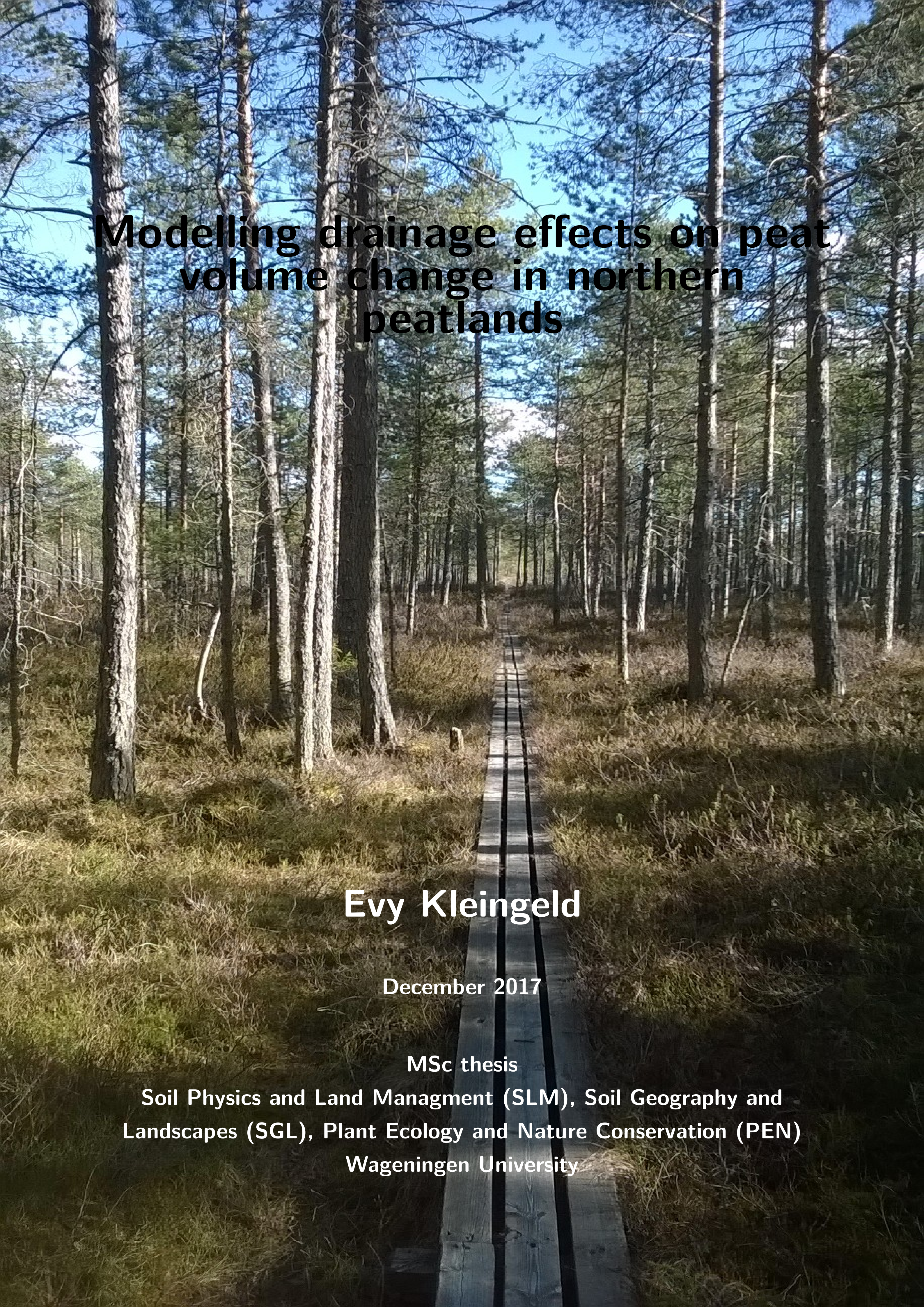

Modelling drainage effects on peat volume change in northern peatlands

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MSc thesis

Soil Physics and Land Managment (SLM), Soil Geography and Landscapes (SGL), Plant Ecology and Nature Conservation (PEN)
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Abstract

Peatlands cover less than 3% of the surface area, but store almost one third of the global pool of soil carbon. To predict the behaviour of (and carbon storage in) northern peatlands under changing conditions (land use and climate), detailed knowledge is required about the processes and feedbacks occurring in these peatlands. The water table is a key factor in controlling many ecohydrological feedbacks within peatlands. Models can help to predict peatland behaviour, however model complexity needed to adequately simulate peatland behaviour under changing conditions is yet unknown.

In this study, data was collected from two different types of peatlands with a contrasting influence of lateral flow (fen and bog) and different hydrological treatments (undrained, recently drained, longterm drained and natural deep groundwater level) for peat volume change, groundwater levels and volumetric water content. Peat volume change was analysed in order to see differences in processes occurring at these different sites and model simulations were run to investigate the model performance for the different sites. The model was extended with lateral flow and it was tested if the increased model complexity significantly improved model performance.

Results indicated a higher peat volume change for the undrained and natural bog sites compared to its fen's equivalents. All drained sites showed larger peat volume change than undrained sites, possibly due to higher groundwater level fluctuations and an increase in specific storage. The increase in specific storage was unexpected, but possibly caused by an increased presence of methane. Moreover, a decrease in total storativity was found for drained sites, likely due to increased compaction of drained peat. Lateral flow was higher for the undrained sites compared to the recently drained sites. The used model is not yet complex enough to sufficiently capture these different types (fen and bog) and treatments (undrained and recently drained). However, lateral flow significantly improved model performances for the fen sites.

The impact of these results on the hydrological self-regulation of peatlands is twofold. As increased GWL fluctuations influence the hydrological self-regulation in a negative way, but an increase in specific storage is positive for the hydrological self-regulation. The net balance between these two processes is yet unknown.

keywords: northern peatlands, peat volume change, hydrology, drainage, model complexity, climate change

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1 | Introduction

Peatlands are wetlands with a peat layer consisting of at least of 30% dead organic matter and with a minimal depth of 30 centimetres (Batzer and Baldwin, 2012). These ecosystems occupy 2.6% of the total land surface (Joosten and Clarke, 2002). Northern peatlands are peatlands located above a latitude of 45°N, and account for 82% of the total global peatland area (Nijp, 2015). The diversity within peatlands is very large. The two main peatland types are determined by their hydrological and nutrient regime and are called bogs and fens (Batzer and Baldwin, 2012). A bog is only precipitation fed, consequently low in nutrient availability, and usually located a bit higher in the landscape (Rydin and Jeglum, 2013). A fen is precipitation- and groundwater fed, and therefore higher in nutrient availability and usually located lower in the landscape (Rydin and Jeglum, 2013).

Peatlands are very important ecosystems as they provide important services such as carbon storage, biodiversity, and freshwater storage (Waddington et al., 2015). Peatlands store around one third of the total world pool of soil carbon (Gorham 1991; Joosten and Clarke 2002; Strack 2008), and if all this carbon would be released to the atmosphere the current CO_2 level in the atmosphere would be doubled (Dlugokencky and Tans, 2017); peatlands provide habitat to a wide range of species and species at risk (Joosten and Clarke, 2002); and they store 10% of the global freshwater resources (Joosten and Clarke, 2002). To be able to predict the resistance and resilience of peatlands towards changing conditions it is essential to understand the hydrological feedbacks taking place in peatlands (Waddington et al., 2015). For the end of the 21^{th} century more extreme precipitation events with longer dry periods in between are predicted (O'Gorman and Schneider, 2009). These climate change predictions, or drainage due to land use changes, may cause the water table of peatlands to go deeper (Ise et al. 2008; McCarthy 2014; Roulet et al. 1992; Whittington and Price 2006).

The water table depth is one of the key factors controlling the accumulation of carbon in the soil (Gong et al. 2012; Hilbert et al. 2000; Moore et al. 1998; Waddington et al. 2015) and plays a central role in many ecohydrological feedbacks (e.g. transmissivity/ hydraulic conductivity feedback, peat decomposition feedback, specific yield feedback and moss productivity feedback). An overview of these feedbacks is presented by Waddington et al. (2015). It is essential to understand these hydrological, ecological, and biogeochemical feedbacks related to the water depth to be able to predict the behaviour of peatlands for changing conditions (Whittington and Price, 2006). Thereby accurate models are needed to simulate future scenario's with respect to changing climate and land use. Multiple peatland models already exist, varying in their objectives and model complexity (Nijp et al., 2017). Examples are presented by Baird et al. (2012), Binet et al. (2013), Frolking et al. (2010), Gong et al. (2013), Granberg et al. (1999), Kennedy and Price (2005), Price and Whittington (2010), Roulet et al. (1992), Walter et al. (2001) and Yurova et al. (2007). The model complexity needed to predict future peatland behaviour is yet unknown, but directly coupled to the understanding of feedbacks. Models that do not include certain feedbacks can provide a biased prediction, while models with (almost) all feedbacks included can increase fieldwork costs even if these parameters do not add to the model performance (Nijp et al., 2017). The model of Nijp et al. (2017) systematically investigated if moss water storage and peat volume change could significantly improve model performance towards future climate change predictions for moss drought predictions, as these two processes (moss water storage and peat volume change) are central processes in the hydrological self-regulation of northern peatlands. That study showed that including both feedbacks improves the model performance. Furthermore Nijp et al. (2017) stressed that it seems that lateral flow is essential to adequately simulate groundwater dynamics in peatland models.

A very important characteristic of peatlands is the ability of the surface to swell in wet periods and shrink during dry periods (Almendinger et al. 1986; Kellner and Halldin 2002; Kennedy and Price 2005; Price 2003; Price and Schlotzhauer 1999). This process is called peat volume change. Peat volume change is important in the hydrological self-regulation of peatlands, as it reduces the amplitude of water table fluctuations which guarantees a constant water supply to the living moss layer (Dommain et al., 2010). This change of surface elevation in peat soils is due to primary or normal consolidation, secondary compression, shrinkage, and oxidation. The first three processes define reversible peat volume change whereas oxidation is irreversible. Primary consolidation explains 90% of the total peat volume change in natural peatlands (Kennedy and Price, 2005). Primary consolidation is due to changes in effective stress, which in turn are caused by groundwater level fluctuations during the growing season. As overlying peat dries, it puts pressure on the peat fibers in the peat matrix thereby increasing the effective stress, and causing the peat matrix to compress (Terzaghi 1943; Kennedy and Price 2005; Nijp 2015). Secondary compression occurs after primary consolidation, and is due to the process of re-arrangement of the saturated peat matrix into a more stable configuration (Kennedy and Price, 2005). This happens under a changing load from the fluid (groundwater) on the soil structure (Kennedy and Price, 2005). Shrinkage occurs in the unsaturated zone due to contraction of peat layers because of negative pore water pressure as peat dries (Kennedy and Price, 2005).

Drainage, for example due to climate or land use changes, lowers the groundwater level and therefore the thickness of the unsaturated zone increases and the thickness of the saturated zone decreases and the peat decomposition increases. Therefore the primary consolidation, secondary compression and shrinkage will work towards a new equilibrium and oxidation of the peat will increase. Moreover, this shift in peat volume change capacity is directly correlated to other hydrological properties. For example, the hydraulic conductivity, as drained peatlands have a lower hydraulic conductivity due to increased compression in the peat matrix (Price 2003; Waddington et al. 2010). This is also a hydrological self-regulation feedback to prevent further water losses (Price, 2003).

In terms of hydrology, the large compressibility of peat soils translates into a difference in the ratio of the two components which determine the total water storage (total storativity). This is an important characteristic in peatland hydrology. In incompressible soils the total aquifer storativity only consists of the specific yield, which is the water storage change due to groundwater level fluctuations. In peatlands, however, the change in total storativity also consists of an elastic storativity or the vertical specific storage component (specific storage). This specific storage is related to the elastic properties of the peat material itself, dependent on the total depth of the peat layer. Price and Schlotzhauer (1999) showed that this specific storage component should be included in the total storativity and water balance of peatlands as this term can even be higher than the specific yield. Especially in peatlands with a relatively high compressibility (e.g. thick and poorly decomposed peat layers) the specific storage should be taken into account.

An important knowledge gap in peatland sciences is the effect of hydrological feedbacks on ecohydrological behaviour of peatlands under changing conditions. One of these changes can be a water table drawdown due to climate change and/or land use change. In this study, an analysis of peat volume change capacity for drained and undrained conditions will be executed for both a fen and a bog, as these peatlands are contrasting in the influence of lateral flow. The model of Nijp et al. (2017) will be tested on its performance for these different peatland types and hydrological treatments. The model will be expanded by implementing lateral flow to make the model more process based. It will be analysed if this extended model significantly improves the model performance. This leads to the following research questions:

1. **What is the difference in peat volume change capacity for different drainage treatments and types of peatlands in northern peatlands?**
   Bogs are expected to have a higher peat volume change capacity as the urge for bogs to swell and shrink is higher due to lower amounts of groundwater flow they receive and the bog plant species have to cope with higher groundwater level fluctuations. Peat volume change is expected to decrease for increasing drainage intensity, as primary consolidation is expected to decrease due to a decrease in saturated zone depth. Specific storage is expected to decrease for increasing drainage intensity as well, due to the increased decomposition and compression of drained peat the compressibility and thus specific storage is expected to decrease.

2. **Which mechanisms underlie these differences in drainage effects for different treatments and types of peatlands?**
   It is expected that lateral flow differs for undrained and drained sites and is one of the underlying mechanisms.

   a) *Can the peat volume change be modelled with the model of Nijp et al. (2017) and what is the hydrological model performance for the different treatments and types?*
   An undrained bog is expected to perform best, as the model was developed for a natural bog.

   b) *Does inclusion of lateral flow significantly improve the model performance for different treatments and types?*
   The inclusion of lateral flow is predicted to mainly increase the performance of fen sites, as lateral flow is a more important component of the water balance for a fen than for a bog. The highest improvement is expected for an undrained fen as hydraulic conductivity and lateral flow is theoretically higher in undrained sites.

2 | Method

2.1 Site description

The research sites were chosen as three different hydrological treatments (undrained, recently drained, longterm drained) were present due to drainage in the past and a natural deep groundwater level site was present for a bog and a fen (Lakkasuo) and a natural reference bog and fen located nearby (Siikaneva). Both field work sites are located in Finland, which means they are northern peatlands. Furthermore the needed infrastructure (boardwalks and field station) and meteorological measurements are available. The sites are located north-east of Tampere (Figure 2.1). The meteorological station at Hyytiälä is an official FMI station (Finnish Meteorological Station), located in between Lakkasuo and Siikaneva at the Forestry Field Station from the Department of Forest Sciences from the University of Helsinki.

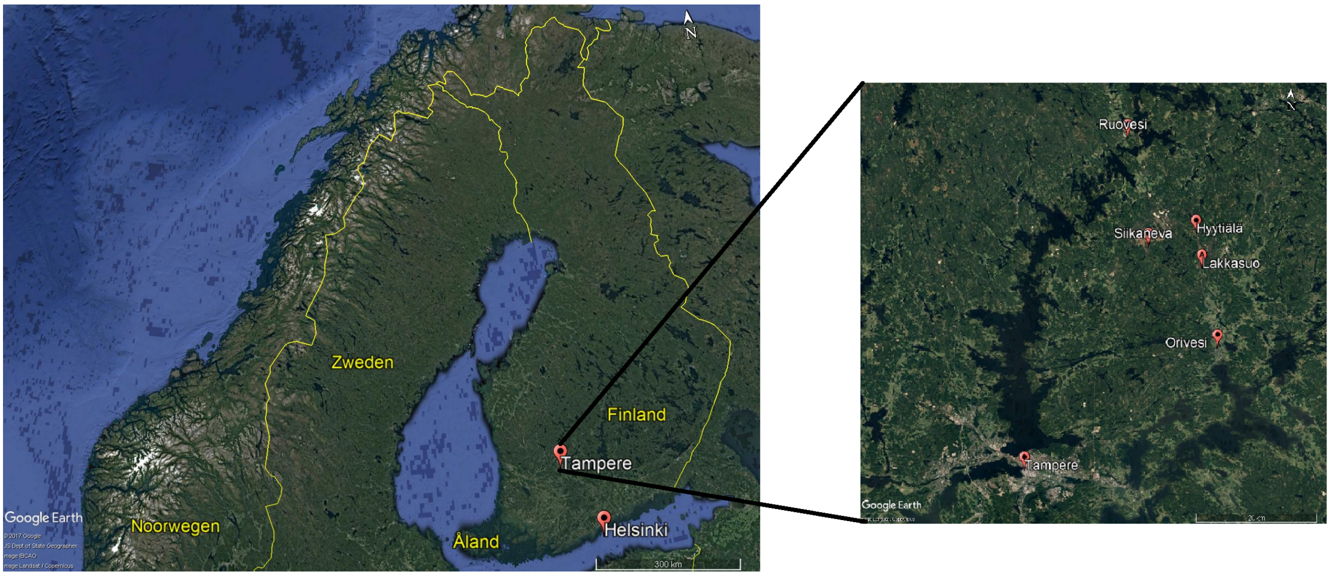

Figure 2.1: Map of Finland, at the right side zoomed in on the fieldwork area, with the peatlands Lakkasuo and Siikaneva and meteorological station at Hyytiälä. Tampere, Orivesi and Ruovesi are for the topographical context, source: Google Earth, 2017.

2.1.1 Lakkasuo

One of the research sites was Lakkasuo (61°48'N, 24°19'E, 150 m ASL) in southern Finland, located 18 km above Orivesi. Lakkasuo is an eccentric raised bog (slope in one direction, located on valley-side, upslope end abuts in mineral soil, (Davis and Anderson, 1991)), with an annual precipitation of 709 mm, of which one third is snow. The average temperature for January and July are respectively -8.9°C and 15.3°C (weather station Juupajoki for the period of 1961-1990). This site description is based on a field guide about Lakkasuo from Laine et al. (2004); more details can be found in this field guide.

The development of the Lakkasuo peatland, started with the retreat of glaciers and coverage of the present peatland area by the Yoldia Sea. Wave-action moved fine particles from the Vatiharju esker to accumulate on top of the coarse ground moraine deposits at the edges of the esker. When these parts of land became higher than sea level these nutrient-poor sandy soils were covered by forests. Thereafter the area has been covered by different types of tree species (e.g. birches, Scots pine, alder, oak) for a long time (ca. 10000 to 7500 BC). The peatland only started to develop in the more humid Atlantic period (ca. 7500 to 6000 BC). At that time the vegetation was dominated by a mixed oak forest and the Atlantic period ended with the appearance of Norway spruce. Peat started to accumulate through paludification of forest soils and the nutrients decreased as the peat layer grew thicker, initiating a transition to pine peatland vegetation.

Figure 2.2: Left: Map of the Lakkasuo peatland and surroundings, the pink rectangle surrounds the Lakkasuo peatland and the Vatiharju/ Konilamminkangas esker on the left side with the main road on top (red), the yellow dots are old sampling plots from a different research, source: Laine et al. (2004). Right: Colour-infrared airphoto of the Lakkasuo peatland with the water inflow locations from the Vatiharju/ Konilamminkangas esker; Pv1, Pv2, Pv3 and Spring (blue arrows), again with the old sampling plots (white squares, 1-24), source: Laine et al. (2004).

Lakkasuo is classified as an eccentric bog, as the central part of the peatland (56% of the total area) is ombrotrophic. However, the remainder is minerotrophic (oligotrophic and mesotrophic) receiving their water and nutrients from the surrounding catchment area, which is mainly from the Vatiharju/ Konilamminkangas esker. The mean depth of the peat layer is 1.8 m. Most of the peat thickness is varying between 1 and 2 meter deep, at the southern side a layer of 3 m deep peat can be found.

The hydrogeology and eskers surrounding the Lakkasuo peatland influence the water flow and the water quality of the Lakkasuo peatland. The esker on the western side of the Lakkasuo peatland is the Vatiharju/ Konilamminkangas (Figure 2.2, left). The eskers act as 'buckets' due to the high permeability in the centre of the eskers and the lower permeability at the edges of the eskers. At some locations the sides of the buckets are lower than in other parts and the bucket flows over. This happens at four locations in the western side of the Vatiharju/ Konilamminkangas esker and the mineral rich water flows into the Lakkasuo peatland (Figure 2.2, right) the dominant flow direction in the peatland is eastwards. The ombrotrophic part in the south of the peatland could develop because the surrounding soils were less permeable and more fine grained. Therefore these soils have decreased the groundwater flow to the peatland and created favourable conditions for paludification. This resulted in a peatland in which the northern part is minerotrophic with vegetation like sedges and woody peat, especially at the water inlets from the eskers. The central southern part is ombrotrophic and Sphagnum dominated.

2.1.2 Siikaneva

The other research site is the Siikaneva peatland. The climatological circumstances at Siikaneva are similar to Lakkasuo as the distance between the two sites is approximately 10 kilometres. This site description is based on an excursion guide from Tolonen et al. (1979).

Siikaneva is a very diverse peatland complex, consisting of eccentric raised bogs and aapa-mire parts (large patterned fens). It is located in southern Finland (61°41'N, 24°06'E, 160 m ASL) within the municipalities of Orivesi and Ruovesi. The total area of Siikaneva is 1560 ha and the peat depth varies between 2 and 6 metres (Mathijssen et al., 2016). This peatland complex is more pristine than other peatlands in this district, since state owned forest was not logged for a long time. Only small parts have been drained for forestry in contrast to the forest drainage in neighbouring peatlands. The Siikaneva peatland complex is a protected nature area.

The Siikaneva peatland developed in a basin which is bordered by hills with till deposits (east and south), and gravel and sand plateaus (north and west). The peatland's hydrology is quite complex due to the varying peat structures like hummock ridges, strings, flarks, bog pools and hollows. The peatland complex has eight different outlets, into various directions. The hydrological complexity is shown in Figure 2.3, which shows among others dominant flow directions, the outlets and dominant peat structures. The bog parts are mainly located in the western and northern part of the peatland on the sandy soils. The aapa-mire or fen sites are mainly located in the southern and south-eastern part in the depressions, receiving their water from the surrounding hilly landscapes.

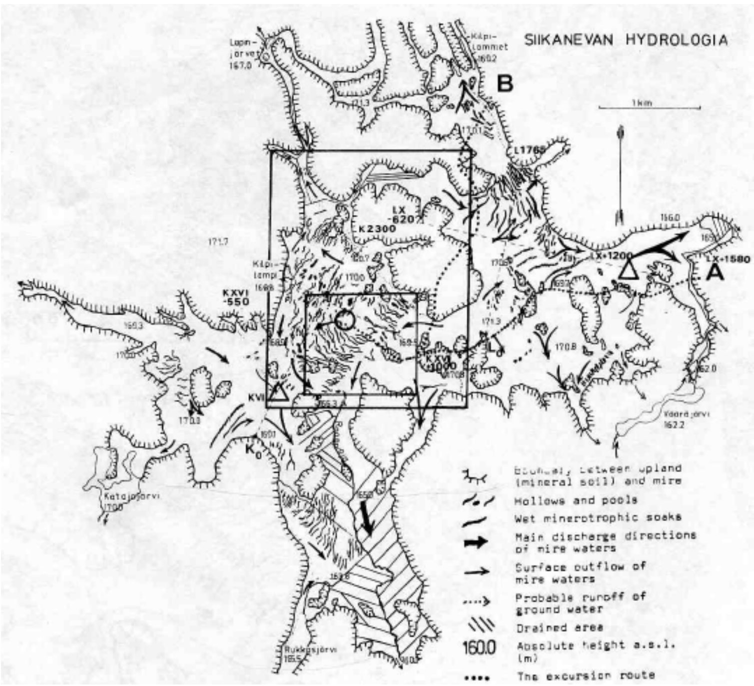

Figure 2.3: Map of the hydrology in Siikaneva, with dominant flow directions, outlets and dominant peat structures, and relics (e.g. transects and sampling points) from a different research, source: Tolonen et al. (1979).

2.1.3 Experimental design

Ten different experimental sites were investigated in this research. Varying in location (Lakkasuo and Siikaneva), peatland type (fen and bog) and hydrological treatment (undrained, recently drained, longterm drained and a natural deep groundwater level site) (Table 2.1). The different hydrological treatments originated from drainage in Lakkasuo. The Lakkasuo peatland has been drained and maintained for forestry in 1961 at the eastern side of the peatland. During that time, the research at Lakkasuo focussed mainly on the potential of forest production capacity on peat-

lands. In recent years, the focus changed towards climate change and the importance of peatlands for the global carbon balance. In 2001/2002 the peatland was drained again in between the natural peatland (west) and the drains for the forest at the eastern side of Lakkasuo. These drains are less deep than the forestry drains. Hereby, three different treatment types for peatlands are present. An extra site are the natural deeper groundwater level fen and bog site. They are located higher and different within the landscape compared to the other sites. For example this oligotrophic fen site is much thicker than the other three sites.
For the purpose of reference measurements in an (more) natural peatland, measurements were performed at Siikaneva, both at a natural bog and fen site.

Table 2.1: Experimental design, all ten measurement sites, their used names and their dominant current vegetation. The left column shows their description (treatment) and the first row shows the peat type. Small and medium spruces indicate that the spruces where smaller than the spruces in the drained for forestry sites.

treatment/ peat type:	oligotrophic fen	ombrotrophic
natural/undrained	undrained fen (*Sphagnum* and some small spruces)	undrained bog (*Sphagnum* and some small spruces)
medium drained	recently drained fen (*Sphagnum* and small spruces)	recently drained bog (*Sphagnum* and some small spruces)
drained for forestry	longterm drained fen (spruces)	longterm drained bog (spruces)
natural located higher	natural deeper GWL fen (*Sphagnum* and some spruces)	natural deeper GWL bog (*Sphagnum* and some medium spruces)
reference	Siikaneva fen (*Sphagnum*)	Siikaneva bog (*Sphagnum* and some medium spruces)

2.2 Data collection

The measurement equipment and collected data will be explained in more detail in the following sections. All measurements were done in between a higher elevated area (hummock) and a lower area (hollow), namely a lawn. A representative location was based on the local height and vegetation. All field measurements were executed with a measurement frequency of 15 minutes (except for the slug tests). The fieldwork period took place from 1-5-2017 to 16-6-2017, thereafter the measurements (except for the slug tests) continued until 8-8-2017 without supervision. Ten identical measurement set-ups are installed at different sites (Table 2.1 and Figure 2.4). Peat volume change was measured to analyse the difference in peat volume change capacity for the different sites. Groundwater levels were used as explanatory variable for the changes in peat volume change capacity. Peat volume change and groundwater level were needed to calculate the specific storage. Peat volume change, groundwater levels and volumetric water content were needed for the modelling study. Hydraulic conductivity and water level in the ditches were measured for the extended model version, to simulate lateral flow.

2.2.1 Peat volume change

A fixed reference frame was installed into the mineral soil underlying the peat. The frame consists of two 1 m wide wooden planks at each side of the tubes in which a magnetostrictive position sensor (MTS Linear Position Sensor Type CM250AVH2, MTS Sensor Technologie, Lüdenscheid, Germany) was installed. On the peat surface a PVC construction was made with a magnet sensor attached to a PVC tube resting on the peat surface which moves along the rod of the linear position sensor (Nijp et al., 2017). The data from the sensor was transferred to a datalogger (Campbell Scientific CR1000); the volt signal is converted into a position level. The surface level is referenced to the first measured value (8 May, 7:30 UTC). Positive values indicate a highering of the surface level (swell) and negative values indicate a lowering of the surface level (shrink).

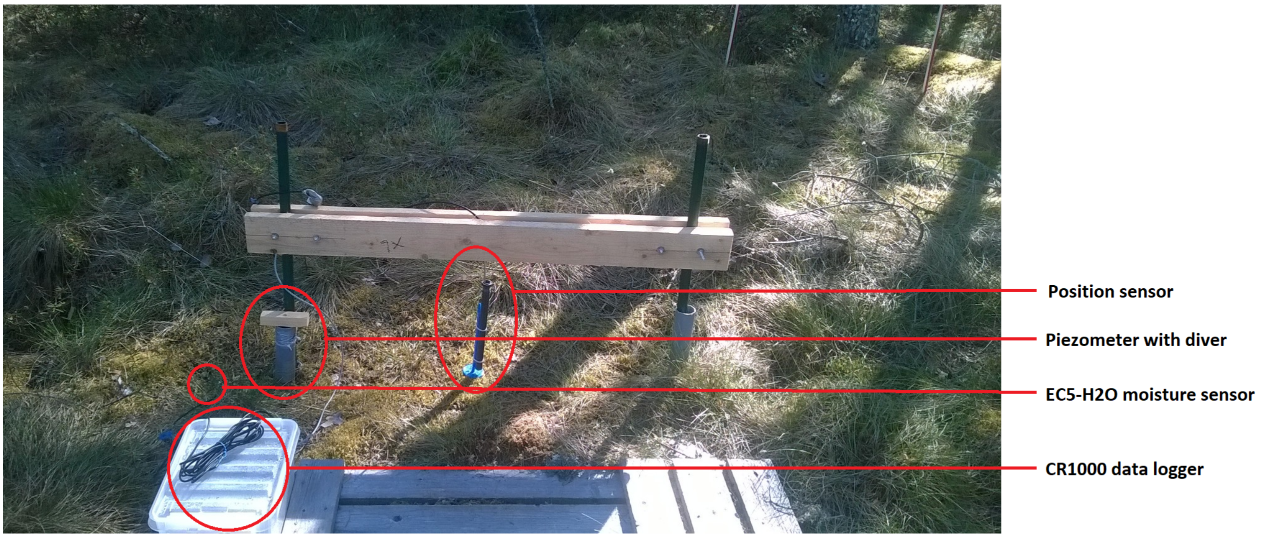

Figure 2.4: One of the measurement sites (Lakkasuo longterm drained bog) with all measurement equipment installed. Position sensor for the peat volume change, piezometer with diver for the groundwater level, EC5-H2O moisture sensor for the volumetric water content and the CR1000 data logger to store the data of the position sensor and the EC5-H2O moisture sensor.

2.2.2 Groundwater level

The depth of the absolute groundwater level, relative to the local coordinate system, was measured with the help of perforated tubes (piezometers). These piezometers were placed into the peat, attached to one of the tubes of the peat volume change reference frame. Divers (Van Essen Instruments and Schlumberger Water Services) were placed in these piezometers to measure the pressure difference. To calculate the water column, the air pressure is subtracted from the total pressure of the diver and this pressure is converted to a water column [m] above the diver (WC). The air pressure is measured with a barodiver in the bog part of the Lakkasuo peatland.

$$WC = 9806.5 \cdot \frac{P_{diver} - P_{baro}}{\rho \cdot g} \tag{2.1}$$

In which ρ is the density of water [kg/m^3], g the gravity [m/s^2] and P_{diver} and P_{baro} the pressure levels [hPa].To calculate the absolute groundwater level (GWL), the water column is referenced to an absolute reference level, as follows:

$$GWL = depth_{peat} - (L_{cable} - L_{piezometer}) + WC \tag{2.2}$$

In which $depth_{peat}$ is the depth of the peat layer [m], L_{cable} is the length of the cable from the diver [m], $L_{piezometer}$ is the length of the piezometer above the surface and WC is the water column above the diver [m]. Water levels were also measured in the ditches next to the undrained and recently drained sites in Lakkasuo according to the same method described above, to obtain a head gradient for the lateral flow. To obtain the head gradient the relative positions of the different measurement locations were also required (height of the piezometer on the site and the height of the piezometer in the ditch). Therefore, the relative positions of the different piezometers within the Lakkasuo bog and fen were determined with a local coordinate system measured with a total station (Nikon). This relative coordinate system was referenced to a general coordinate system with a dGPS (Trimble GEO 7X handheld).

2.2.3 Volumetric water content

The volumetric water content (VWC) of the living moss layer was measured with EC5-H_2O moisture sensors (Decagon Devices, Pullman, USA). These sensors were installed as presented in Cobos (2015) at 5 cm below the surface and sample a volume of 240 mL. The output of the sensor is in voltage and transferred to the data loggers (Campbell

Scientific CR1000), and converted into VWC [m3 H_2O / m3 *Sphagnum*] according to Equation 2.3 in which EC_5 is the measured value by the EC5-$H_2$0 moisture sensor in mV (Nijp et al., 2014). This equation is species specific and in this research the equation for *Sphagnum balticum* was used, as this was the dominant species present at the measurement locations. Volumetric water content was measured next to the peat volume change measurement on a representative location, but not too close to prevent disturbance.

$$VWC = 1 - e^{-(\frac{EC_5 - 244.5}{296.1})^{1.930}} \tag{2.3}$$

2.2.4 Hydraulic conductivity

Saturated hydraulic conductivity (K_{sat}) measurements were needed to enable simulations of lateral flow. This was done by performing in-situ slug tests. A volume of water (0.10 L) was poured into a groundwater well creating a head difference. The groundwater well had a filter of 10 cm length, and due to the created head difference the water flowed through these holes into the peat. By measuring the water level over time and analysing the data the saturated hydraulic conductivity at a specific depth was estimated. These slug test were executed once per plot to limit the disturbance and at various depths only at the undrained and recently drained sites in Lakkasuo. The measurement depths were selected based on theory (K_{sat} decreases over depth (Päivänen et al., 1973)) and practical reasons (time, tube and diver availability, and tube length) (Table 2.2). The tube diameter was 5 cm. Measurements were done on a representative location neighbouring the peat volume change measurements but with at least 1 meter distance in between to prevent disturbance of the peat volume change measurements.

Table 2.2: Slug tests measurement depths, measured relative to the surface level [cm].

fen		bog	
undrained	recently drained	undrained	recently drained
-20	-40	-10	-20
-40	-60	-30	-40
-60	-100	-50	-60
-90	-	-90	-80
-110	-	-190	-

2.3 Data analysis

2.3.1 Peat volume change

To analyse peat volume change, one dry and one wet period were chosen to compare behaviour between swelling and shrinking conditions, and summarize differences in peat volume change magnitude among sites. The shrinking (dry) period was from 13-5-2017 to 16-5-2017 and the swelling (wet) 8-6-2017 to 9-6-2017 period (a rain event). For these periods the ranges of swell and shrink were analysed. These periods have the same order of precipitation excess (8.2 mm) and evapotranspiration deficit (7.6 mm).

2.3.2 Specific storage

The total storativity of an aquifer (S_t, [-]) consist of the specific yield (S_y, [-]) and the specific storage(S_s, [-]) (Equation 2.4). The total storativity indicates how much water is released form storage per unit surface area of the aquifer per unit decline in hydraulic head. Specific storage is the elastic storage component of the total storativity, in other words the component of the total storativity that can be assigned to the compressibility of the peat.

$$S_t = S_y + S_e = S_y + S_s \cdot depth \tag{2.4}$$

To calculate the specific storage Equation 2.5 was used, in which PVC is the peat volume change [cm], GWL the groundwater level [cm] and peat_depth the depth of the peat layer up to the mineral soil [cm]. Hysteresis loop occurred due to the dependency of the historical state of GWL and PVC on each other and were visible as a result of the dense data availability (15 minutes). To correct for these hysteresis loops, average 12 hourly values for the GWL and PVC were used.

$$S_s \cdot depth_{peat} = \frac{\Delta PVC}{\Delta GWL} \tag{2.5}$$

2.3.3 Hydraulic conductivity

The K_{sat} was calculated according to Bouwer and Rice (1976), based on the Thiem solution (Equation 2.6). The performance of the shapefactor of Bouwer and Rice ($\frac{1}{ln(R_e/r_w)}$) in realistic field situation is limited (van Dijk et al., 2017; Hyder and Butler, 1995); Zlotnik et al. (2010) therefore developed a more general, analytic expression for the Bouwer and Rice shape factor. The Zlotnik shape factor was used in this study as it meets or even exceeds the results obtained by semi-empirical approaches like Bouwer and Rice (1976) (Zlotnik et al., 2010). The Zlotnik shape factor is valid for any filter length, depth, aquifer thickness and anisotropy in hydraulic conductivity (Zlotnik et al., 2010). The only assumption in the Zlotnik shape factor is that specific storage is negligible (van Dijk et al., 2017). This is not valid in peatlands (Almendinger et al., 1986; Price and Schlotzhauer, 1999), but as the aspect ratio (ratio between the filter length and filter radius) used in this study was small the influence was minimal (Hyder and Butler, 1995). The Zlotnik shape factor and the calculations of the K_{sat} were executed with R-software (Nijp, 2015; R Core Team, 2011).

$$Q = 2\pi \cdot K_{sat} \cdot L \cdot \frac{y}{ln(R_e/r_w)} \tag{2.6}$$

In which Q is the flow into the piezometer [m^3/d], K_{sat} is the saturated hydraulic conductivity [m/d], L is the length of the filter (through which water flows into the piezometer) [m], y is the difference between the GWL in and outside the piezometer [m], R_e is the effective radius [m], and r_w is the piezometer radius [m].

The raw pressure data from the slug tests is corrected for air pressure variations and precipitation according to the following formula:

$$P = P_i - P_{air} - \frac{R}{\phi} \tag{2.7}$$

In which P is the corrected diver pressure [hPa], P_i is the initial diver pressure [hPa], P_{air} is the air pressure [hPa], R is precipitation [mm] and ϕ is the porosity of the peat [-] obtained from literature (0.9; Walczak et al. (2002)). Precipitation was obtained from the FMI weather station at Hyytiälä.

2.3.4 Lateral flow

Lateral flow was calculated according to Darcy's Law (Equation 2.8). The dh [m] was obtained by measuring the water level in the ditch next to the plot, and the groundwater level within these plots. This was a valid method as the preferential groundwater flow is eastwards for all sites (see figure 2.2 right). The water level in the ditch was measured with a diver in a piezometer placed in the ditch according to the method of section 2.2.2. The dx [m] was the measured distance between the measurement location of the GWL within the plot and in the ditch, perpendicular to the ditch. The $K_{sat,\ measured}$ [m/d] parameter varies with depth and therefore an integrated K_{sat} value over depth was calculated. Due to the limited amount of measurements all $K_{sat,\ measured}$ measurement for all sites were combined to determine one function which was used for all sites ($K_{sat,\ measured}(x)$), with the peat depth as lower boundary and the GWL as upper boundary, because no lateral flow occurs above the GWL (Equation 2.9, all variables in meters and K_{sat} in meter/day).

$$q = -K_{sat} \cdot \frac{dh}{dx} \tag{2.8}$$

$$K_{sat} = \frac{\int_{depth_{peat}}^{GWL} K_{sat,measured}(x)dx}{depth_{peat}} \tag{2.9}$$

2.4 Modelling

The modelling study was done in order to investigate if different types of peatland and hydrological treatments could be modelled with the current processes included in the model of Nijp et al. (2017), and if lateral flow would increase the model performance for certain peatland types or treatments. In this modelling study eight different model versions were made. For each model version a separate calibration and validation was executed. Only the undrained and the recently drained fens and bogs were modelled, due to data and time availability. These sites were essential in order to compare different types of peatland (fen and bog) and different hydrological regimes (undrained and recently drained).

2.4.1 Model structure and implementation

The model used in this study is a model developed by Nijp et al. (2017). The model is a vertical column at a single point in space, assumed to be homogeneous over depth with a no flow boundary condition at the bottom of the peat column (impermeable layer). The main structure and fluxes are shown in Figure 2.5. The model version which is used in this research is the M_1V_1 version, indicating that moss water storage and peat volume change are included, as this version turned out to perform best according to Nijp et al. (2017). The models' state variables are Peat Volume (PV), Groundwater Table (GWT) and Volumetric Water Content (VWC).
The model is implemented in the Ventana Simulation Environment (Vensim DSS double precision 5.01c, Ventana Systems Inc., Harvard, USA) using Euler forward as numerical integration scheme. The numerical time step was chosen as the largest time step in which none of the model versions became numerically unstable according to the Courant number ($1 > Cr = q\ \Delta t/\Delta z$), the water balance was closed and no visual differences in simulated state variables occurred. The chosen time step was $6.035 \cdot 10^{-5}$ d^{-1}.

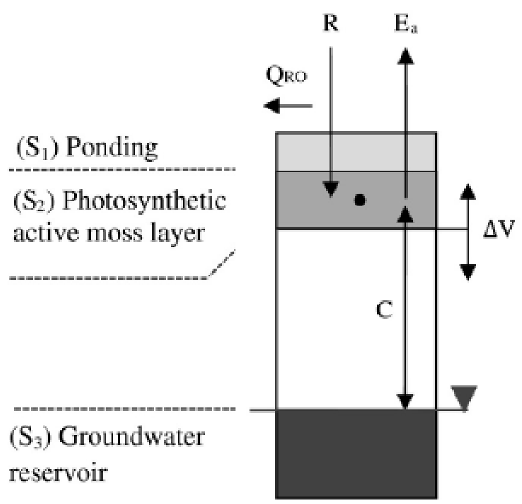

Figure 2.5: Overview of the model structure, adjusted from Nijp et al. (2017). In which R = rainfall [cm/d], E_a = moss evaporation [cm/d], Q_{RO} = runoff [cm/d], C = capillary flux [cm/d] and ΔV = peat volume change [cm].

2.4.2 Model input

Initial and boundary conditions

All three state variables required initial values (Table A.4). Peat depth was given as a measured value, the initial groundwater level was the first measured value and moss water storage was calculated with the water retention function using the groundwater level (Nijp, 2015).

Only rainfall and reference evapotranspiration were needed as forcing data for the model. They determine the model's boundary conditions. Rainfall was obtained from the weather station at Hyytiälä, measured on a hourly basis. Reference evapotranspiration was calculated according to Hargreaves and Samani (1985), see equation 2.10 (Figure A.1).

$$ET_0 = 0.0023 \cdot R_a \cdot T_D^{0.5} \cdot (T_{mean} + 17.8) \tag{2.10}$$

In which ET_0 is the reference evapotranspiration [mm], R_a is the extraterrestrial radiation [mm/d], T_D is the difference between the daily maximum and minimum temperature [°C], T_{mean} is the average daily temperature [°C]. The temperature data was obtained from the weather station at Hyytiälä.

Model parameters

An overview of the model parameters is given in Table A.1. The parameters obtained from the sandbox and ET experiment were executed by Nijp et al. (2017). The same parameters were used for all model versions (different sites and different complexity). The specific storage and the calibrated parameters were the only parameters which changes per model version, specific storage is obtained according to section 2.3.2.

2.4.3 Model calibration and validation

Four parameters which had not been measured were calibrated. In Vensim, this was done according to the payoff definition. The payoff is a single number which expresses the model's descriptive quality. The payoff needed to be defined and is based on the minimum sum of squares implemented according to the Powell method (Powell, 1965). In this modelling study the payoff was defined as a combination of all three state variables with a decreasing weight for the least important state variable (PV>GWT>VWC). To increase the chance of finding a minimum the optimization was run with multiple start values. The calibrated parameters with their boundaries are shown in Table A.2 and the final calibrated values are shown in Table A.3 per model version. The time series are split into a calibration (9-5-2017 to 12-06-2017) and validation (12-06-2017 to 30-07-2017) period. This was done based on data availability (data gaps) and meteorology (dry and wet periods in both time series).

2.4.4 Model extension

The initial model version is extended with lateral flow. Lateral flow is implemented as a flux according Darcy's law (Equation 2.8). Calculations of the different parameters were shown in 2.3.4. K_{sat} and dh vary over time and were therefore imposed as input time series and dx as a new parameter.

2.4.5 Model performance

Model performance was assessed according to the Root Mean Square Error (RMSE) (see Equation 2.11), to compare absolute errors for the different state variables and different model versions. To enable model performance comparison between different state variables the RMSE was normalised, according to formula 2.12. This NRMSE [-] was averaged over the three state variables to get an average or overall NRMSE.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(obs_i - sim_i)^2} \tag{2.11}$$

$$NRMSE = \frac{RMSE}{range(quantile_{97.5\%-2.5\%}(obs_i))}100\% \tag{2.12}$$

A likelihood ratio test was performed to test if the more complex model (model version with lateral flow) performs significantly better than the simpler model version (model version without lateral flow) taken into account the extra number of parameters. If Q exceeds 95% quantile of the reference distribution the simpler model was rejected and the more complex model was adopted (Lewis et al., 2011). If Q becomes negative the likelihood of the simpler model is higher than the likelihood of the more complex model and the more complex model is not beneficial.

$$Q = 2 \cdot (log(Model_{complex}) - log(Model_{simple})) \tag{2.13}$$

3 | Results

3.1 Peat volume change

The change in surface elevation over time clearly shows a response to precipitation events by swelling (increase in surface elevation) and to dry periods by shrinking (decrease in surface elevation) (Figure 3.1 and Figure 3.2). The amount of swelling and shrinkage varies between the sites, the total surface elevation ranged between -34.6 and 6.6 mm. The undrained fen site and reference fen site shows a smaller swelling and shrinking response compared to the undrained and reference bog site, but for the recently and longterm drained sites the fen sites tend to show an increased response for swelling and shrinkage compared to the bog sites (Figure 3.1 and Figure 3.2). Swelling and shrinking response tend to increase for recently and longterm drained sites for both the fen and the bog, with the highest decrease in surface level for the longterm drained sites. Measured time series for the groundwater level and volumetric water content for the corresponding period for all sites can be found in Appendix B (Figure B.1, Figure B.2, Figure B.3 and Figure B.4).

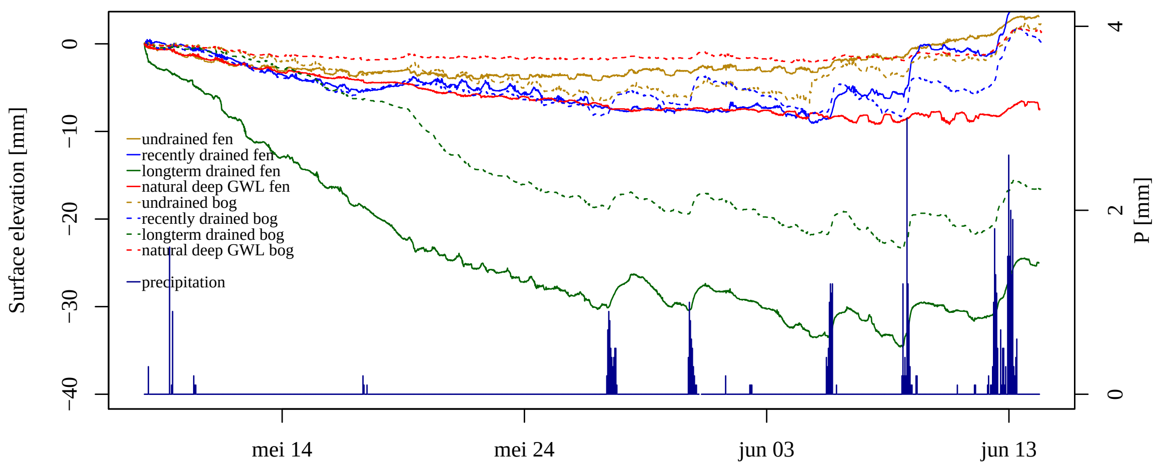

Figure 3.1: Surface elevation and precipitation over time for all Lakkasuo sites, relative to the first measurement.

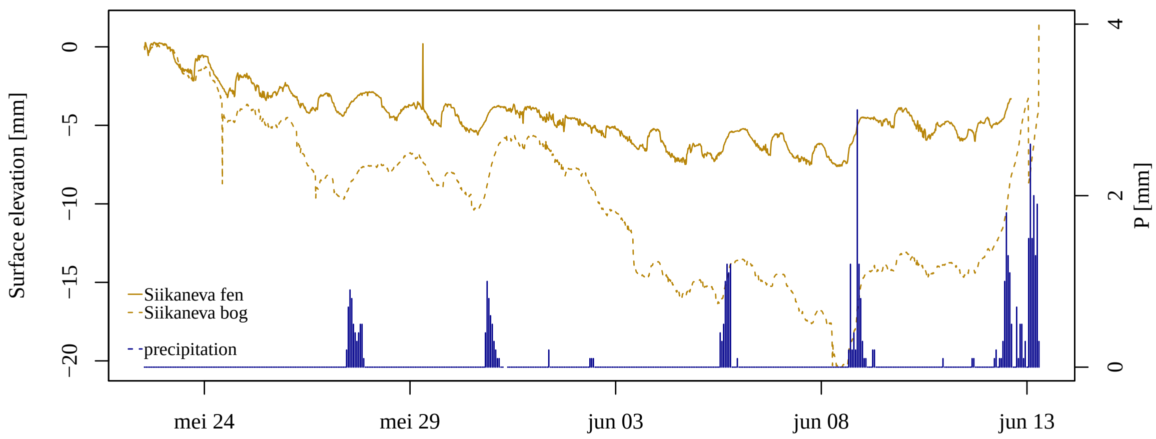

Figure 3.2: Surface elevation and precipitation over time for the Siikaneva sites, relative to the first measurement.

The undrained fen site shows a lower swelling and shrinkage range than the undrained bog site (Figure 3.3). But for increasing drainage intensity (recently and longterm) the swell and shrink range increases more for the fen sites than for the bog sites. This can indicate that for drained sites the bogs become more stable after drainage and the fen sites become more unstable due to drainage. The longterm drained sites show higher shrinkage ranges than the recently drained sites, although the swelling ranges are higher for the recently drained sites. Both natural deep GWL sites show low ranges for swell and shrink. The swelling and shrinkage ranges cannot be compared to each other as the GWL fluctuations in the compared periods are different.

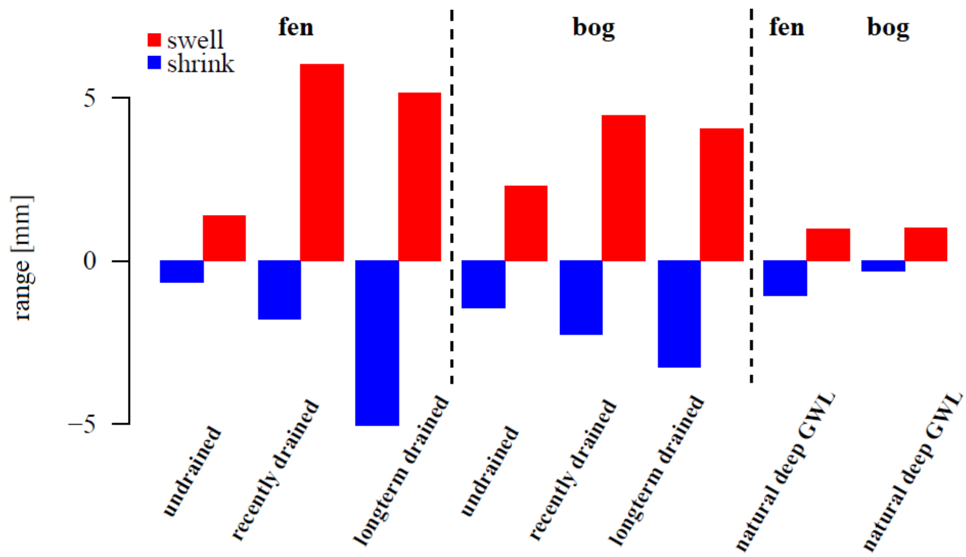

Figure 3.3: Range in surface elevation for a swelling (8-6-2017 to 9-6-2017) and shrinking (13-5-2017 to 16-5-2017) period with the same order of magnitude for precipitation excess (swell) and evapotranspiration deficit (shrink) for all Lakkasuo sites, n=1.

3.2 Lateral flow

The function from $K_{sat,\ measured}$ over depth is Equation 3.1 (all variables in metres; Figure 3.4). This function is used to calculate an integrated K_{sat} over depth (Equation 2.9) and calculate the lateral flow. In general all sites show a decreasing trend in the lateral flux in the beginning (Figure 3.5). Thereafter the lateral flow becomes more pronounced with highs and lows. The undrained sites show the highest lateral flow flux.

$$K_{sat,measured} = 0.0047 \cdot depth^{-3.455} dx \quad (3.1)$$

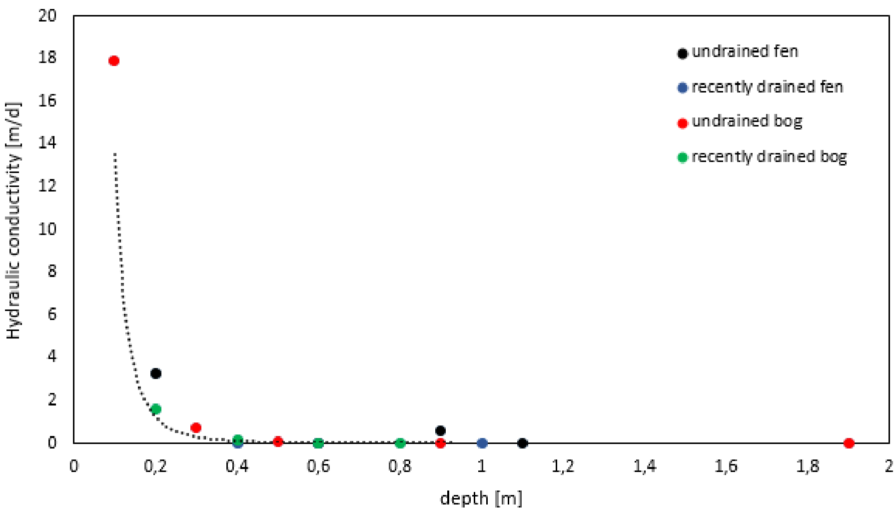

Figure 3.4: K_{sat} values obtained by the in-site slug test for all sites and depths, the R^2=0.76 for the fit of Equation 3.1. The depth is relative to the surface level.

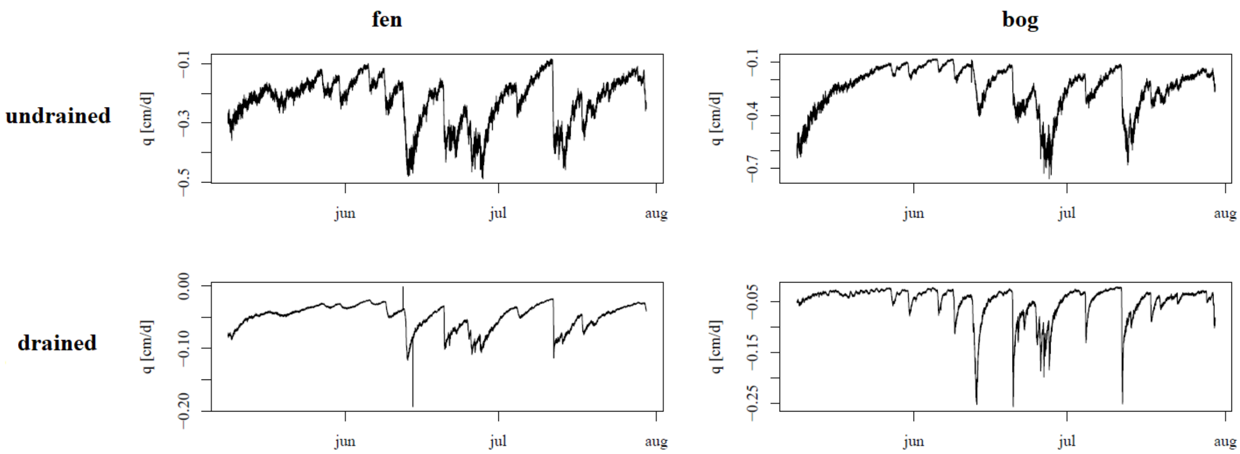

Figure 3.5: One dimensional lateral flow time series from all modelled sites (the undrained and drained fen and bog). Negative values indicate an outflow of groundwater from the sites.

3.3 Modelling

The average model performance (overall NRMSE) for the initial models is best for the recently drained bog, the worst performance is for the undrained bog (Table 3.1). The best absolute performance per state variable (RMSE) are given in bold in Table 3.1.

In terms of NRMSE the model performance increases with the inclusion of lateral flow for all modelled sites except for the recently drained bog (Table 3.1). For the recently drained bog the model fit decreases with lateral flow included, despite that it still has the lowest average NRMSE. According to the NRMSE the undrained bog model performs second best, due to the relatively big decrease in GWT error. The undrained fen model performed second-last and the recently drained fen model performed worst.

For the bog sites only the prediction quality of the GWT significantly increases (Table 3.2). For the fen sites the predictive quality of two state variables significantly increases; for both the PV and for the undrained fen the VWC and for the recently drained fen the GWT (Table 3.2). More generally for the fen sites the prediction for two of the three state variables increases significantly and for the bog sites only one state variable does. In the undrained bog the fit becomes better, although not good enough to justify the increase in model complexity. At the recently drained bog the fit becomes worse with increased model complexity. Model simulation time series for the validation period for all model versions, all sites and all state variables are given in Appendix C (Figure C.1, Figure C.2, Figure C.3 and Figure C.4).

Table 3.1: Model performance for all model versions, in which (N)RMSE is the (Normalised) Root Mean Square Error. The smallest RMSE per state variable and per model version are shown in bold. The PV for the undrained bog only has a data series of n=541, instead of n=4609 for all the other sites and variables, due to an error in the measurement device.

Model version			NRMSE			average NRMSE	RMSE		
			PV	GWT	VWC		PV	GWT	VWC
			[-]	[-]	[-]	[%]	[cm]	[cm]	[m^3/m^3]
Initial	fen	undrained	40.98	81.21	69.25	63.81	**0.21**	6.47	0.23
		recently drained	38.70	46.40	134.00	73.03	0.79	8.78	0.14
	bog	undrained	53.36*	124.63	55.74	77.91	**0.21***	10.11	**0.01**
		recently drained	26.67	49.00	72.35	49.34	0.23	**5.94**	0.08
With lateral flow	fen	undrained	29.95	102.60	47.03	59.86	**0.15**	8.17	0.16
		recently drained	36.15	39.37	136.64	70.72	0.73	7.45	0.14
	bog	undrained	78.57*	105.20	55.93	55.93	0.31*	8.54	**0.01**
		recently drained	55.09	27.61	72.35	51.68	0.48	**3.35**	0.08

Table 3.2: Results of the likelihood ratio test, in which P is the level of significance and the degrees of freedom is one for each model comparison.The simple model is always used as the initial model and the complex model is the model version with lateral flow.

Modelled site	PV		GWT		VWC	
	likelihood ratio	P	likelihood ratio	P	likelihood ratio	P
undrained fen	1981.88	<0.001	-1768.49	1	2154.80	<0.001
recently drained fen	294.46	<0.001	678.11	<0.001	-93.05	1
undrained bog	-1229.48	1	5839.00	<0.001	-4.72	1
recently drained bog	-666.64	1	2952.36	<0.001	0	1

4 | Discussion

4.1 Peat volume change

The observed ranges in swell and shrink show that the undrained bog and the Siikaneva bog, both considered as natural peatlands, had a larger swell and shrink range than their fen equivalents. This is in line with the hypothesis, due to the fundamental difference between fen and bog hydrology. These findings are in line with the results from Almendinger et al. (1986) for a spring fen and a raised bog.

The swell and shrink range of the recently and longterm drained sites were higher than their undrained equivalents (Figure 3.3). This was not in line with the hypothesis, but can be explained by the change in two processes which determine the swell and shrink (ΔPVC). Namely the change in GWL fluctuations and the change in specific storage (Equation 2.5, in which peat depth is assumed to be constant).

The fluctuations in GWL show significantly higher ranges in the recently drained sites and the longterm drained fen site (See Figure 4.1). As GWL fluctuations is one of the two main drivers behind peat volume change (Price et al., 2005; Waddington et al., 2015), higher GWL fluctuations can explain higher ranges in peat volume change. A higher increase in the GWL fluctuations for the fen drained sites could explain the increased swell and shrink range for the fen sites compared to the bog sites. Higher GWL fluctuations in drained fens compared to undrained fens were also mentioned by Whittington and Price (2006) and Price and Schlotzhauer (1999). Whittington and Price (2006) state that this increased GWL fluctuations are a consequence of drainage, because the peat has become denser due to irreversible compression. As a consequence, the porosity and therefore the total storativity decreases for more compressed peat (Boelter, 1968).

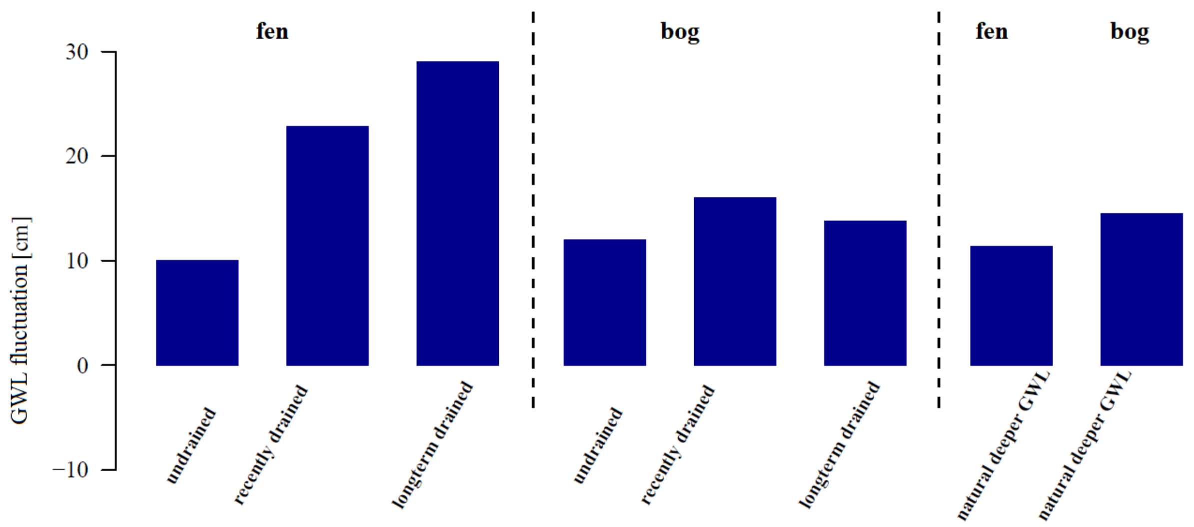

Figure 4.1: The maximum GWL fluctuations over the period 9-5-2017 to 12-6-2017 for all Lakkasuo sites.

A decrease in total storativity with increasing drainage intensity (Table 4.1) is found in this study, and is in line with earlier work from Boelter (1968). The total storativity consists of the specific storage and specific yield and is an important hydrological characteristic which shows how much water is released from storage per unit surface area per unit hydraulic head decline. The total storativity (S_t) per site was analysed based on hydraulic head (GWL) fluctuations in response to a rain event (June the 12th, 21 mm; Figure 4.2). This figure clearly shows an increased response in GWL fluctuations for the recently and longterm drained fen, indicating a lower storativity or faster response. The undrained bog site shows an increased response to a rain event in GWL fluctuations compared to the undrained fen, indicating higher storativity or slower response. The drained bog sites also show an increased response to a rain event in GWL fluctuations, but less obviously. A Limitation of this analysis of the total storativity is that the influence of the catchment wide GWL changes are assumed negligible. The GWL fluctuations are assumed to be completely caused by local properties.

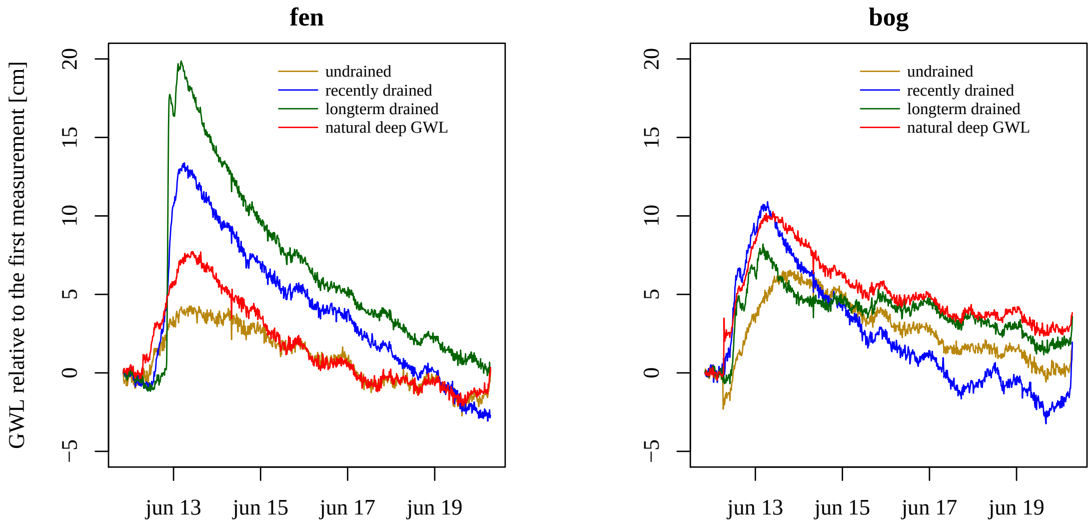

Figure 4.2: Response of the GWL to a rain event of 21 mm, for all Lakkasuo sites. The first measurement is referenced to zero [cm]. The left figure shows the fen sites and the right figure shows the bog sites.

An increase in specific storage for all the drained sites is found (Table 4.1). This result is unexpected, as the specific storage mainly depends on compressibility and this compressibility is expected to decrease for drained (more decomposed) peat. Therefore, the specific storage is expected to decrease as well . But an increase in specific storage could (partly) explain the increased swell and shrink ranges found for the recently and longterm drained sites compared to the undrained sites together with the already discussed increased GWL fluctuations.
One explanation for the increase in S_s could be the role of gas (and especially methane) on the compressibility of the peat. Yager and Fountain (2001) showed that water table drawdown can increase the soils compressibility and therefore the specific storage. This explanation is as follows; drainage causes a reduction in pore pressure that lowers the gas solubility and results in exsolution, the exsolved gas displaces the water from storage and because gas compressibility is much higher than the compressibility of water or peat material, the specific storage increases (Yager and Fountain, 2001).
According to the feedbacks described in Waddington et al. (2015) peat thickness depends on a combination of change in buoyancy and peat consolidation. The consolidation is expected to decrease in drained situations (Whittington and Price, 2006). However, the uplift due to buoyancy is expected to increase, as increased peat decomposition cause an increased (entrapped) gas content (Strack et al., 2005). On the other side, the longterm drained peat sites are very dense compacted compared to the undrained sites and contains much more trees. This increase in weight of the peat layer can cause a decrease in buoyancy. To determine which of these two process who influence the buoyancy is dominant, more research is needed. Again, the net balance between the two processes buoyancy and peat consolidation, determines the total (measured) change in peat thickness. This could have caused an overestimation of S_s, as the assumption behind the calculated S_s is that the difference in peat thickness (ΔPVC) is only based on peat consolidation and not on changes in buoyancy.
In Price (2003) methane is also one of the possible factors influencing the results. The author states that methane behaviour within peatland has been studied well, but not their direct hydrological implications. Therefore, and because no methane measurements were done in this research, further research is needed to investigate the role of methane on peatland hydrology and in this case on the specific storage.

Another influencing factor of the S_s could be the snow and ice melt in the beginning of the measurement period. This could have influenced the ΔGWL and/or ΔPVC and therefore the calculations of S_s (Equation 2.5). The local ΔGWL could have been influenced by the discharge of melt water from the whole peatland/ catchment, as local changes were hidden behind the regional/catchment wide melt water discharge. A high amount of lateral flow in the beginning of the measurement period could indicate this (Figure 3.5). To conclude, follow-up research is needed to gain more insight in the underlying mechanisms in specific storage for increasing drainage intensity.

Table 4.1: Specific storage (S_s), peat depth and S_t per site. S_s (model calibration period, 9-5-2017 to 12-6-2017) and S_t (response to rain event of Figure 4.2) are obtained for different periods within the time series and no error analysis is done, consequently S_s and S_t cannot be used to calculate S_y.

Site		S_s $\cdot 10^{-3}$[cm^{-1}]	peat depth [cm]	S_t [-]
fen	undrained	0.12	150	0.49
	recently drained	0.38	150	0.16
	longterm drained	1.28	131	0.11
bog	undrained	0.14	323	0.32
	recently drained	0.22	336	0.19
	longterm drained	5.14	327	0.26
fen	natural deep GWL	0.33	363	0.27
bog	natural deep GWL	0.05	359	0.20

The longterm drained bog site, does not fit the above explanation as this site shows a decrease in GWL fluctuations and an increase in total storativity (Figure 4.1 and Table 4.1). The observations are based on one measurements per site, therefore, multiple or duplicate measurements are needed to confirm the results. Possible influencing factors of the feedbacks and therefore this behaviour can be based on the difference in vegetation (forest) on this peatland (e.g. increased interception, increased ET, root systems) combined with bog characteristics (only/mainly precipitation fed) (Waddington et al., 2015). Another anomaly in the results is the decreased swelling range for both the bog and fen longterm drained sites (Figure 3.3). This can be due to a different GWL fluctuation for the swelling and shrinkage period or a difference in the processes occurring for a swelling and shrinkage period. Again more detailed research is needed to be able to find an explanation, but forest characteristics and/or feedbacks should definitely be taken into consideration.

The natural deep GWL sites are hard to compare to the other sites as they are located at different landscape positions within the Lakkasuo peatland system. They have a much thicker peat layer (especially the fen), and their exact formation and composition are unknown. However, it is remarkable that both the natural deep GWL bog and fen site show a decrease in swell and shrink range compared to their undrained equivalents (except for the fen's shrinkage range); their order of GWL fluctuations are comparable to the undrained sites; and their total storativity decreases compared to the total storativity of the undrained sites.

To summarize, for an undrained site the bog shows a higher peat volume change capacity than the fen site. For drainage this tends to turn around; the peat volume change for the drained fen sites is higher than for the drained bog sites. The peat volume change capacity increases in general for all drained sites due to changes in GWL fluctuations and S_s. The increase in specific storage is unexpected, but shows a clear trend with increasing drainage intensity and therefore needs a more detailed investigation. The relative changes in ΔGWL and S_s causing the increase in ΔPVC should be investigated in more detail, e.g. a start could be made with a sensitivity analysis.

In this study differences in peat volume change for two different types of peatland (fen and bog) and four different hydrological regimes (undrained, recently drained, longterm drained, natural deep GWL) are established. This combination of treatments and types investigated during the same period and at the same site, is to the author's knowledge unique in literature and therefore provides very useful and important information. The implications on the hydrological self-regulation of peatlands is twofold. Increased groundwater level fluctuations compared to swell and shrink ranges are negatively influencing the hydrological self-regulation of peatlands as it decreases the constant water supply to the living moss layer. But an increase in specific storage is positive for the hydrological self-regulation of peatlands as it ensures a more compressible and elastic peat matrix. The net balance between these two processes and thus the implications for the hydrological self-regulation of peatlands for drained conditions is yet unknown, and needs to be investigated in more detail.

The main limitation of this research is the data collection period. It would be better to measure a full growing season (installation of frames and tubes should be done before the winter) or even multiple seasons. In this study the start is theoretically correct, as the equipment was installed straight after the snow melt. However, the data has shown that the peat was either not fully saturated or not at maximum swelling capacity (e.g. weight of snow on surface) at the start, as the peat volume change became positive later in the season (see Figure 3.1). Furthermore, multiple measurement location per site or duplicate measurements would increase the reliability and decrease the uncertainty in the collected data.

4.2 Lateral flow

The decreasing trend in lateral flow at the beginning of the season indicates the discharge of melt water from snow and ice. The increased variability indicates that the sites are not saturated with (melt)water any more and these peaks are a response to precipitation events. Lateral flow is highest in the undrained sites which is in line with literature, as the recently drained sites are more compacted and the hydraulic conductivity is lower and thus less water can be transported laterally (Price, 2003; Whittington and Price, 2006; Kennedy and Price, 2005).

The obtained results support earlier work by Price (2003); there is a decrease in lateral flow for drained sites compared to undrained sites. This is an underlying mechanism for the difference between undrained and drained sites.

In this study the K_{sat} integral was assumed equal for all sites, which is not in line with literature, because multiple studies show that the K_{sat} differs between drained and undrained sites (Price, 2003; Whittington and Price, 2006; Kennedy and Price, 2005). A different K_{sat} for drained and undrained sites could increase the difference in lateral flow flux and increase reliability. A lower K_{sat} for the drained sites would enhance the difference in lateral flow for the undrained and drained sites, and not cancel out the differences, therefore it was a safe assumption to use only one K_{sat} value.
A sensitivity analysis was done for the parameter which was most sensitive to measurement errors, the hydraulic gradient (dh). As an error in the absolute position of the piezometers and thus divers (in the site and in the ditch) could lead to a systematic error in the hydraulic gradient and over- or underestimate the lateral flow. The sensitivity analysis showed that changes (measurement errors) in this parameter did not lead to significantly different behaviour of the lateral flow time series.

4.3 Modelling

The initial model performed best for the recently drained bog. It was expected this would occur for the undrained bog but according to the overall NRMSE this model version performs worse. The model performance of the undrained bog could have been influenced by the short validation period of PV for this undrained bog. Beside that, no clear explanation can be given except that it is of course one measurement location and sensitive to the exact location and measurement errors. There is no clear pattern in the difference between the undrained and the drained sites. Theoretically the recently drained sites should perform worse because the model is developed for natural/undrained sites. This was only true for the fen sites. This can also be caused by the particularly bad performance of the undrained bog.

The results show that extending the hydrological model with lateral flow significantly improves the model performances for fen systems and not for bog systems. This proves that lateral flow is essential/ more important in fen systems (Rydin and Jeglum, 2013) and can therefore not be neglected in hydrological modelling. The undrained fen improved most by adding lateral flow, which is as expected as lateral flow is in general higher in undrained sites (Price, 2003). Explained by a decreased integrated K_{sat} for drained sites as a lower GWL relative to the surface level in drained sites results in a lower integrated K_{sat} over depth. In practice, it should be taken into account that this inclusion of lateral flow implies additional measurements (the hydraulic gradient and K_{sat}) and thus an increase in costs.

This modelling study has tested if the processes included in the model developed by (Nijp et al., 2017) is complex enough to use it for different hydrological treatments and types of peatlands. This has gained insight in model performance for these different treatments and types and the importance of lateral flow. The model is not yet complex enough to adequately simulate the different types of peatland and hydrological treatments, as the absolute model performance is limited (Appendix C). It is proven that lateral flow significantly improves the model performance for fens, and therefore cannot be neglected in hydrological models for fen peatlands. Hereby a start is made in systematically testing the increase in hydrological model complexity and their consequence for hydrological model performance of the model as suggested by Nijp et al. (2017). Further research is needed to systematically test if more processes improve model performance, as peatlands are complex systems with many feedbacks and therefore including more processes will likely improve the model performance (Nijp et al., 2017). Again, the overview with feedbacks from Waddington et al. (2015) could be used. It is advised to continue with a separate model for a fen and bog because different processes can be uneven important in a bog or a fen. When the model purpose is land use changes or climate change it is advised to use a separate model for undrained and drained sites as well.

In this research different model versions are compared. However, the absolute model performance is not yet satisfactory (Appendix C). It is expected that this can be increased by adding more processes to the model, but as stated before, this should systematically be tested.

5 | Conclusion

1. **What is difference in peat volume change capacity for different drainage treatments and types of peatlands in northern peatlands?**
   The data show that the undrained and natural bog have a higher peat volume change range than the corresponding treatment in the fen. The drained sites show higher GWL fluctuations and an increased specific storage which can cause the higher measured peat volume change compared to the undrained sites. Anomalies in the above given general explanation should be investigated in more detail to be able draw conclusions about these measured deviations.

2. **Which mechanisms underlie these differences in drainage effects for different treatments and types of peatlands?**
   In this study it was investigated if lateral flow is one of these underlying mechanisms. Based on measurements it was shown that lateral flow is higher in undrained peatlands, due to a higher hydraulic gradient (dh) and consequently a higher integrated K_{sat} over depth (K_{sat} is higher at shallower depth). Other possible mechanisms found are a decrease in total storativity and an increase in specific storage for the recently and longterm drained sites. Further research is needed to be able to draw conclusions about storage changes for different hydrological treatments. As peatlands are complex systems with many feedbacks, multiple mechanisms can underlie the differences in drainage effects and influence each other.

   a) **Can the peat volume change be modelled with the model of Nijp et al. (2017) and what is the hydrological model performance for the different treatments and types?**
   The different hydrological treatments and types of peatland can be modelled with the model of Nijp et al. (2017), but improvements should be made to adequately simulate different peatland types and hydrological treatments. This should be done by systematically increasing the model complexity to improve the overall model performance. Model performance of the initial model version was highest for the drained bog, then decreasing for the undrained fen, the drained fen to the undrained bog.

   b) **Does inclusion of lateral flow significantly improve the model performance for different treatments and types?**
   Lateral flow has shown to significantly improve the model performance of the fen sites only, with highest improvement for the undrained fen.

6 | Recommendations

For future research within the direction of (simulating) hydrological feedbacks under changing conditions in northern peatlands I would recommend the following based on the main limitations of this research and follow up questions:

- Expand the data collection period to a full growing season (installation of equipment done before the season starts) or even multiple seasons (sensitive sensors should be removed during winter).
- Multiple measurements within the same site or duplicates to increase reliability of the data. E.g. to validate the anomalies found in peat volume change ranges.
- Increase the number of slug test to get a more reliable K_{sat} value which is site specific. Moreover, intensify the measurements over depth per site, to get a more detailed depth profile of the hydraulic conductivity per site.
- Methane measurements to gain more insight in the processes which can influence the S_s; measure the concentrations and volumes of methane in peat samples from different sites (undrained and drained) in a laboratory. This can give insight in the amount of methane present and to which extent it can influence other measurements (e.g. peat volume change). If the amount of methane is significant more detailed research can be done, for example methane emissions from undrained and drained sites. More general, investigate the direct hydrological implications of (differences in) methane behaviour.
- Systematically test if extension of the model with other ecohydrological processes (e.g. from Waddington et al. (2015)) significantly improves the model performance and differentiate between different treatments and types.
- Duplicate this research on a different location within the northern peatland zone, to check the universality of the results and the model.

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References

Almendinger, J. C., Almendinger, J. E., Glaser, P. H., 1986. Topographic fluctuations across a spring fen and raised bog in the lost river peatland, northern minnesota. The Journal of Ecology, 393–401.

Baird, A. J., Morris, P. J., Belyea, L. R., 2012. The digibog peatland development model 1: rationale, conceptual model, and hydrological basis. Ecohydrology 5 (3), 242–255.

Batzer, D. P., Baldwin, A. H., 2012. Wetland habitats of North America: ecology and conservation concerns. Univ of California Press.

Binet, S., Gogo, S., Laggoun-Défarge, F., 2013. A water-table dependent reservoir model to investigate the effect of drought and vascular plant invasion on peatland hydrology. Journal of hydrology 499, 132–139.

Boelter, D., 1968. Important physical properties of peat materials.

Bouwer, H., Rice, R., 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water resources research 12 (3), 423–428.

Cobos, D., 2015. Measurement volume of decagon volumetric water content sensors. Decagon Devices, Inc.: Pullman, WA, USA.

Davis, R. B., Anderson, D. S., 1991. Tb146: The eccentric bogs of maine: A rare wetland type in the united states.

Dlugokencky, E., Tans, P., 2017. Trends in atmospheric carbon dioxide. www.esrl.noaa.gov/gmd/ccgg/trends/.

Dommain, R., Couwenberg, J., Joosten, H., 2010. Hydrological self-regulation of domed peatlands in south-east asia and consequences for conservation and restoration. Mires & Peat 6.

Frolking, S., Roulet, N. T., Tuittila, E., Bubier, J. L., Quillet, A., Talbot, J., Richard, P., 2010. A new model of holocene peatland net primary production, decomposition, water balance, and peat accumulation. Earth System Dynamics 1 (1), 1–21.

Gong, J., Kellomäki, S., Wang, K., Zhang, C., Shurpali, N., Martikainen, P. J., 2013. Modeling co 2 and ch 4 flux changes in pristine peatlands of finland under changing climate conditions. Ecological modelling 263, 64–80.

Gong, J., Wang, K., Kellomäki, S., Zhang, C., Martikainen, P. J., Shurpali, N., 2012. Modeling water table changes in boreal peatlands of finland under changing climate conditions. Ecological modelling 244, 65–78.

Gorham, E., 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. Ecological applications 1 (2), 182–195.

Granberg, G., Grip, H., Löfvenius, M. O., Sundh, I., Svensson, B., Nilsson, M., 1999. A simple model for simulation of water content, soil frost, and soil temperatures in boreal mixed mires. Water Resources Research 35 (12), 3771–3782.

Hargreaves, G. H., Samani, Z. A., 1985. Reference crop evapotranspiration from temperature. Applied engineering in agriculture 1 (2), 96–99.

Hilbert, D. W., Roulet, N., Moore, T., 2000. Modelling and analysis of peatlands as dynamical systems. Journal of Ecology 88 (2), 230–242.

Hyder, Z., Butler, J., 1995. Slug tests in unconfined formations: An assessment of the bouwer and rice technique. Groundwater 33 (1), 16–22.

Ise, T., Dunn, A., Wofsy, S., Moorcroft, P., 2008. High sensitivity of peat decomposition to climate change through water-table feedback, nat. geosci., 1, 763–766.

Joosten, H., Clarke, D., 2002. Wise use of mires and peatlands. International Mire Conservation Group and International Peat Society 304.

Kellner, E., Halldin, S., 2002. Water budget and surface-layer water storage in a sphagnum bog in central sweden. Hydrological Processes 16 (1), 87–103.

Kennedy, G., Price, J., 2005. A conceptual model of volume-change controls on the hydrology of cutover peats. Journal of Hydrology 302 (1), 13–27.

Laine, J., Komulainen, V., Laiho, R., Minkkinen, K., Rasinmäki, A., Sallantaus, T., Sarkkola, S., Silvan, N., Tolonen, K., Tuittila, E., et al., 2004. Lakkasuo: a guide to mire ecosystem. Lakkasuo: a guide to mire ecosystem.

Lewis, F., Butler, A., Gilbert, L., 2011. A unified approach to model selection using the likelihood ratio test. Methods in Ecology and Evolution 2 (2), 155–162.

Mathijssen, P. J., Väliranta, M., Korrensalo, A., Alekseychik, P., Vesala, T., Rinne, J., Tuittila, E.-S., 2016. Reconstruction of holocene carbon dynamics in a large boreal peatland complex, southern finland. Quaternary Science Reviews 142, 1–15.

McCarthy, J., 2014. Climate Change 2014–Impacts, Adaptation and Vulnerability: Regional Aspects. Cambridge University Press.

Moore, T., Roulet, N., Waddington, J., 1998. Uncertainty in predicting the effect of climatic change on the carbon cycling of canadian peatlands. Climatic change 40 (2), 229–245.

Nijp, J. J., 2015. Fine scale ecohydrological processes in northern peatlands and their relevance for the carbon cycle. Ph.D. thesis, Wageningen University.

Nijp, J. J., Limpens, J., Metselaar, K., Zee, S. E., Berendse, F., Robroek, B. J., 2014. Can frequent precipitation moderate the impact of drought on peatmoss carbon uptake in northern peatlands? New Phytologist 203 (1), 70–80.

Nijp, J. J., Metselaar, K., Limpens, J., Teutschbein, C., Peichl, M., Nilsson, M. B., Berendse, F., van der Zee, S. E., 2017. Including hydrological self-regulating processes in peatland models: effects on peatmoss drought projections. Science of the Total Environment 580, 1389–1400.

O'Gorman, P. A., Schneider, T., 2009. The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. Proceedings of the National Academy of Sciences 106 (35), 14773–14777.

Päivänen, J., et al., 1973. Hydraulic conductivity and water retention in peat soils. Suomen metsätieteellinen seura.

Powell, M., 1965. A method for minimizing a sum of squares of non-linear functions without calculating derivatives. The Computer Journal 7 (4), 303–307.

Price, J. S., 2003. Role and character of seasonal peat soil deformation on the hydrology of undisturbed and cutover peatlands. Water Resources Research 39 (9).

Price, J. S., Cagampan, J., Kellner, E., 2005. Assessment of peat compressibility: is there an easy way? Hydrological Processes 19 (17), 3469–3475.

Price, J. S., Schlotzhauer, S. M., 1999. Importance of shrinkage and compression in determining water storage changes in peat: the case of a mined peatland. Hydrological Processes 13 (16), 2591–2601.

Price, J. S., Whittington, P. N., 2010. Water flow in sphagnum hummocks: Mesocosm measurements and modelling. Journal of Hydrology 381 (3), 333–340.

R Core Team, R., 2011. R: a language and environment for statistical computing r foundation for statistical computing, 2.13. vienna, austria. Tech. rep., ISBN 3-900051-07-0, URL http://www. R-project. org.

Roulet, N., Moore, T., Bubier, J., Lafleur, P., 1992. Northern fens: methane flux and climatic change. Tellus B 44 (2), 100–105.

Rydin, H., Jeglum, J. K., 2013. The biology of peatlands, 2e. Oxford university press.

Strack, M., 2008. Peatlands and climate change. IPS, International Peat Society.

Strack, M., Kellner, E., Waddington, J., 2005. Dynamics of biogenic gas bubbles in peat and their effects on peatland biogeochemistry. Global Biogeochemical Cycles 19 (1).

Terzaghi, K., 1943. Theory of consolidation. John Wiley & Sons.

Tolonen, K., Raikamo, E., Lahti, T., Viista, J., 1979. Siikaneva mire complex. In: International symposium on classification of peat and peatlands. International Peat Society, Helsinki.

van Dijk, G., Nijp, J. J., Metselaar, K., Lamers, L. P., Smolders, A. J., 2017. Salinity-induced increase of the hydraulic conductivity in the hyporheic zone of coastal wetlands. Hydrological Processes 31 (4), 880–890.

Waddington, J., Kellner, E., Strack, M., Price, J., 2010. Differential peat deformation, compressibility, and water storage between peatland microforms: implications for ecosystem function and development. Water Resources Research 46 (7).

Waddington, J., Morris, P., Kettridge, N., Granath, G., Thompson, D., Moore, P., 2015. Hydrological feedbacks in northern peatlands. Ecohydrology 8 (1), 113–127.

Walczak, R., Rovdan, E., Witkowska-Walczak, B., 2002. Water retention characteristics of peat and sand mixtures. International agrophysics 16 (2), 161–166.

Walter, B. P., Heimann, M., Matthews, E., 2001. Modeling modern methane emissions from natural wetlands: 1. model description and results. Journal of Geophysical Research: Atmospheres 106 (D24), 34189–34206.

Whittington, P. N., Price, J. S., 2006. The effects of water table draw-down (as a surrogate for climate change) on the hydrology of a fen peatland, canada. Hydrological Processes 20 (17), 3589–3600.

Yager, R. M., Fountain, J. C., 2001. Effect of natural gas exsolution on specific storage in a confined aquifer undergoing water level decline. Groundwater 39 (4), 517–525.

Yurova, A., Wolf, A., Sagerfors, J., Nilsson, M., 2007. Variations in net ecosystem exchange of carbon dioxide in a boreal mire: Modeling mechanisms linked to water table position. Journal of Geophysical Research: Biogeosciences 112 (G2).

Zlotnik, V. A., Goss, D., Duffield, G. M., 2010. General steady-state shape factor for a partially penetrating well. Groundwater 48 (1), 111–116.

Appendices

A. Model settings

In this section different tables and graphs show the parameter settings, initial conditions and forcing data of the calibration and validation period.

Table A.1: Overview of model parameters, their value, unit, description and source. X indicates that the value differs per model version (calibration or input). All values were obtained from Nijp (2015).

Parameter	Value	Unit	Description	Source
θ_{sat}	0.975	m^3/m^3	Saturated water content	Sandbox experiment
θ_{res}	0	m^3/m^3	Residual water content	Sandbox experiment
λ	0.28	-	Shape factor	Sandbox experiment
h_b	-0.005	m	Air entry value	Sandbox experiment
k_s	$1.5 \cdot 10^{-3}$	m/s	Saturated hydraulic conductivity	modified permeameter
k_a	X	-	Shape factor	Calibration
k_b	X	-	Shape factor	Calibration
k_c	X	-	Crop factor	Calibration
α_E	-0.171	-	Shape factor	ET experiment
β_E	0.416	-	Shape factor	ET experiment
E_{max}	0.245	mm/d	Constant	ET experiment
S_y	X	-	Specific yield	Calibration
S_s	X	m^{-1}	Specific storage	Field data
D_1	0.10	m	Moss layer thickness	
Δt	$6.035 \cdot 10^{-5}$	d	Time step	
rnd	0.50	-	Relative node depth	

Table A.2: Calibration ranges for all calibrated parameters. The S_y upper boundary is site dependent. All parameters are dimensionless.

Parameter	Explanation	lower boundary	upper boundary
K_a	shape factor	0.5	1.5
K_b	shape factor	$5 \cdot 10^{-5}$	$5 \cdot 10^{-4}$
S_y	Specific yield	0	$1-S_S*depth_{peat}$
K_c	crop factor	0.75	1.50

Table A.3: Final values for all calibrated parameters per model version. All parameters are dimensionless, LF= lateral flow.

Model version	K_a	K_b	S_y	K_c
undrained fen	1.00001	$5 \cdot 10^{-5}$	0.98158	1.5
undrained fen with LF	1.5	0.00015	0.241406	0.812499
recently drained fen	0.999998	$5 \cdot 10^{-5}$	0.94	1.5
recently drained fen with LF	0.999998	$5 \cdot 10^{-5}$	0.942415	1.5
undrained bog	0.975588	0.000149971	0.23457	0.75
undrained bog with LF	0.99549	0.000103561	0.91963	0.75
recently drained bog	0.996902	0.000143411	0.431046	0.75
recently drained bog with LF	0.996902	0.000140257	0.634011	0.75

Table A.4: Specific storage and inital conditions for all sites for the calibration (cal) and validation (val) period. Specific storage is a calculated value from measured data for GWL and PVC, Equation 2.5.

Site	S_s [cm^{-1}]	initial peat depth (cal) [cm]	initial GWT (cal) [cm]	inital peat depth (val) [cm]	inital GWT (val) [cm]
undrained fen	0.0001228	150.0	134.02	150.09	130.99
recently drained fen	0.0003839	150.0	119.51	149.86	111.59
undrained bog	0.0001426	323.0	313.24	322.82	305.48
recently drained bog	0.0002214	336.0	318.14	335.50	314.72

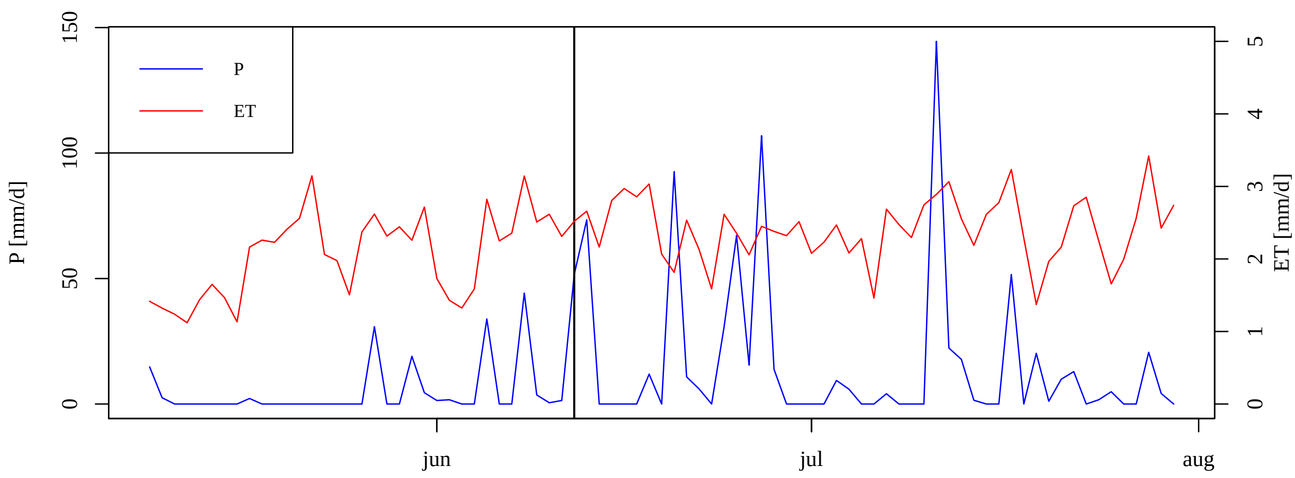

Figure A.1: The rainfall intensity (P) and reference evapotranspiration (ET) according to the FMI weather station in Hyytiälä for the calibration (9-5-2017 to 12-6-2017) and validation (12-6-2017 to 30-7-2017) period, the black line indicates the change between the calibration (left) and validation (right) period.

B. Time series

This sections shows the measured time series of the groundwater level and the volumetric water content for all sites.

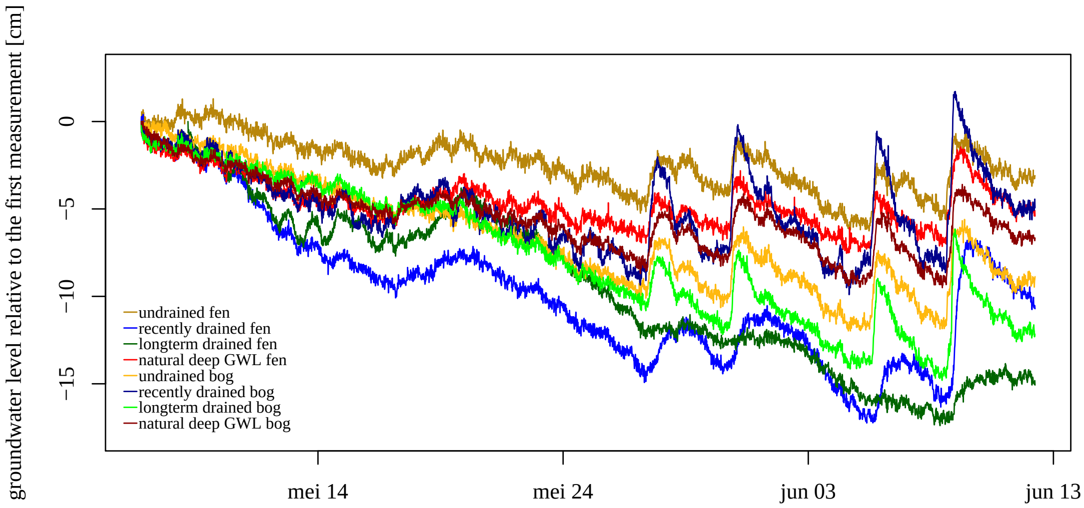

Figure B.1: Groundwater level over time for all Lakkasuo sites, relative to the first measurement.

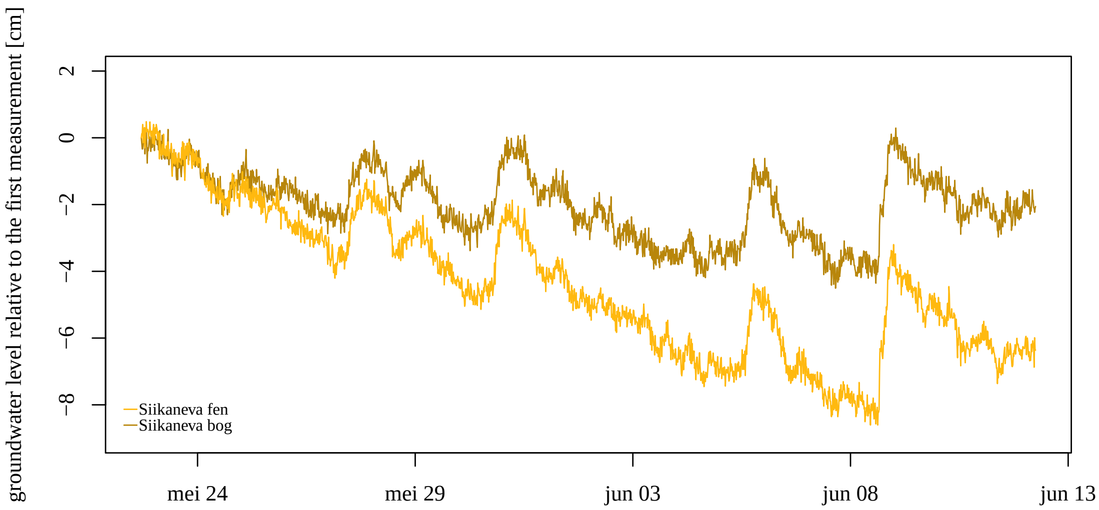

Figure B.2: Groundwater level over time for the Siikaneva sites, relative to the first measurement.

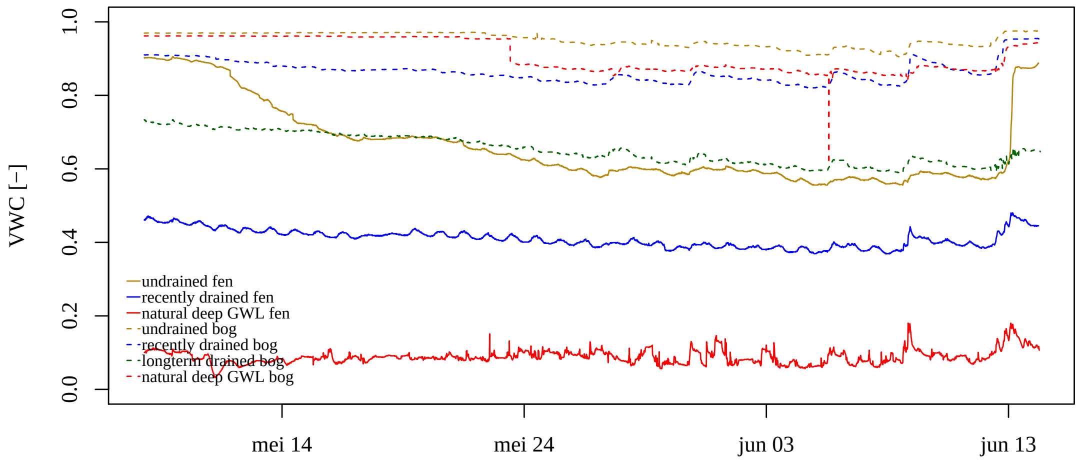

Figure B.3: Volumetric water content over time for all Lakkasuo sites except for the longterm drained fen due to a lack of working measurement devices.

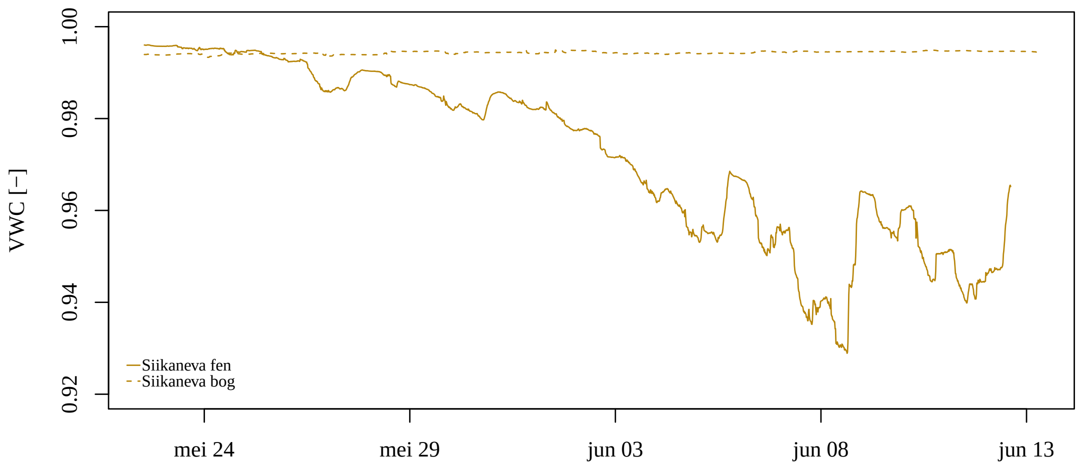

Figure B.4: Volumetric water content over time for the Siikaneva sites.

C. Model simulations

In this section the model validation time series (12-6-2017 to 30-7-2017) are shown, for all model versions (initial and with lateral flow), for all state variables (PV=surface level, GWT= GWL, VWC) and all modelled sites (undrained and drained, fen and bog). If the initial model version results are not visible, they lie exactly behind the model version with lateral flow. Some data gaps occur in the observed time series, due to a temporary lack of power for the measurement devices.

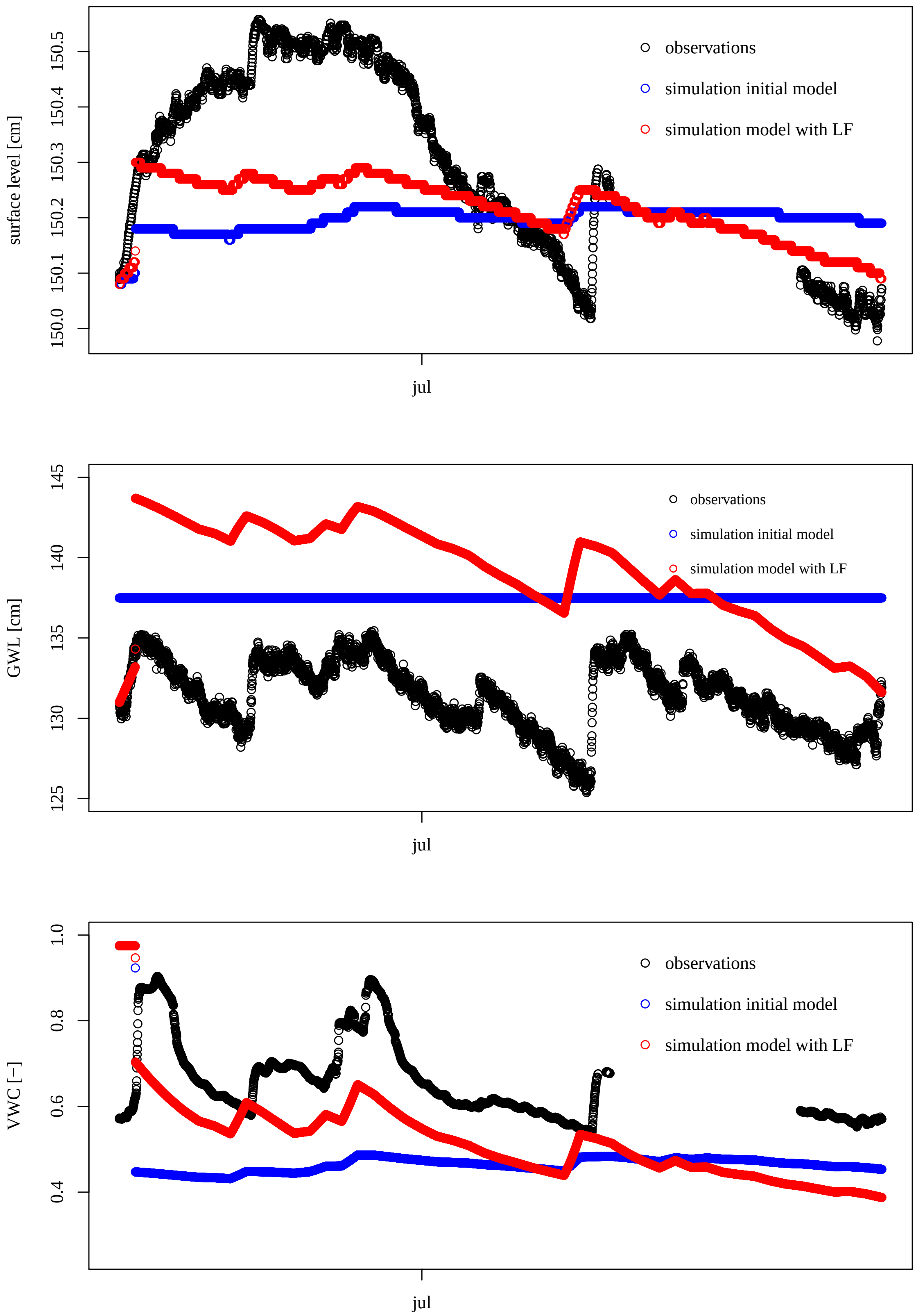

Figure C.1: Model results for the undrained fen.

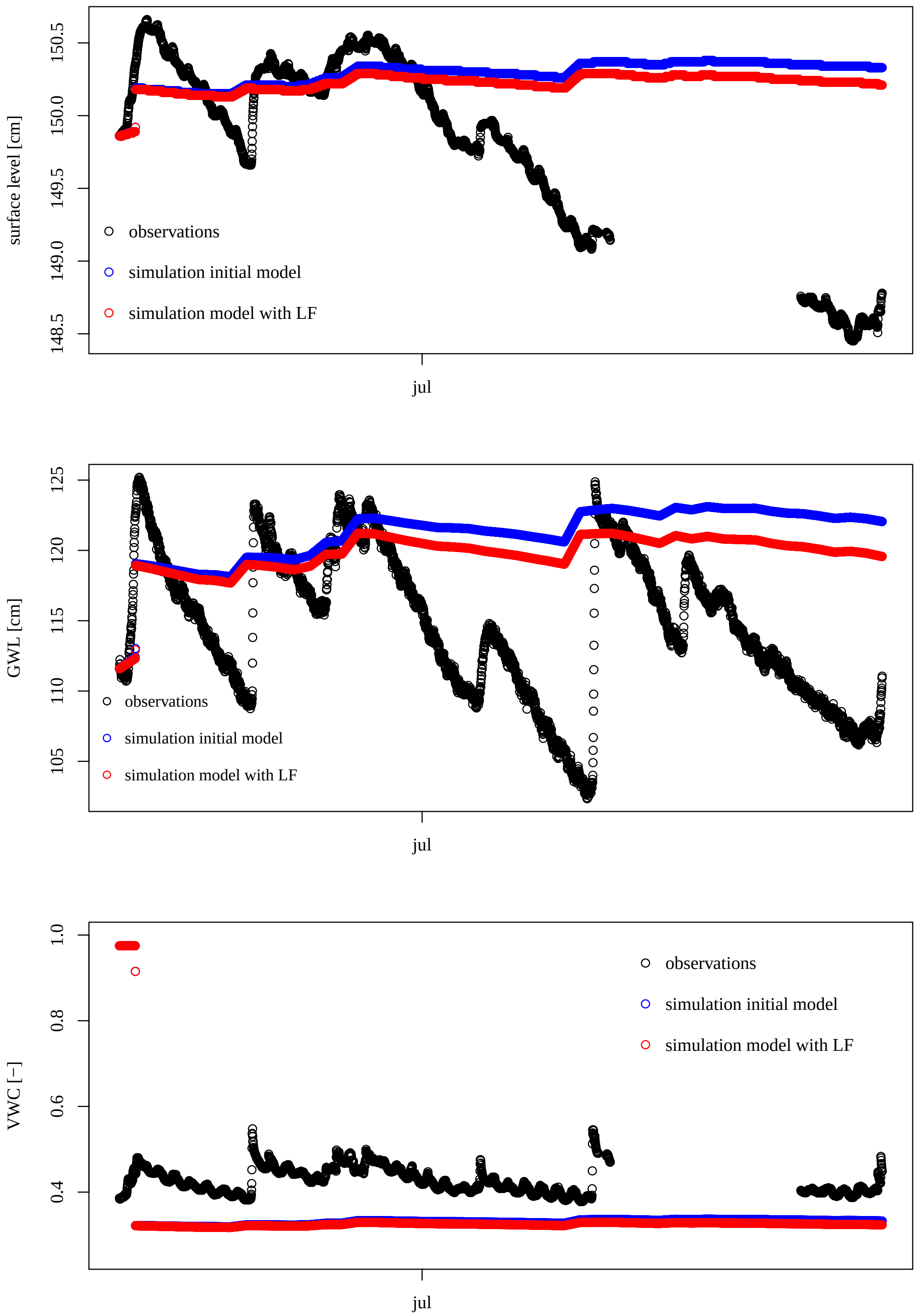

Figure C.2: Model results for the drained fen.

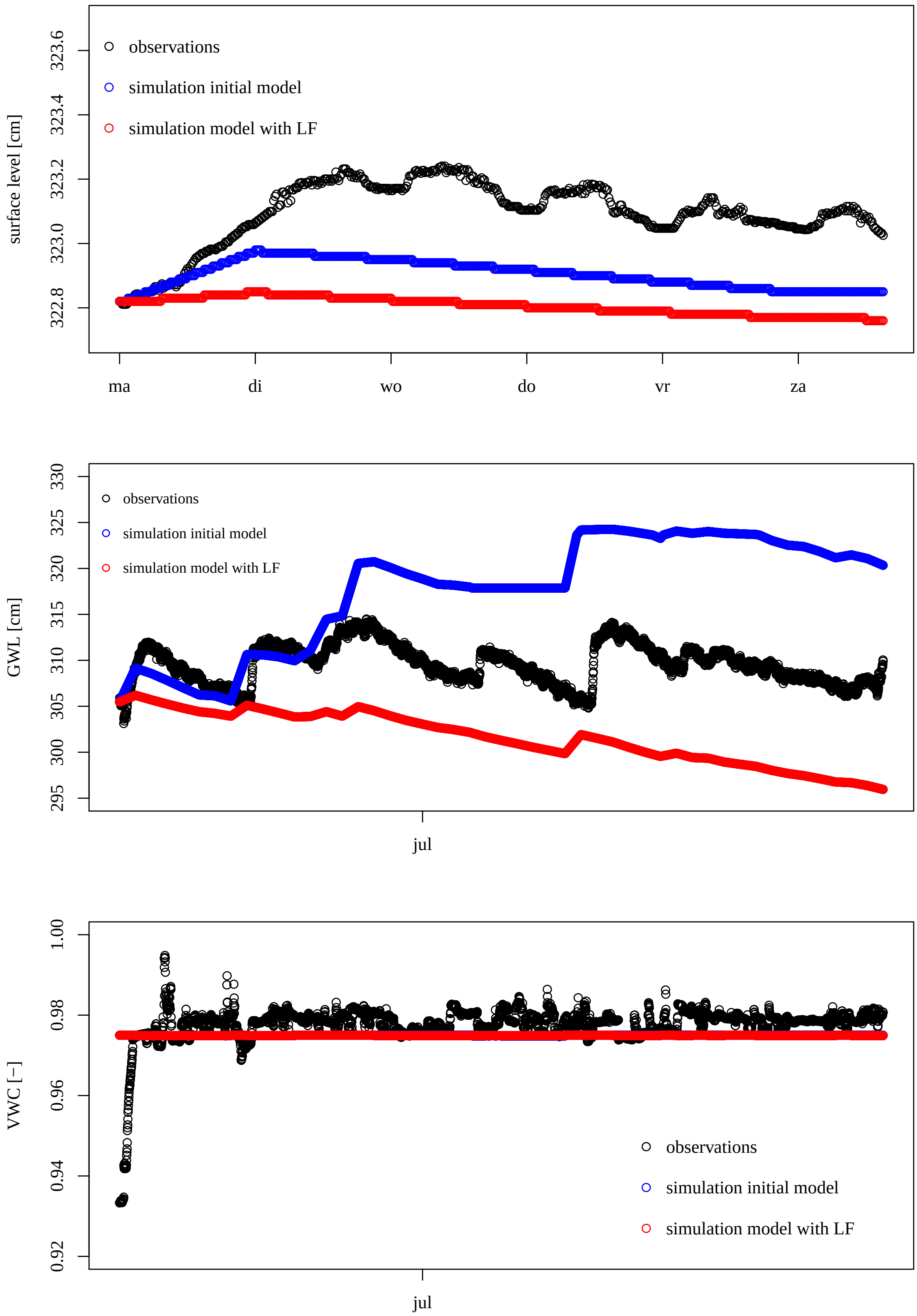

Figure C.3: Model results for the undrained bog. The state variable PV only has data from 12-6-2017 00:00 UTC to 17-6-2017 15:00 UTC.

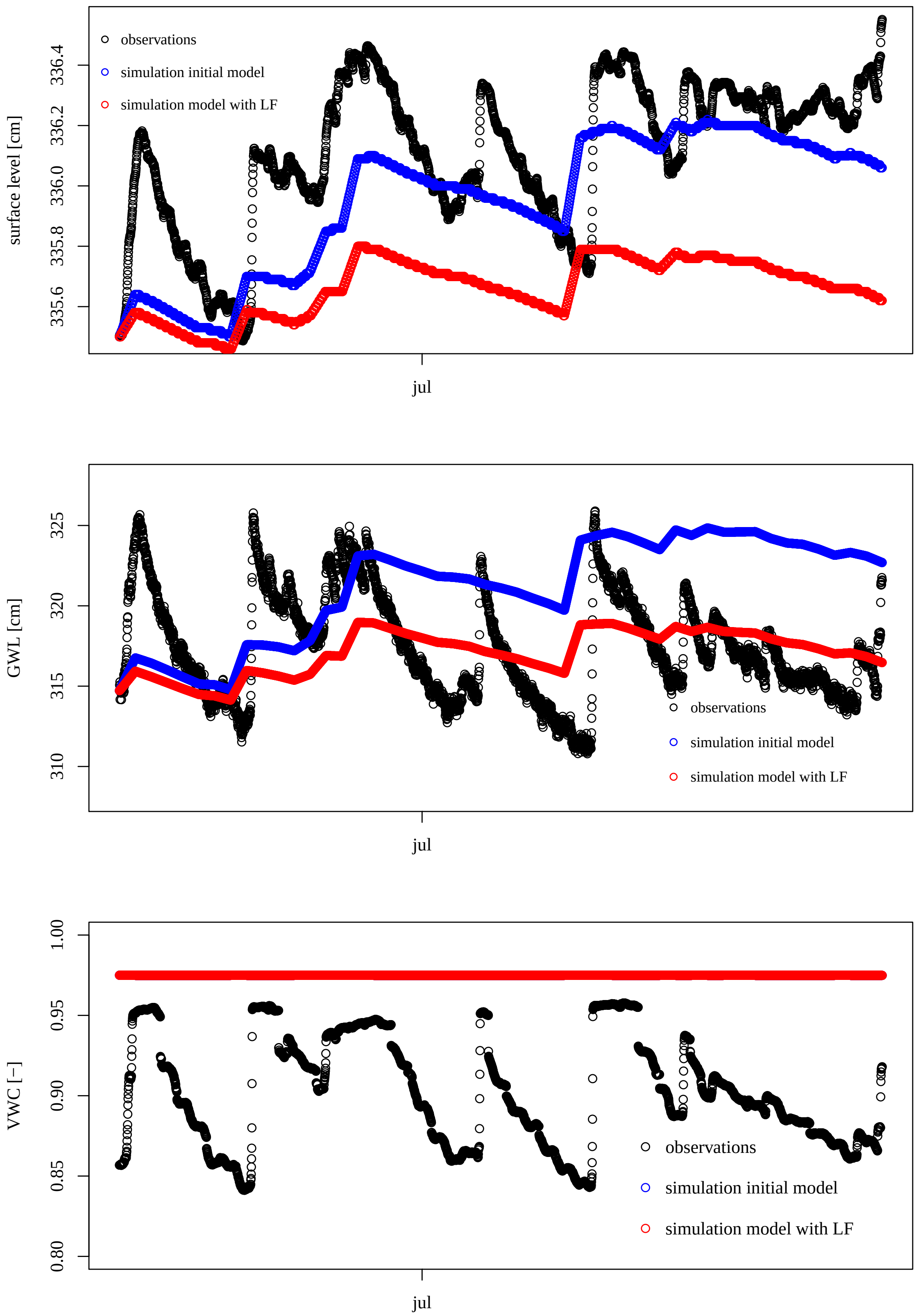

Figure C.4: Model results for the drained bog.