missing values), maximum 50 iterations and with the predictive mean matching method (Buuren and Groothuis-Oudshoorn 2010). The average of the 5 estimations was used in the model simulations.

Due to lack of radiation measurements sufficiently near the study area, longwave radiation was estimated from weather data using the clear-sky method developed by Dilley and O'brien (1998) (eq. 7) where w is water vapor pressure and T_0 is air temperature. This method was chosen based on comparisons done by Niemelä et al. (2001) due to its simplicity and performance.

$$F_{LW,clr} = 59.38 + 113.7T_0 273.16^6 + 96.96w/25 \tag{7}$$

A correction method for cloudy conditions developed by Niemelä et al. (2001) (eq. 8) was used to account for the influence of cloud cover on longwave radiation. $F_{LW,s}$ is upward longwave radiation from the surface (calculated using the Stefan-Boltzman law describing radiation from black body as σT_s) and c total cloudiness (%).

$$F_{LW,all} = 1 + F_{LW,s} F_{LW,clr} - 10.87c^{3.49} F_{LW,clr} \tag{8}$$

Global radiation was extracted from Finnish Meteorological Insitute (2018). For JSBACH it was corrected with an estimation of potential global radiation after running into problems with the original values. The correction was done so that an estimation for potential global radiation was calculated from the whole 50 year dataset and then a fraction of the actual radiation compared to the potential radiation was calculated. This correction value was then used by multiplying it with hourly potential radiation data to get an estimation of the actual global radiation (Böttcher et al. 2016).

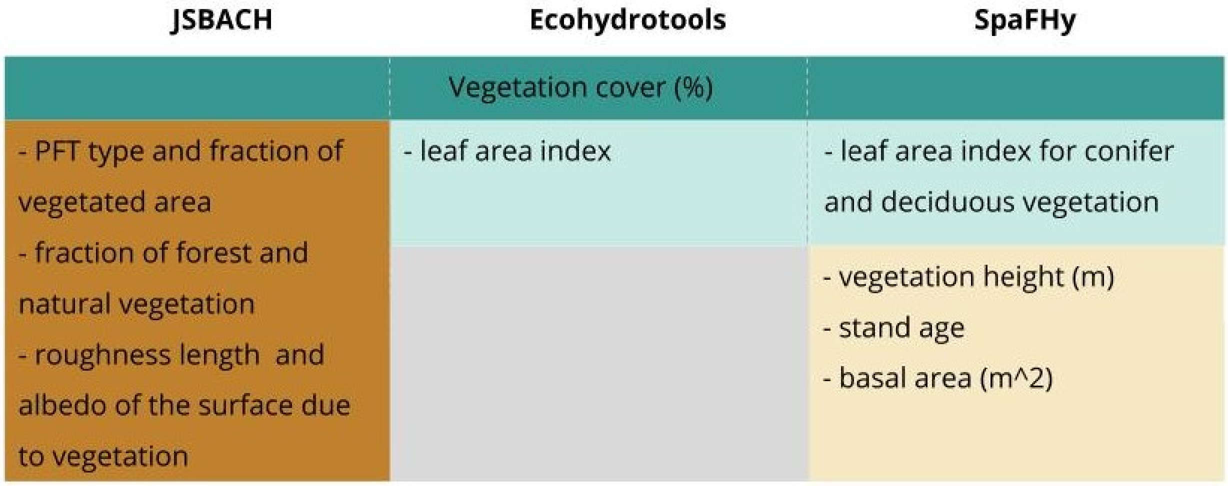
For SpaFHy, relative humidity was changed to partial water vapor pressure which is relative to saturated vapor pressure (eq. 9).

$$esa = 0.6112exp(\frac{17.67 \cdot T_{mean}}{T_{mean} + 273.16 - 29.66}) \tag{9}$$

There is currently no option to give meteorological data as input to the microclimate model that calculates spatial evapotranspiration for EHT. Therefore, all meteorological input data for the microclimate model except precipitation is generated by the model by downloading global weather data in 2° resolution using an R package developed by Kemp et al. (2012).

6.1.2 Vegetation

Vegetation cover for JSBACH and EHT was calculated from the infrared aerial images produced by NLS (National Land Survey of Finland 2017). NDVI (normalized difference vegetation index) values were calculated from the near-infrared and red bands and then, through visual interpretation, all areas with NDVI values less than 0.2 were classified as having no vegetation and areas with 0.2 or higher were classified as vegetated areas. Vegetation cover in percentages was then calculated by averaging the reclassified NDVI map to the required spatial resolution.



JSBACH	Ecohydrotools	SpaFHy
	Vegetation cover (%)	
- PFT type and fraction of vegetated area - fraction of forest and natural vegetation - roughness length and albedo of the surface due to vegetation	- leaf area index	- leaf area index for conifer and deciduous vegetation
		- vegetation height (m) - stand age - basal area (m^2)

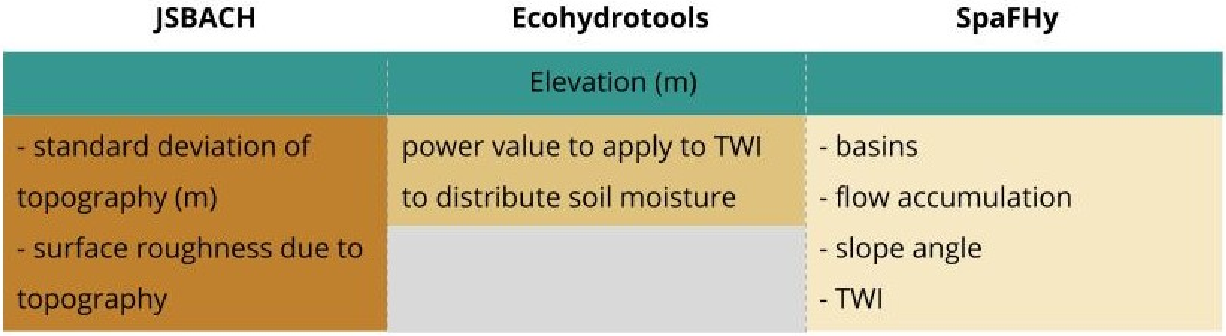
Figure 14: Parameters related to vegetation required by each model. PFT means plant functional types. Each variable is given as a raster layer.

Leaf area index (LAI) was calculated for SpaFHy by following the procedure of Launiainen et al. (2019) where the leaf biomass rasters were converted to conifer and deciduous one-sided LAI based on an estimation by Härkönen et al. (2015). LAI for microclima (and EHT) was calculated by summing the conifer and deciduous LAI values from SpaFHy's input data. Rest of the layers for SpaFHy were readily available from the multi-source National Forest Inventory database.

For JSBACH, values for forest fraction, fraction of natural vegetation, roughness length due to vegetation and surface albedo were set to match vegetation classes from Hagemann (2002) according to table 2. The cover types representing PFTs were estimated from a parameter file, lctlib, in JSBACH source code listing all plant functional types and their phenology attributes. There are three classes in the PFTs that could be suitable for the area: C3 grass, tundra and peatlands. In the first run, mineral soil vegetated areas were set to half C3 grass and half tundra. Bare ground areas were set to tundra and peatland areas to peatlands. However, the results showed relatively high estimations for LAI in sparsely vegetated areas and so another setup depicting all vegetation over mineral soil as tundra was used in later simulations. The percentage of each class inside the grid cells was then calculated and attributed to the respective tiles.

Table 2: Classification for vegetation attributes in JSBACH.

Vegetation class	classification rule
polar and alpine desert	NDVI < 0.2
upland tundra	NDVI ≥ 0.2
fen, bog, mire	surficial deposit = peatland



JSBACH	Ecohydrotools	SpaFHy
Elevation (m)		
- standard deviation of topography (m) - surface roughness due to topography	power value to apply to TWI to distribute soil moisture	- basins - flow accumulation - slope angle - TWI

Figure 15: Variables related to topography in each model.

6.1.3 Topographical parameters

All models require spatial elevation data in which the digital elevation model (DEM) from NLS was used (figure 9). JSBACH's standard deviation of topography and surface roughness are meant for larger scale modeling and not very useful in depicting small scale topographical variation. Their influence was tested in two runs - in one, the values were set according to previous simulations (Holmberg et al. 2019) and in one they were set to zero. The effect on soil moisture variation was very small and therefore, the values across the study area were set to match previous simulations.

SpaFHy's variables related to TWI (flow accumulation, i.e. upslope contributing area, basins and slope angle) are calculated from the DEM with ArcGIS's spatial analyst tools. TWI is calculated from the flow accumulation and slope (converted to radians) (eq. 1) and the whole study area is depicted as one basin which matches basin delineation in the larger DEM covering also the surrounding areas of Saana and Jehkas. EHT requires less topographical parameters because it is capable of calculating the required parameters itself. It delineates basins from the DEM and then calculates TWI.

6.1.4 Soil properties

In JSBACH all soil parameters are directly defined by the user, instead of requiring a classification of the area into different soil classes with predetermined properties like SpaFHy or EHT. The parameters in JSBACH regarding soil hydrological properties (Clapp & Hornberger parameter, saturated moisture potential, soil porosity, field capacity, wilting point, saturated hydraulic conductivity and pore size distribution index) were taken from Hagemann and Stacke (2015) according to table 3. Soil depth was originally set to the average calculated from the measurements done by Kemppinen et al. (2018) in mineral soils (approximately 30 cm), to one meter in peatland areas for vegetation to survive and to 10 cm in rock outcrops and boulder areas. However, with these parameters vegetation wasn't able to survive and after testing several depths, soil (and root) depth was set to 1 meter in peat-

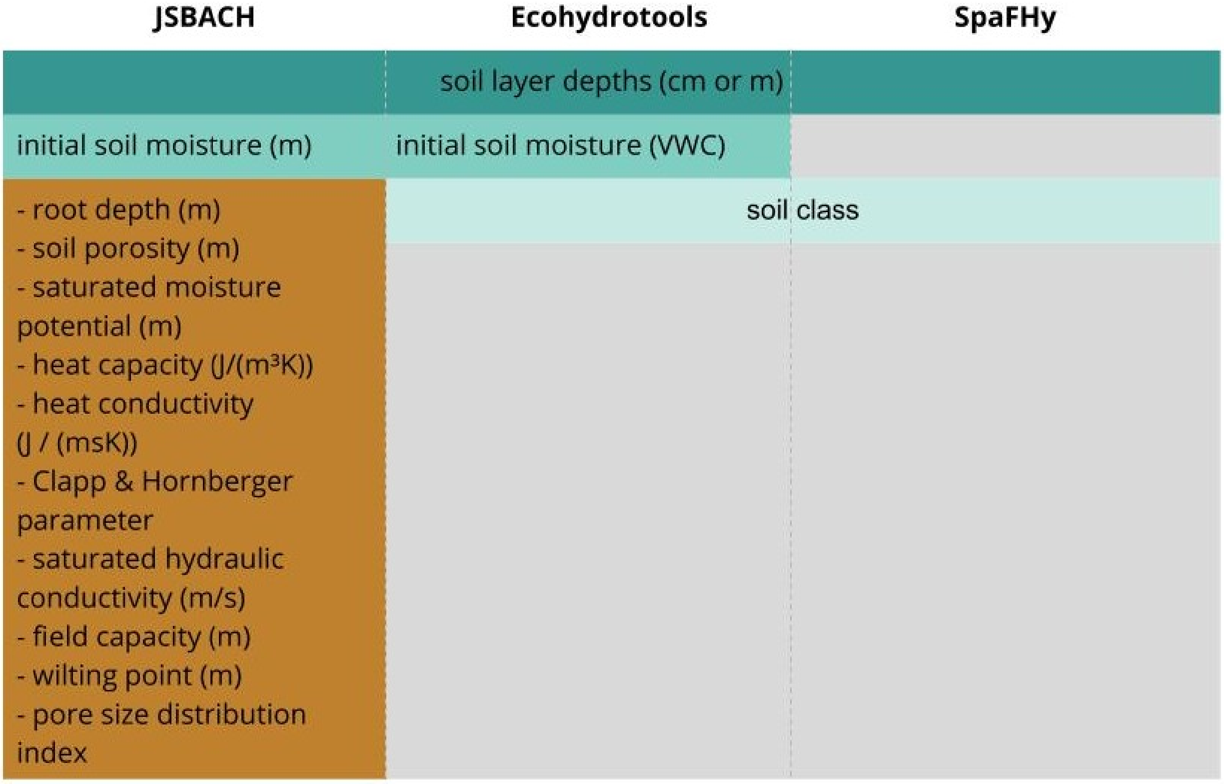


Figure 16: Soil properties required by each model. In SpaFHy and EHT, soil properties are embedded in the model as parameters which is why they don't have to be given as explicitly as in JSBACH. However, they can also be changed by altering the values in the model code.

lands and to 50 cm everywhere else. Soil properties in areas consisting of boulders and rock outcrops were then set to coarse soil parameters. Heat capacity and heat conductivity were taken from previous simulations (Holmberg et al. 2019). Initial soil moisture was set to half of soil porosity.

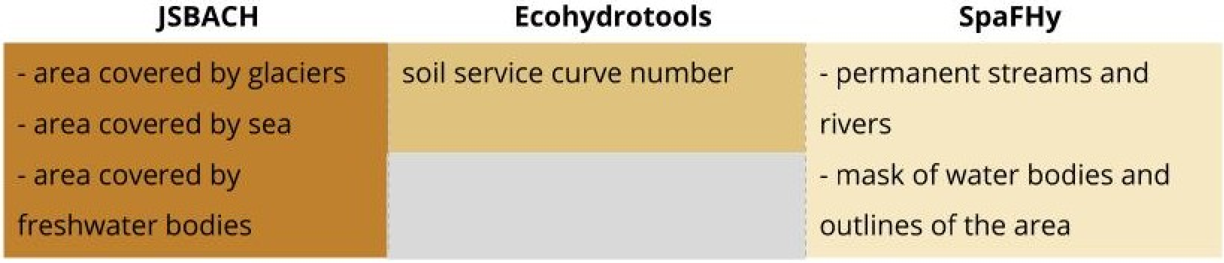
Table 3: Classification of the surficial deposit types (figure 9) to soil classes matching classes used by Hagemann and Stacke (2015) and Launiainen et al. (2019).

surficial deposit class	soil class
peatland	peat
fluvial	coarse
glacial till	loamy sand or medium
boulders	coarse or rock outcrops
rock outcrops	coarse or rock outcrops

In SpaFHy, soil properties were given in the source code and the model required the area to be classified into different soil classes: fine, medium, coarse, peat and humus. These were given according to table 3 and an additional class, rock outcrops, was created with soil properties from the coarse soil class but with soil depth of 1 cm. The code was additionally modified to include soil depth in the spatially varying soil properties. Soil depth in the coarse and medium classes was set to 30 cm and to 1 meter in peatlands. Soil properties that matched those in JSBACH (soil porosity, field capacity, wilting point and saturated hydraulic conductivity) were then changed to match the values in JSBACH to keep the input data as similar as possible.

EHT allows for two different ways of defining soil properties. They can be given as soil classes that match the classification in the R package in which case it retrieves the matching van Genuchten soil parameters defining soil hydraulic properties (Genuchten 1980). Alternatively these properties can be defined either as raster layers or as a single list by the user, allowing for more soil types to be included. However, as the model is still being developed, only a single soil class for the whole area was possible and so it was defined as loamy sand which is included in the readily defined soil parameters. Initial moisture was set to the default value of 0.35.

6.1.5 Land cover and masks



JSBACH	Ecohydrotools	SpaFHy
- area covered by glaciers - area covered by sea - area covered by freshwater bodies	soil service curve number	- permanent streams and rivers - mask of water bodies and outlines of the area

Figure 17: Land cover and other land surface related variables required by the models.

The land cover and surface variables include mainly a set of different masks meant to crop out water bodies. Since the streams and ponds in the study area vary throughout the summer due to snow melt, they were not included in the masks. The soil service curve number required by EHT was estimated using the land cover class consisting mainly of dwarf scrubs in NRCS (2017) and the hydrologic soil group, which describe soil runoff potential, was defined as group B based on Ross et al. (2018).

6.2 Simulations

JSBACH was run as an offline version with user generated forcing data (meteorological data) with modules bethy, phenology, albedo and yasso turned on to keep the simulation simple. SpaFHy was run with all three submodules as a catchment scale version and EHT was run as a spatial hydrological model. SpaFHy and JSBACH were run from the beginning of 2010 to check that there were no trends ongoing trends caused by input data in variables such as soil temperature, soil moisture and vegetation properties. EHT lacks a proper representation of cold environment processes so running it through several years is unlikely to have a realistic influence on the estimations. Starting the simulation in EHT too close to the time of interest on the other hand produced a decreasing trend in soil moisture, so the simulation was started in July 2016.

7 Results

The results are shown in 50 meter resolution. The results of SpaFHy and EHT were resized to 50 meters by calculating the average VWC inside each cell. JSBACH soil moisture values which are given by the model in mm where changed to VWC by dividing the water content with soil depth. The results show the depth weighted average soil moisture of the top two layers. In SpaFHy and EHT this means the surface layer and the root layer and in JSBACH it means the top two layers which reach to a depth of 32 cm.

7.1 Spatial variation in the whole study area

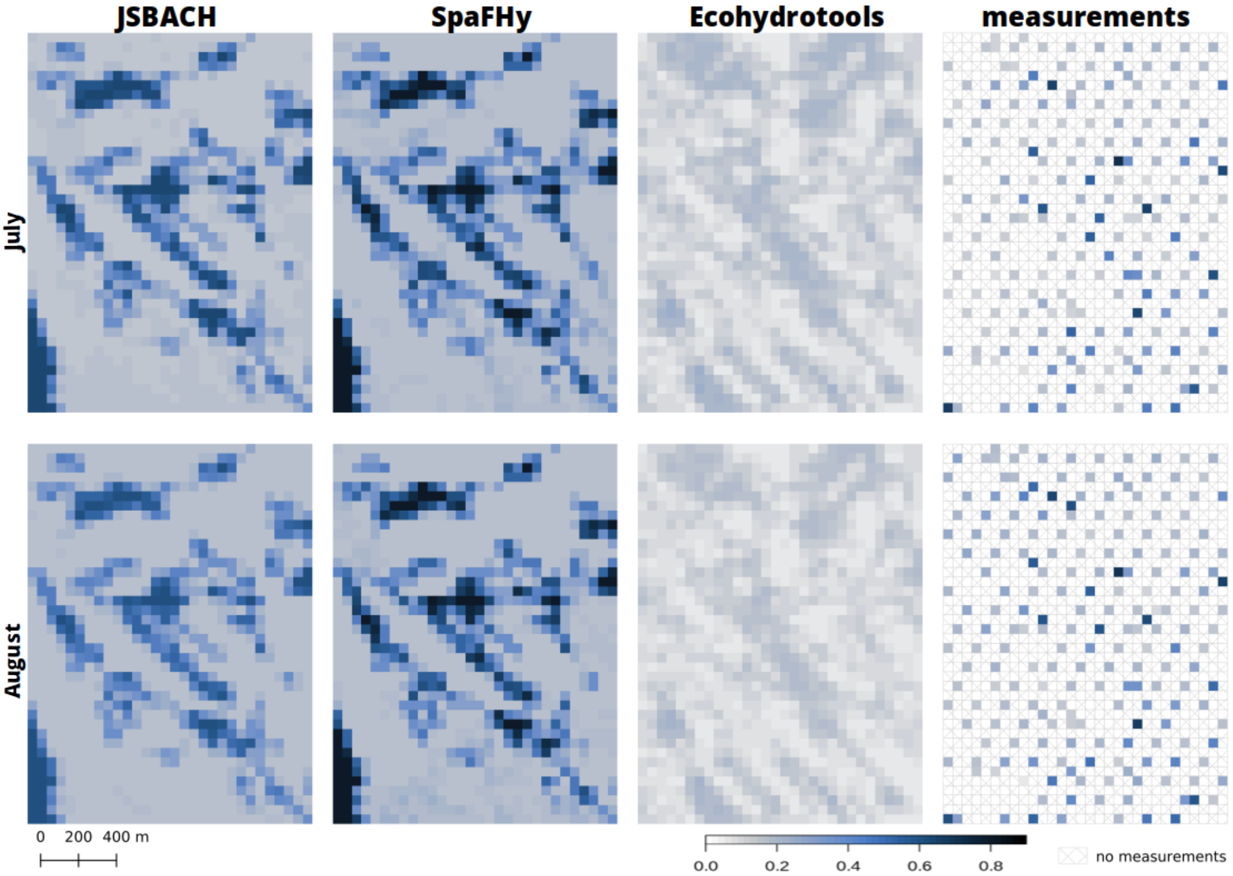


Figure 18: Modelled and measured soil moisture content (VWC) during the late July (21.-23.7.) and late August (21.-23.8.) field measurement campaigns in 2017. Soil moisture values in the models were calculated as averages of the campaign days. Measurements are shown as averages of each site's 5 plots, excluding plots with impartial measurements.

Simulated soil moisture values show similarities as well as discrepancies throughout the study area in their spatial distribution of soil moisture content (figure 18). All models predict higher soil moisture values in the centre of the study area where topography is flatter and there is more organic soil (figure 9). These areas are also visible in the measured soil moisture values. However, there is less agreement between the models and measurements regarding the actual moisture content in these areas. In JSBACH, SpaFHY and the measurements, moisture contents are quite high, varying between 0.4 and almost 0.9 (table 4). EHT on the other hand underestimates moisture content considerably, with the highest VWC reaching only 0.25.

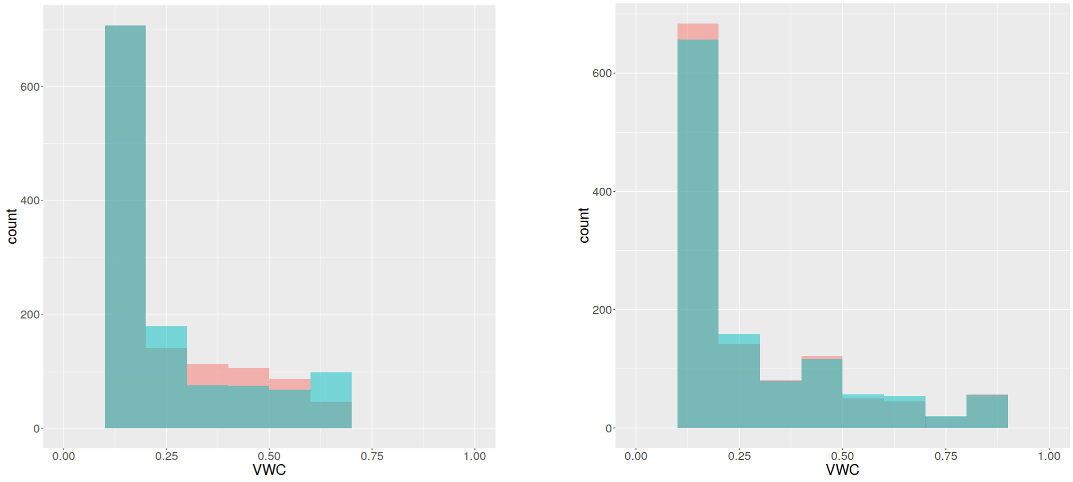
In drier areas there is more discrepancy between the models and the measurements. There are larger dry areas with moisture content varying between 0.05 and 0.4 that show up in all models and measurements but there is also also great variation in some areas as well as in the actual moisture contents. In JSBACH and SpaFHy, drier areas are quite similar with VWC of 0.16-0.17 and very little, if any, spatial variation. EHT estimates soil moisture in drier areas to be much smaller, between 0.05 and 0.1 but also finds more spatial variation in these areas. This is more in line with the measurements which show considerably more spatial variation than JSBACH and SpaFHy.

Table 4: Mean, standard deviation, range and the coefficient of determination (r^2) of soil moisture values (VWC, %) averaged first over the days of the measurement campaigns and then over the study area. The r^2 value was calculated between each model and the measurements.

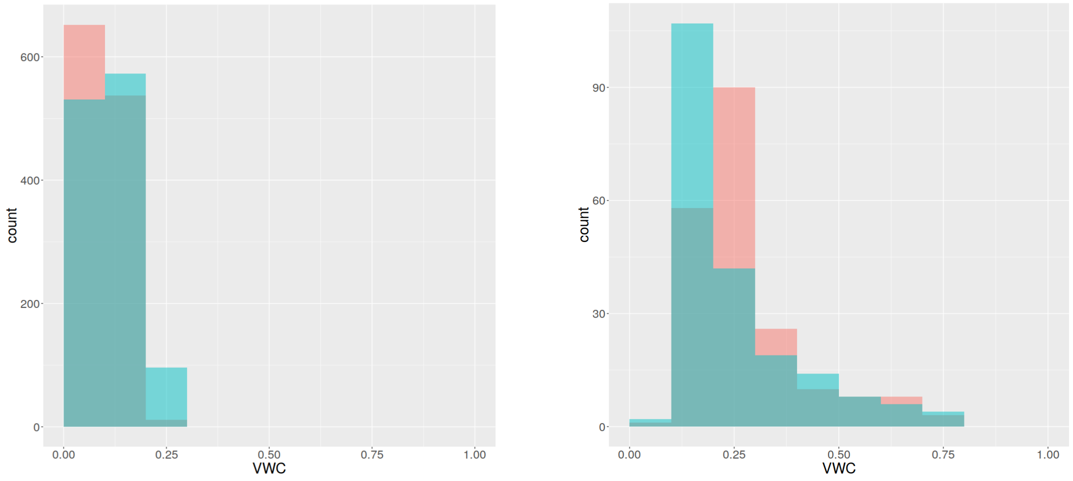
	JSBACH		SpaFHy		Ecohydrotools		measurements	
	July	August	July	August	July	August	July	August
mean	26.5	26.5	30.2	30.0	11.6	10.3	25.7	27.6
st. dev.	16.1	14.4	19.4	19.0	4.8	4.0	15.0	13.4
max	69.2	65.3	88.0	88.0	24.9	22.6	78.7	77.4
min	16.0	16.7	16.1	17.6	5.4	5.4	7.5	7.8
r^2	21.5	23.2	23.6	24.0	14.9	17.8	-	-

There is variation also in the distribution of soil moisture values (figure 19). JSBACH and SpaFHY have a similar distribution pattern with each other and the measurements with a large majority of the study area being relatively dry and higher moisture values being rarer. However, both models underestimate very low moisture contents (below 0.1) as well as areas with moisture content of 0.2-0.3. They also overestimate the portion of very wet areas compared to measurements. EHT behaves differently, estimating all areas to have moisture content below 0.25, although comparing to figure 18, the distribution shows similar characteristics to the other models and measurements if the range is ignored.

The patterns of spatial variation in the models and measurements change in some aspects during the summer. In JSBACH and SpaFHy the driest areas get wetter (an increase of 0.01-0.02) which is also visible in the measurements (table 4). EHT shows a different pattern of an increase in the number of dry cells (figure 19c). In SpaFHy there are also more



(a) JSBACH (b) SpaFHy



(c) Ecohydrotools (d) measurements

Figure 19: Histograms depicting the distribution of soil moisture (VWC) in late July (green) and late August (red).

drier cells although the minimum moisture value increases by almost 2 percentage points. The maximum values on the other hand decrease in all models and measurements by 1-3 percentage points, except in SpaFHy in which very wet areas show almost no variation. This results in a decrease in the range of variation which is visible in all models and measurements, although the pattern is smaller in SpaFHy (table 4). The strongest discrepancy between the measurements and models is the scale of the increase in the measured VWC in relatively dry areas (figure 19d). While JSBACH and SpaFHy show some wettening of the dry areas, the magnitude is clearly smaller than in the measurements where the mean moisture content increases by 0.02.

The general agreement between each model and the measurements varies (figure 20 and table 4). EHT shows a relatively even disagreement throughout the study area with simulated values approximately 20 - 30 percentage points smaller than the measured values. The difference is larger in areas with higher measured moisture content. JSBACH and SpaFHy show very similar spatial patterns in their difference to measurements. Neither of them shows a spatially uniform trend of simulating higher or lower moisture contents but rather moist areas in organic soils seem to be overestimated while for example soil moisture in the southernmost area is underestimated. The r^2 value which indicates agreement between the measured and simulated values is slightly higher in JSBACH and SpaFHy compared to EHT (table 4). However, the difference decreases in August due to EHT's increase in r^2.

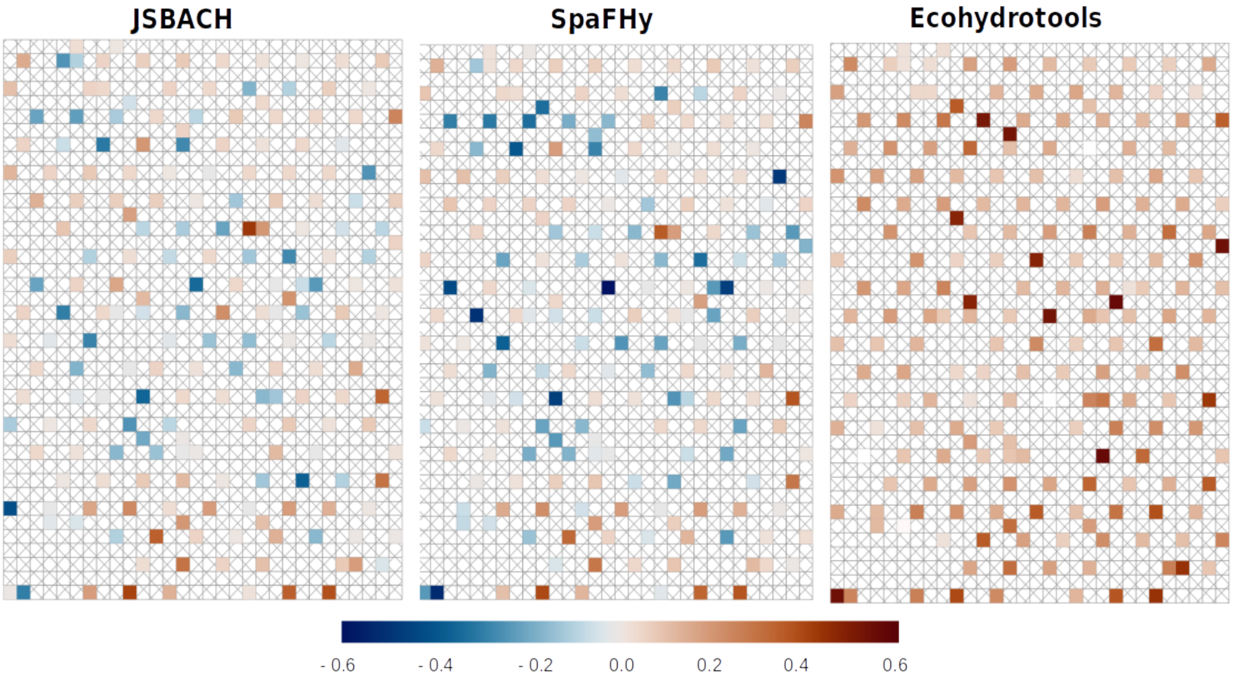


Figure 20: Difference between measured and simulated soil moisture content (VWC) in each of the models during the late August campaign. Red values indicate that measured soil moisture content is higher than the simulated moisture whereas blue areas show higher simulated soil moisture content than in the measurements.

7.2 Spatial variation in different land cover types

The following results have been done by classifying the area to three land cover classes: 1) peatland areas with the majority of the grid cell consisting of peatland soil, 2) areas with less than 25 % of vegetation cover on mineral soil and 3) areas with more than 25 % vegetation cover on mineral soil (figure 21). This classification was used because it also represents a large part of the topographical variation and variation in the other soil classes (figure 9). TWI shows small differences between the classes, with sparsely vegetated areas being the driest and peatland areas wettest (table 5).

7.2.1 Peatland areas

In peatland areas, the mean VWC is higher than in the whole study area in all models and measurements (table 6). The same applies to the minimum values except in EHT which finds

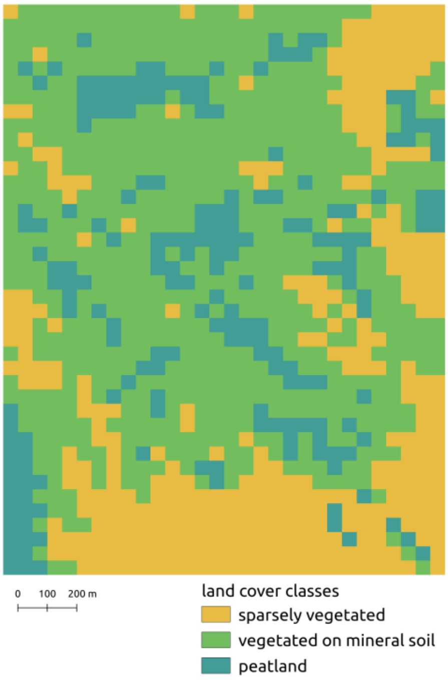


Figure 21: The distribution of land cover classes used to examine the results.

Table 5: Size of the land cover classes and the mean topographic wetness index (TWI) and its range in each class.

	sparsely vegetated	vegetated	peatland
area (%)	29	54.5	16.5
number of measurements	53	111	40
mean TWI	5.3	5.6	5.7
range of TWI	3.0 - 12.1	3.5 - 8.6	3.6 - 8.8

very dry areas also in these areas. There is more discrepancy in the distribution of moisture (figure 22). In the models, the standard deviation is smaller than in the whole study area and the range is smaller as well whereas in the measurements the standard deviation is higher due to the relatively even distribution of moisture to drier and wetter areas. The distribution patterns are also different in the models: in JSBACH the distribution is inclined towards wet areas but in SpaFHy the distribution is more even. EHT also finds more wet areas than dry areas in this class, although the values are considerably smaller than in the other models or measurements. However, EHT has a considerably higher r^2 value of over 20 % compared to the very low values of 0-2 % in JSBACH and SpaFHy. This suggests that while EHT underestimates VWC, it is better at finding the spatial variation of the measurements than the other two models. However, it is important to notice that the number of measurements in the peatland class is quite low (41 sites) which is likely to affect the r^2 values considerably here and in the sparsely vegetated class as well.

There is also variance in the results between the July and August campaigns. The mean VWC decreases in the models but increases slightly (0.5 percentage points) in the measurements (table 6). The minimum values show a contrasting trend whereas standard deviation decreases in models and measurements except in SpaFHy. There is a slight improvement in the agreement between JSBACH, SpaFHy and the measurements in August.

Table 6: Statistical properties of peatland areas in models and measurements. The values were averaged first over the days of the measurement campaigns and then over peatland areas.

	JSBACH		SpaFHy		Ecohydrotools		measurements	
	July	August	July	August	July	August	July	August
mean	55.9	52.4	66.0	65.4	14.0	12.3	40.3	40.8
st. dev.	12.0	9.7	15.6	15.8	4.7	3.9	19.4	18.5
max	69.2	65.2	88.0	88.0	22.3	19.3	78.7	77.4
min	24.4	25.5	32.3	33.3	5.4	5.4	13.4	12.2
r^2	0.1	2.7	0.2	1.7	23.0	21.1	-	-

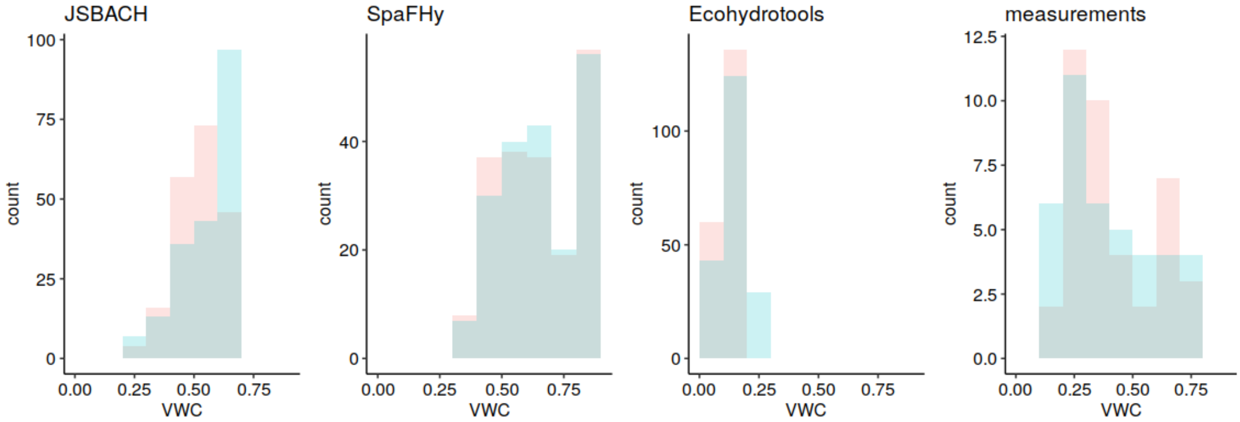


Figure 22: The distribution of soil moisture (VWC) in peatland areas during the campaigns in July (green) and August (red).

7.2.2 Vegetated areas

In vegetated areas over mineral soils, the results show more similarities between models and measurements than in the peatland areas. The mean VWC and standard deviation are slightly lower than in the whole study area and the values in JSBACH and SpaFHy are close to the measured values (table 7). The maximum values in JSBACH, SpaFHy and the measurements are close to each other and lower than in the peatland areas and the whole study area by approximately 10 percentage points. In EHT, however, the highest soil moisture values are located in the mineral soil vegetated areas rather than in peatland areas. The variance in r^2 values also shows different characteristics than in peatland areas. JSBACH and SpaFHy show slightly better agreement while EHT shows almost no agreement with the model.

The distribution patterns are quite similar between all models and measurements: all are clearly inclined towards dry conditions (figure 23). However, they are less similar in August due to a clear shift in the measurements towards wetter conditions. This is visible in the mean and minimum soil moisture values of the measurements (table 6). In the models, this trend is only slightly visible in JSBACH while SpaFHy and Ecohydrotools show an increase in dry conditions.

Table 7: Mean, standard deviation, range and the coefficient of determination (r^2) of soil moisture values (VWC, %)averaged first over the days of the measurement campaigns in vegetated areas. The r^2 value was calculated between each model and the measurements.

	JSBACH		SpaFHy		Ecohydrotools		measurements	
	July	August	July	August	July	August	July	August
mean	22.4	23.0	25.2	24.7	11.4	10.1	21.8	23.9
st. dev.	10.1	9.6	11.5	10.9	4.7	3.9	11.2	8.4
max	61.6	55.8	69.4	69.3	24.9	22.6	65.0	63.1
min	16.0	16.7	16.1	17.6	5.4	5.4	7.5	10.6
r^2	5.2	6.5	8.7	7.8	2.3	5.2	-	-

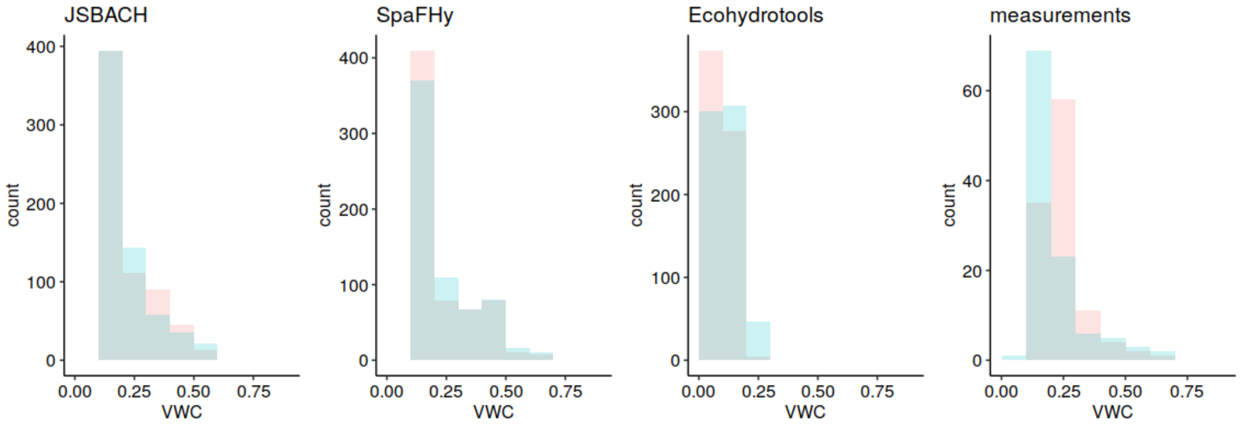


Figure 23: The distribution of soil moisture (VWC) in vegetated areas during the campaigns in July (green) and August (red).

7.2.3 Sparsely vegetated areas

In sparsely vegetated areas, the results between the models and measurements show large variation. The mean VWC is lower in the models than in the measurements whereas the maximum and minimum values are higher in JSBACH and SpaFHy than in the measurements (table 8). The standard deviation is very low in all models, varying between 4 and 5 % but is close to the average of the whole study area in measurements. This is also visible in the distribution of soil moisture (figure 24). All models show a very similar distribution pattern with almost only dry condistion whereas the distribution in the measurements is much more dispersed although dry conditions are more common. As with peatland areas, the r^2 value is close to zero in JSBACH and SpaFHy and much higher, over 20 % in EHT, indicating again that there is spatial variation that the first two models are not able to detect.

The trend towards wet conditions in August is also visible in measurements, although in this land cover class the trend is visible also in the already wet areas, with maximum VWC increasing from 0.52 to 0.57 (figure 24 and table 8). This is not clearly visible in the models, although SpaFHy's distribution shifts slightly towards wet conditions and there is a small increase of less than 1 percentage point in the mean VWC in JSBACH and SpaFHy.

Table 8: Statistical properties of soil moisture in sparsely vegetated areas.

	JSBACH		SpaFHy		Ecohydrotools		measurements	
	July	August	July	August	July	August	July	August
mean	17.7	18.4	19.5	20.0	10.7	9.7	22.7	25.2
st. dev.	4.5	4.3	5.5	5.1	4.6	4.0	10.9	11.1
max	58.6	52.7	65.3	64.8	24.8	22.5	52.0	57.7
min	16.0	16.7	16.7	17.8	5.4	5.4	8.7	7.8
r^2	0.0	0.0	0.2	0.0	22.4	28.6	-	-

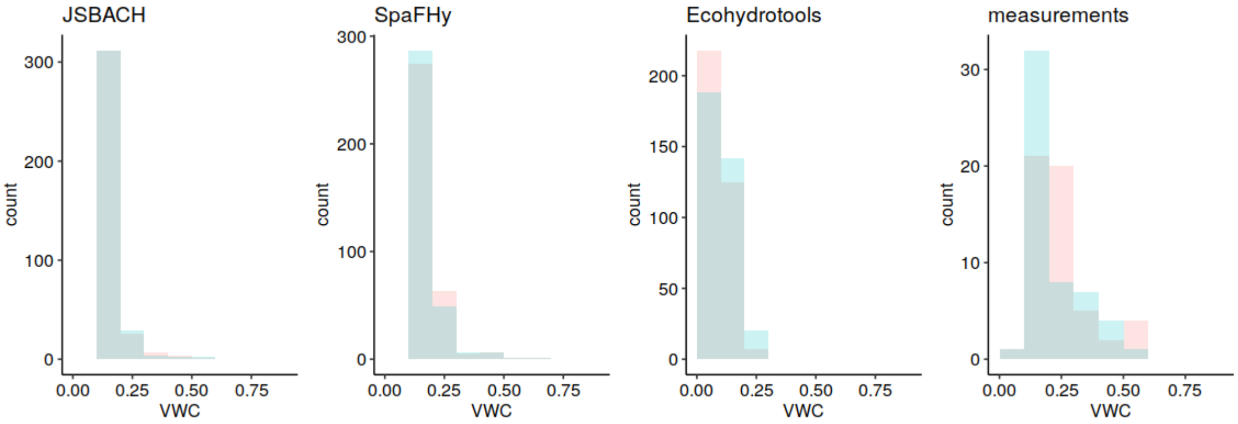
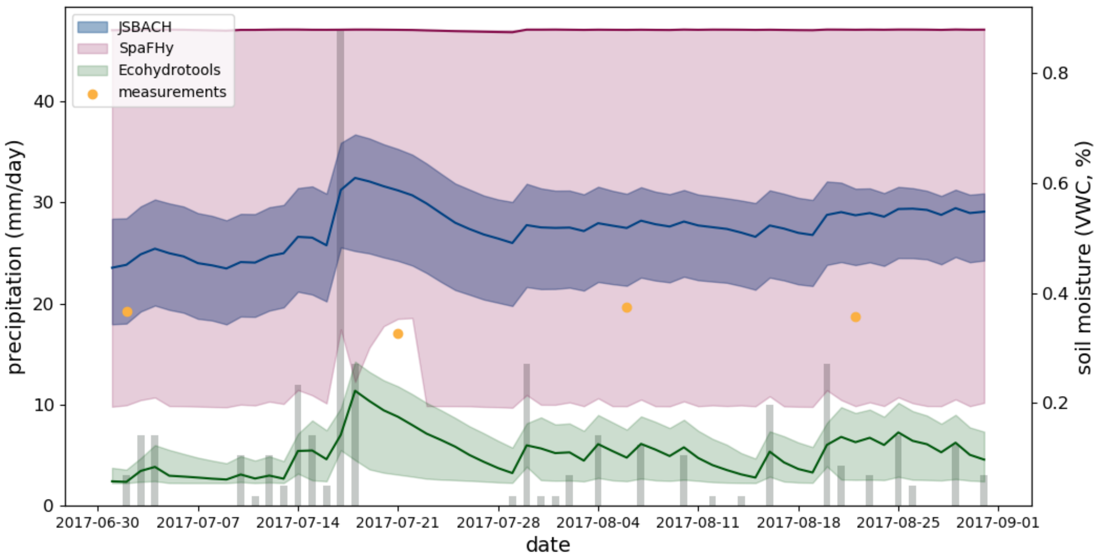


Figure 24: The distribution of soil moisture (VWC) in sparsely vegetated areas during the campaigns in July (green) and August (red).

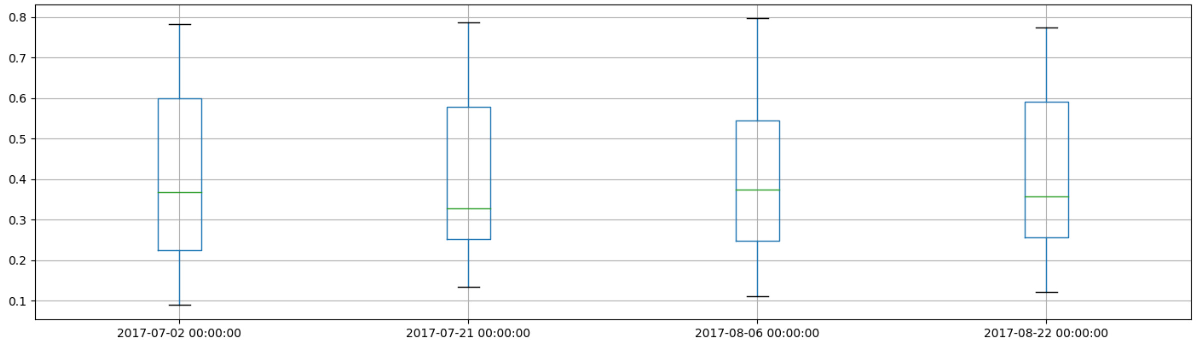
7.3 Temporal variation

7.3.1 Peatland areas

There is large variation between the models in their simulation of the temporal variation of soil moisture in peatland areas (figure 25a). In SpaFHy, most areas have very high soil moisture content with no visible temporal variation but there seem to be no cells with moderately high soil moisture values leading to the very low limit of the 1st quartile. In JSBACH, the variation is more symmetrical around the median value and the values are



(a) Time series of soil moisture variation in peatland areas. Darker lines indicate median values of each model and shading with the same colour indicates the area between the 1st and 3rd quartiles. Notice that in SpaFHy median and 3rd quartile are the same. Precipitation is shown as a barplot and mean values of measurements as dots.



(b) Boxplots of the soil moisture measurements in peatland areas done during the July and August field campaigns.

Figure 25: Temporal variation of soil moisture in peatland areas according to the models and measurements.

generally lower whereas in EHT the first quartile is constantly very low but the variation is also more symmetrical compared to SpaFHy.

The measurements show quite large variation in the distribution of soil moisture but less temporal variation (figure 25b). For example, the precipitation event in late July is not visible at all in the measurements whereas in the models it does show quite clearly. In fact, the late July campaign which is shortly after the precipitation event shows on average drier conditions than the other campaigns. Generally precipitation events are visible in the models as small peaks, although the response is not as sharp as in mineral soils (figures 26 and 28). There also seems to be a slight increasing trend in JSBACH and EHT which is not visible in the measurements or in SpaFHy.

7.3.2 Vegetated areas

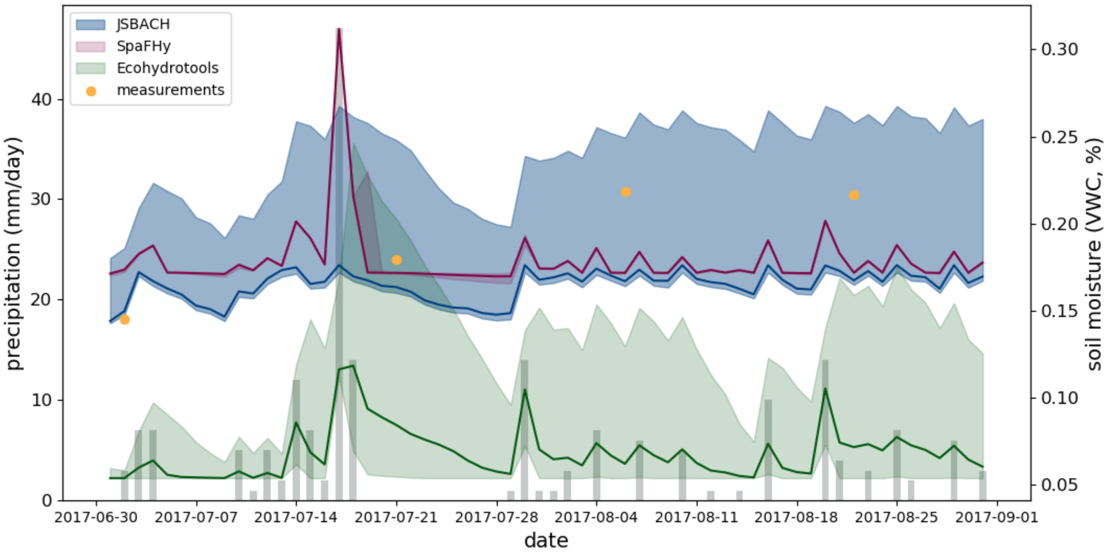


Figure 26: Time series of soil moisture variation in areas with more vegetation. Darker lines indicate median values of each model and shading with the same colour indicates area between the 1st and 3rd quartiles. The dots show the median value of soil moisture.

In vegetated areas on mineral soil, the models show quite distinctive patterns compared to peatland areas (figure 26). JSBACH shows large variation in above median values and almost no difference between the median and 1st quartile while SpaFHy shows almost no variation at all and EHT shows considerably larger variation than in peatland areas. The temporal variation in JSBACH and SPaFHy is now much closer to one other and the precipitation peaks are clearly visible in both of them although the reactions in SpaFHy are slightly stronger which is particularly visible in the precipitation event in mid-July. The variation in the median value is larger during July in JSBACH and seems to settle to a more constant state in August, with only small reactions to the rainfall events. In SpaFHy the variation is small throughout the summer and in EHT it increases towards August.

There is considerably less variation in the measurements close to the mean values compared to peatland areas, although there are also very wet outliers (figure 27). In this land cover class, there is a clear reaction in the measurements to the rainfall event in mid-July but the measurements continue getting wetter also in August. This trend is only slightly visible in JSBACH where the third quartile gets higher towards the end of August. The precipitation event does explain the drying trend visible in EHT's results in the spatial comparisons (figure 18 and tables 4 and 6). The reaction to the precipitation event is strong and continues to affect the results for longer than in the other two models, causing the values during July campaign in EHT to be higher than in August.

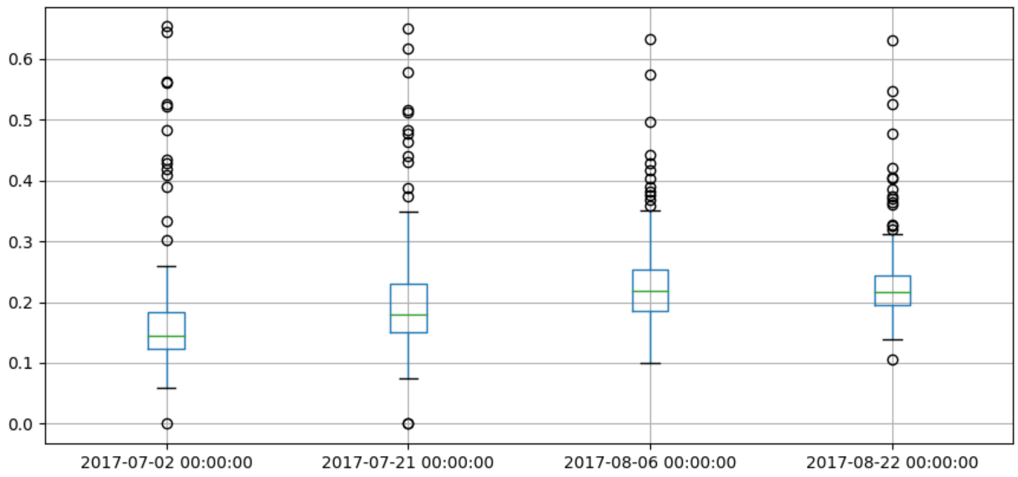


Figure 27: Boxplots of the soil moisture measurements in vegetated areas done during the July and August measurement campaigns.

7.3.3 Sparsely vegetated areas

Soil moisture in sparsely vegetated areas shows quite similar trends as in vegetated areas but there are also some discrepancies (figure 28). JSBACH and EHT show less variation in the distribution of soil moisture whereas SpaFHy shows a rather unique trend of wetter areas reacting more strongly to precipitation events. Otherwise there is very little variation in SpaFHy's results. The pattern of having a fairly constant state with small reactions to precipitation events is very similar to the pattern in vegetated areas and is more pronounced in EHT's results where the median values are very close to the values of the 1st quartile. SpaFHy's temporal variation is more abrupt and the moisture content returns to the conditions prior precipitation events more quickly than in JSBACH and EHT. In JSBACH and EHT, the influence of a precpitation event lasts longer which is most clearly visible after the strong precipitation event in mid-July.

Soil moisture measurements show more variation than in vegetated areas and the wetter areas are wetter as well (figure 29). There is also the same increasing trend as in vegetated areas but in this class it is not visible at all in any of the models. However, it is less pronounced than in vegetated areas and is only visible in the drier areas. In the wetter areas, a slightly drying trend continues until early August.

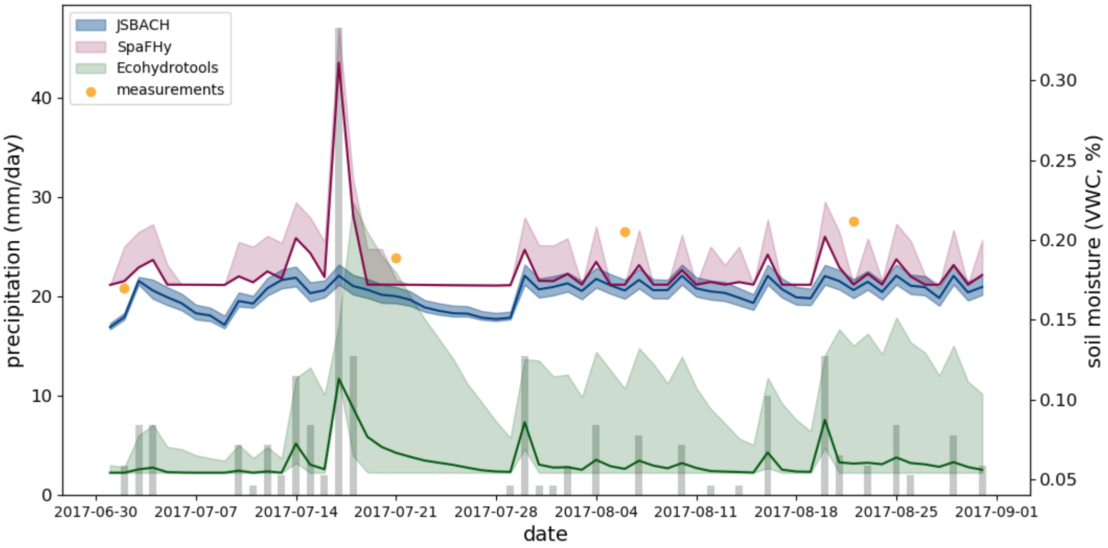


Figure 28: Time series of soil moisture variation in sparsely vegetated areas. Darker lines indicate median values of each model and shading with the same colour indicates area between the 1st and 3rd quartiles. The dots show the median value of soil moisture.

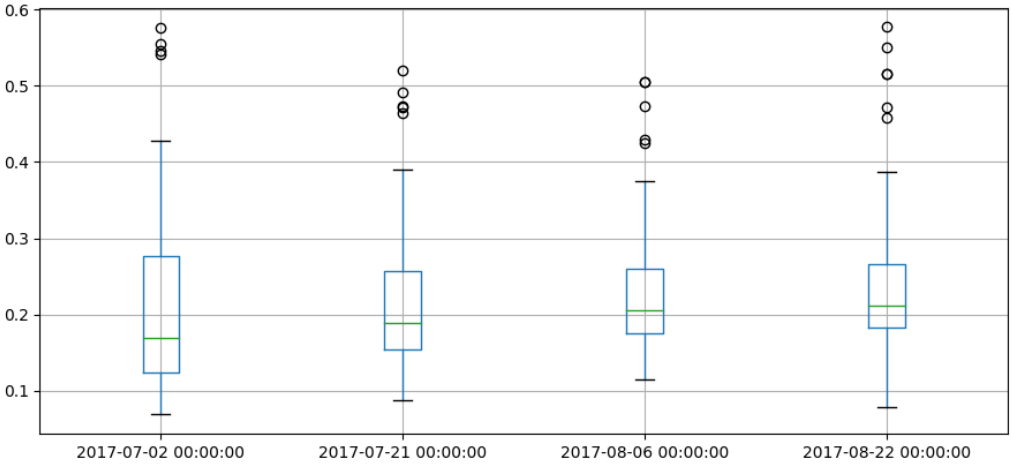


Figure 29: Boxplots of the soil moisture measurements in sparsely vegetated areas.

8 Discussion

8.1 Results in peatland areas

Most of the larger areas with high soil moisture content in the study area are relatively well represented in the models (figure 18). These are areas where several environmental variables controlling soil moisture correlate rather strongly (figure 9). They have generally more peatland cover, more vegetation and are situated in flatter areas downstream from the surrounding higher areas. The correlation between soil moisture and these environmental variables has been shown in the area previously by eg. Kemppinen (2016) and Kemppinen et al. (2018). Higher organic content, resulting in peatlands, is also typical in cold environments in local depressions and flatter areas (Woo et al. 2006). This means that even though there is no information in the input data of EHT concerning the location peatlands, it is still able to locate wetter areas based on TWI values, although the moisture content is considerably lower than in reality or in the other models.

However, while the large scale recognition of wetter areas succeeds in the models, there are large discrepancies inside the areas between models (figures 22 and 25). While SpaFHy and JSBACH show spatially very similar results, their time series are rather different. This is likely due to the different representation of the spatial variation in soil properties in the two models. In JSBACH, soil properties are explicitly defined for each grid cell separately, allowing for more variation in the properties while in SpaFHy they're linked to different soil classes, creating much sharper borders between classes. This leads to most peatland areas in SpaFHy being showing much wetter conditions than in JSBACH where most cells in 50 m resolution contain characteristics of both peatlands and mineral soils. Neither model is also able to fully catch the spatial variation in the measurements (figure 25b and table 22). On the other hand, while EHT clearly underestimates soil moisture in these areas, its results correlate more with the measurements, indicating that topographical variation, which is an important cause for spatial variation in EHT, influences smaller scale soil moisture variation also in these areas (Woo et al. 2006). These results are in line with previous studies showing the difficulty in modeling wetlands and their spatio-temporal variability (Bohn et al. 2015; Z. Zhang et al. 2016).

8.2 Results in vegetated areas

Vegetated areas over mineral soils are more in line with the measurements when compared to the other two land cover classes (figure 23 and table 7). JSBACH and SpaFHy show quite similar results despite the fact that their representation of vegetation in the input data varies greatly. This might mean that neither model is particularly good at representing the processes related to the relationship between vegetation and soil moisture or that the input data is insufficient in both models. The higher r^2 values could be related to better representation of vegetated areas or it could be related to the fact that it is the largest area, having also the largest number of measurements. In EHT, the r^2 value is considerably lower than in peatland areas and in sparsely vegetated areas, in spite of it being the largest land cover class, which might indicate that there are processes or characteristics related to vegetation which it is not able to capture.

The increase in soil moisture towards end of summer, visible in the measurements in table 4 as well as figures 27 and 29, is not as clearly visible in any of the model results. The increase in measurements is likely due to July having the most precipitation during a typical year (figure 6). While there is some slight increase in the lowest soil moisture values in JSBACH and SpaFHy, it's not nearly as clear as in the measurements. This might be a result of the lack of spatial variation in these models which drowns out the magnitude of the increase or it could be due to other features not as clearly visible. Further information is nevertheless required to understand the precise cause for this discrepancy between models and results.

8.3 Results in sparsely vegetated areas

The sparsely vegetated areas show many patterns that are similar to vegetated areas but also clear differences. JSBACH and SpaFHy show similar, almost identical results, showing hardly any spatial variation and little temporal variation (figures 18 and 28). This lack of variation is not in line with the measurements which show considerably drier plots that JSBACH and SpaFHy miss completely (table 4) but also show a much larger range in spatial variation (figure 24). This suggests that there is spatial variation that the models are not able to catch. Kemppinen et al. (2018) and Roux et al. (2013) have shown that there is considerable fine scale variation in soil moisture in high latitudes. The lack of variation could result from too coarse input data, particularly concerning soil properties and its fine scale variation. The problem might also lie in the models' capability to simulate soil moisture processes acting on very fine spatial scales driven by fine scale topographical variation in cold environments. Interestingly, EHT shows more spatial variation in the drier areas as well as better agreement with the measurements in the sparsely vegetated areas (table 8).

8.4 Discussion of uncertainties related to modelling

In any model, there are many different sources of uncertainty that stem from different aspects of modelling and should be identified in order to properly evaluate results and improve the models or hypotheses, depending on the goal (Refsgaard et al. 2006; Montanari 2007). The sources of uncertainty can be divided into three groups - model related, data related and user related (figure 30). The first two are discussed in this section while the third is included in section 9.3.

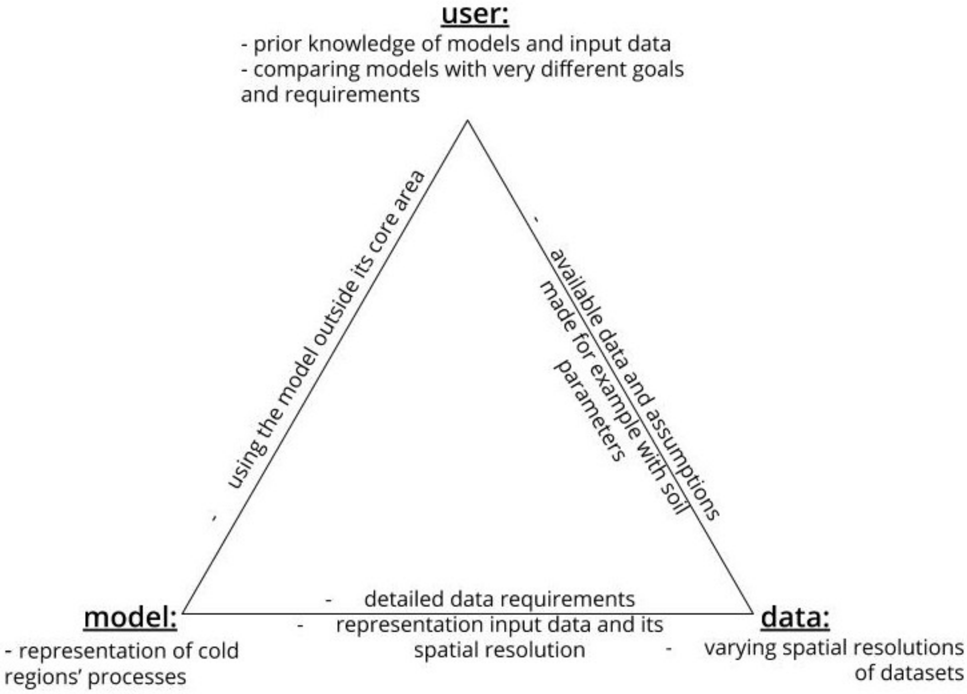


Figure 30: Sources of uncertainty in (process-) modeling. The end-user, model developers and input data all bring uncertainties to the results as well as their interactions with the other sources of uncertainty. The figure shows some examples of the uncertainties related to each aspect in this study but is in no way a comprehensive description.

8.4.1 Uncertainty related to the data

Hydrological process models tend to require spatially and temporally detailed input data that can be difficult to obtain (K. J. Beven 2001; Wood et al. 2011). The spatial and temporal resolution of the available data is often insufficient in capturing fine scale details in the environmental variables. In this study, the resolution of for example global radiation and the meteorological data used for EHT were rather coarse (10 km and 2°s respectively), resulting most likely in some uncertainty in the model results. Changing the resolution of the data is sometimes necessary to keep different layers in similar resolutions such as with changing the resolution of the input layers in SpaFHy and EHT and further changing the resolution when observing the results. However, decreasing the resolution also means losing a large part of spatial variation. While this makes comparing the models simpler, it also means a loss of more detailed information in these models. Therefore, it can be assumed that the comparisons with measurements could be improved by looking at the finer resolution results.

Certain variables are more difficult to obtain and often all data requirements given by a model cannot be met in sufficient spatial or temporal resolution. This forces the user to make assumptions about suitable parameter values and for example interpolate available data to a different spatial or temporal resolution. In this study, the largest data-related uncertainties are most likely the assumptions made regarding soil properties. Due to the lack of measured soil properties, soil classification had to be made by estimating a suitable soil type in the classification done by Hagemann and Stacke (2015). The uncertainty was decreased by testing different options for glacial till soil and comparing model results with measurements but most likely field measured soil properties from different parts of the study area would increase the accuracy of the simulations.

Another variable group that required assumptions was vegetation whose representation varied greatly between the models (figure 14). JSBACH's vegetation properties were set to the global PFT groups which is a coarse estimation of the vegetation properties in the area. SpaFHy's representation of vegetation only includes forest properties and the input data that was used from the National Forest Inventory lacks accurate representation of tundra vegetation. However, the effect of these assumptions is not very clearly visible in the results, considering that simulations in vegetated areas seem to correlate better with measurements than in other land cover areas. The results are still not particularly good which could in any case indicate that improvement of vegetation properties might improve simulation results. EHT showed the least correlation with measurements in vegetated areas (figure 14), indicating that its description of vegetation properties and processes should be improved.

While TWI is a commonly used variable in determining soil water distribution on cathcment scale, it has been shown to be dependent on the method of estimating the upslope contributing area (Sörensen et al. 2006). Furthermore, the suitable calculation method seems to depend on the catchment, highlighting the geographical nature of hydrology (K. J. Beven 2000). It is difficult to say how much the used calculation method affects results in this study without further comparison of different methods but considering the importance of TWI on especially EHT's results, this should be considered in more detail.

Setting the meteorological variables to be constant over the area is also a large simplification of reality, especially in a topographically varying landscape where for example temperature conditions may change quickly (J. Aalto et al. 2013). Global radiation was set to constant in JSBACH and SpaFHy which overlooks the fact that the study area contains two slopes facing opposite directions which influences received radiation and therefore evapotranspiration. Another variable whose spatial variation may play an important role, especially in topographically varying regions is wind ((Wilson 1959; Mott and Lehning 2010; Liu et al. 2012)). It redistributes snow throughout the landscape and influences evapotranspiration patterns which are likely dismissed when setting wind speed and direction to constant.

Comparing field measurements with gridded simulations is another cause of uncertainty. Point scale measurements describe very local conditions in soil moisture, even though this effect is diminished by having several sample plots in each site. Soil moisture measurements are also taken much closer to the surface compared to the model results which probably means that there is more temporal variation in the measurements than in the models and might explain the lower soil moisture values in measurements. Inspecting the measurements in finer temporal resolution could show better how the simulation results and measurements differ in this aspect.

Uncertainty related to input data is typically considered in model simulations by doing an sensitivity analysis in which the input variables and parameters are changed and their influence on the results is measured. This was out of the scope of this study but would undoubtedly be useful in estimating the importance and fitness of different assumptions.

8.4.2 Uncertainty related to the models

Models bring their own uncertainties to simulations. In process-based models, what processes are included and on what scales, influences strongly the simulation results. The land surface model JSBACH has been developed to simulate global geophysical and geochemical processes. Large scale processes can include simplifications that are justified when catchment scale variation is not included but break down with higher resolutions (Bierkens et al. 2015). A simple example is the point scale generalisation which assumes that there is no interaction between grid cells and for example water doesn't flow from higher areas to lower areas. In simulations that cover continent scale areas, the interactions between grid cells can be ignored but this assumption used in a more fine scale model means that JSBACH misses finer scale spatial variation caused by topography (figure 18).

Description of the soil column varies between the models and might be one cause for discrepancies between models and results. While JSBACH's representation is more detailed and physically-based, it exhibited problems with realistic, shallow soil depths, causing insufficient plant available water and reducing plant functionality to almost zero. This meant that soil depth had to be increased which is likely to influence the results. The high minimum values could partly be explained by the fact that there is more space in the soil for water, meaning that it is more difficult for moisture to get as low as in the measurements.

In cold regions, certain processes should be included in order to have a realistic representation of hydrology. An obvious one is snow accumulation during winter and melting during the spring and summer. JSBACH and SpaFHy both include a representation of snow processes but neither of them describe the effect of wind on redistribution of snow which means that for example nivations are not properly represented in these models. This might be one reason for the small spatial variation in mineral soil areas. EHT on the other hand doesn't include a snow model which might also be one reason for the low soil moisture values and the smaller variation in July (figures 25a, 26 and 28).

While process-based models should at least in theory focus on the theoretical processes and therefore require less calibration of parameters compared to simpler conceptual models, it is difficult, if not impossible, to create a model that wouldn't require some calibration to fit the model to different areas (K. J. Beven 2000; Boyle et al. 2001; Bahremand 2016). In this study this is evident in SpaFHy which has especially been developed to be used in boreal forests and is therefore slightly out of place in the tundra environment. A calibration of the parameters controlling evapotranspiration especially would most likely be beneficial. Currently SpaFHy underestimates vegetation outside peatland areas which might cause the lack of variation in these areas (figures 26 and 28). EHT could also benefit from calibration of ET which might be one reason for the very low soil moisture values.

Another problem related to model structure is in EHT which uses microclima package to estimate evapotranspiration. While this allows the model to be used practically anywhere in the world without the need to look for local meteorological data, it does also cause problems. Microclima downloads the meteorological data from NOAA in 2°resolution which compared to the scope of the study area is very coarse. In addition to the coarse resolution, the proximity of the Arctic Ocean means that the meteorological data might represent conditions over sea rather than over land. This also complicates comparing EHT with the other models as the forcing data apart from precipitation is different. It might cause the considerably lower soil moisture values if the estimated evapotranspiration is too large.

8.5 Comparing the models

Table 9: Overview of the model features relevant for this study. Blue color indicates strengths, red weaknesses (particularly concerning this study) and green features that are difficult to classify to strictly strengths or weaknesses.

JSBACH	**SpaFHy**	**Ecohydrotools**
- coarse global scale model	+ catchment scale model	+ fine resolution catchment scale model
+ detailed representation of various land surface processes	+/- detailed representation of (forest) vegetation processes	+ simulates spatially varying estimates of microclimatic conditions
+/- detailed input data and parameters	+ takes advantage of existing GIS data	+/- many data requirements automated
+ detailed description of soil column	- developed for boreal regions	- no spatial variation of soil propreties
- no spatial distribution	+ spatially distributed	+ spatially distributed
+ used and tested in various studies previously	- focus on specific parts of the hydrological cycle	- under development

The three models chosen for this study represent very different approaches in soil moisture modeling and in hydrological modeling in general (table 9). JSBACH represents perhaps the more traditional type of a process-based model in that its internal structure is complex and it requires detailed input data. On the other hand, it's not spatially distributed as most hydrological process-models are. SpaFHy on the other hand is spatially distributed and represents the large collection of hydrological models that have been developed for a specific purpose and region. While it also requires several input variables, the data requirements have been taken into consideration in model development and take advantage of some of the national datasets freely available in Finland. Finally, Ecohydrotools takes a slightly different approach by aiming for simultaneously fine-scale and global modeling, with an emphasis on microclimatic modeling. It also uses free online databases to avoid too burdensome data requirements, although with more automatization than SpaFHy.

By aiming to answer different questions, the models also consider soil moisture and its variation differently. For example, JSBACH is interested in soil moisture in the entire soil column while SpaFHy and EHT are mainly interested in the root zone soil moisture, and represent water below that in much simpler ways than JSBACH. This distinction between the purposes of the models is important when choosing which model to use for different studies and other purposes. All of them represent the relevant processes and all make simplifications in processes that are less relevant to the purpose of the model. This also means that one way of decreasing modelling uncertainty is to use an ensemble of models instead of one single model. This reduces several of sources of uncertainty described here as well as producing some estimate of the possible variation in the results.

In addition to choosing a model that represents the necessary processes, there are also other things to consider. Depending on the goal of the application, it's useful to consider what is the level of complexity that is required of the model (Guswa et al. 2002). For estimations of catchment scale runoff generation, a simple well-calibrated conceptual model may prove more useful than a complex physically-based model. Adding more complexity also increases the prior knowledge required of the user to interpret the results which might not always be beneficial. With a very complex model, such as JSBACH, understanding the key processes affecting the results is difficult which also makes detecting errors or places for improvement challenging. The detailed data requirements also mean that the user often has to make several simplified assumptions on how to describe the input data which is tedious and challenging.

However, theoretically or conceptually simpler models have their limitations and are not suitable for many tasks such as hypotheses testing which is a fundamental task of many hydrological models. They are also most of the time unsuitable for areas where they haven't been calibrated whereas an uncalibrated process-model with coarsely estimated input data such as JSBACH is still able to catch certain relevant patterns and features.

8.6 Further research

Properly used process-based models provide interesting opportunities to investigate further the role of soil moisture in cold regions. One clear study area is the opportunity to simulate future conditions by forcing the models with simulated climate data based on different climate trajectories. Soil moisture has been shown to be an important driver of fine scale vegetation patterns in cold regions and models might be able to enlighten how this relationship might change in future and how it may influence future biogeographical patterns as well as terrestrial carbon balance (Roux et al. 2013).

Another possibility which is strongly linked to understanding soil moisture's role in species distribution is fine scale temporal and spatial modeling. While the models tested here produced daily output of soil moisture, they can also be set to simulate hourly variation and their spatial resolution can also be increased, depending on the available input data and computational limitations. This could provide more information about the fine scale interactions of soil moisture and other environmental variables.

Finally, as has been discussed previously, soil moisture especially is highly local in that the important processes and patterns vary depending on the geographical location. Since none of these models is specifically created for cold environments, it would be helpful to study further which variables in the models influence the fine-scale variation of soil moisture and whether these results are in line with previous research that has investigated soil moisture drivers, such as Kemppinen (2016) and J. Aalto et al. (2013). This could provide useful information on how to better model soil moisture in cold regions and what processes may be currently underestimated.

9 Conclusions

There are many different approaches to simulating soil moisture and its temporal and spatial variation. Each of the models used here, JSBACH, SpaFHy and Ecohydrotools, showed clear similarities as well as clear differences in their results when compared with each other and with measured soil moisture data. The spatial variation of JSBACH and SpaFHy was mostly driven by the variation in soil properties whereas EHT was clearly controlled by the topographic wetness index, even in drier areas where soil properties were similar to the ones used by JSBACH and SpaFHy. Temporal variation depended considerably on the land cover type with peatlands showing most variation between models. In mineral soils, JSBACH and SpaFHy showed relatively similar results while EHT had quite different results. All in all, the model results could be considerably improved with calibration and more spatially detailed and regionally specific input data.

Hydrological process models have potential to illuminate various processes controlling soil moisture variation and how it will change in the future, as well as the importance of soil moisture to other environmental variables such as vegetation patterns. This is particularly relevant in cold regions, where these processes are still not fully understood. However, in order to choose an appropriate model and use it properly, it is important to consider how the model fits the goal of the research question, is there sufficient data available for the model and what are the uncertainties related to the specific model and how will they influence the results. If these questions are adequately considered, process models can be useful tools in environmental research.

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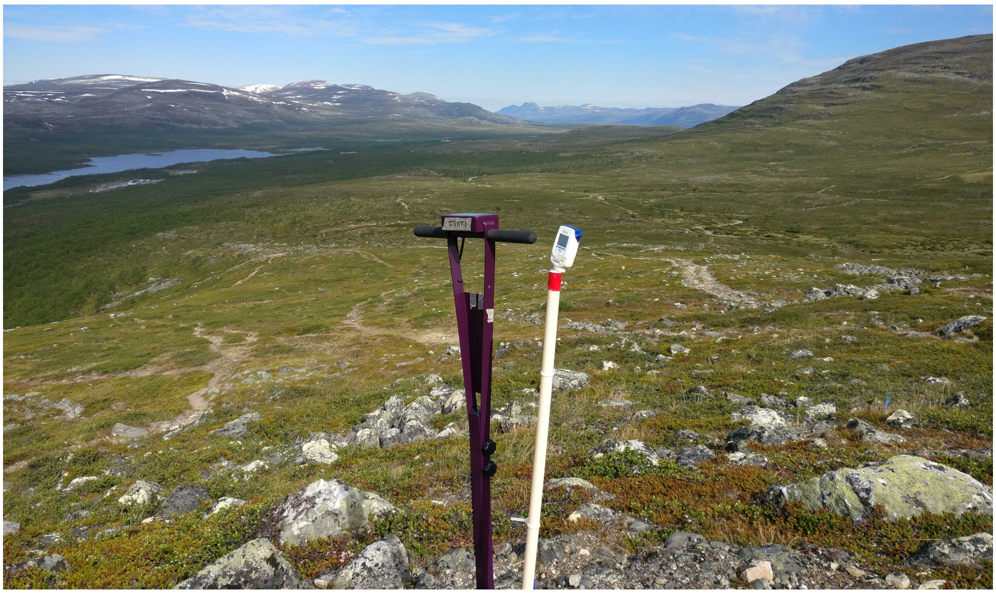

Figure 31: View from the lower hills of mount Saana. On the right is the westside of mount Jehkas and in the middle the valley where the study area is mostly located. In the foreground are devices used to measure soil moisture (on the left) and soil temperature (on the right).

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