Flood Alteration of the Raised Bogs in Entlebuch, Switzerland

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Abstract

Peatlands are assumed to have flood attenuating characteristics. Therefore, worldwide efforts are put into the restoration of peatlands. However, some studies show no or even an enhancing effect of peatlands on floodings. In this study, it was investigated how the raised bogs in Entlebuch, Switzerland alter floods. The water tables were measured over two years and compared to weather parameters. The results show that the water table of the raised bogs react on temperature, amount of dry days in a row and precipitation of the previous day. Degradation and environmental factors, such as topography and vegetation coverage, influenced the water household and therefore the flood altering effect of the bogs. In Entlebuch, most factors discovered had a negative effect on floods. It was often the case that the antecedent water tables were too high and caused too little space in the soil to take up all the precipitation. It was assumed that that could have caused saturation-excess overland flow. Because heavy precipitation events will increase with climate change, it is of high importance to gain more knowledge about the different types of discharge and their occurrence in Entlebuch, and how they influence the downstream flow of water.

Acknowledgement

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Contents

Abbreviations and Acronyms

d_i	day i
d_{i-1}	day before i
d_{i-2}	2 days before i
d_{i-3}	3 days before i
ha	Hectare
K	hydraulic conductivity
K_v	vertical hydraulic conductivity
K_h	horizontal hydraulic conductivity
LME	Linear Mixed Effects Model
m.a.s.l.	meters above sea level
n	porosity

Chapter 1

Introduction

Wetlands are important ecosystems and, according to the UN, they have ecosystem services such as flood control, water purification, drought buffer and groundwater re- and discharge that is all crucial to humans [UN, n.d.]. Not only are wetlands important for the water household but also for carbon storage, and they are home to a unique biodiversity [IPS, 2010; UN, n.d.]. It is considered that wetlands 'act like a sponge', meaning that they absorb water during rainfall and release it when it is dry [Acreman and Holden, 2013; Brotherton, 2021]. They alter downstream water flow with collecting water in the soil, and with altering the runoff pathways they reduce the runoff speed [Wetlands International, n.d.]. This results in a delayed the peak flow, reduced peak or reduced the water volume [Brotherton, 2021; Acreman and Holden, 2013; Cooley, 2015]. The absorption of the water reduces the intensity and frequency of floods, and so the damage caused by floods can be reduced [Cooley, 2015]. This is especially an advantage during periods of heavy rainfall [Brotherton, 2021], which are increasing in frequency with climate change [Tabari, 2020].

Due to human interference, wetlands are being destroyed and degraded [UN, n.d.]. They are disappearing three times faster than forests, and are one of the most threatened ecosystems on Earth, with a loss of 35% since 1970 worldwide [UN, n.d.], and only in Switzerland almost 90% is degraded [BAFUb, 2017]. The reasons for their disappearance are for example drainage to gain agricultural land, pollution, and climate change [UN, n.d.]. Peat is also extracted and used for gardening and horticulture because of its fertilizing effects [Charman, 2009]. Because wetlands are part of the nature-based solutions against floods [Brotherton, 2021], they are promoted through organizations like IUCN, Wetlands International, and the Ramsar Convention on Wetlands of International Importance to be protected and restored [Acreman and Holden, 2013].

However, the term wetland includes many different types of ecosystems [UN, n.d.; Acreman and Holden, 2013]. Bullock and Acreman [2003] investigated the function of those different types of wetlands and their influence on floods. Their research showed that there are clear examples of wetlands that reduce floods, however, there is little support for a general conclusion [Bullock and Acreman, 2003]. Some types of wetlands attenuate floods, some have no impact, and some even increase flood risk [Bullock and Acreman, 2003]. Depending on environmental factors or season of the year, some types of wetlands can have inverse effects on floods [Bullock and Acreman, 2003]. An essential factor in reducing floods is a low enough water table in the soil to have the capacity to absorb and store the precipitation fast enough [Acreman and Holden, 2013]. This is in contrast with the high water tables in wetlands, since they are classified in the highest category according to the WRAP classification [Acreman and Holden, 2013]. However, raised bogs are considered to have a low water table for being a wetland because of the lack of connection to the ground water [Rydin and Jeglum, 2013]. This could benefit their effect on floods.

In this study, the focus is on the raised bogs in UNESCO Biosphere Reserve Entlebuch, Switzerland. A previous study carried out in the same study area by Marty [2021] investigated that the raised bogs took up water in case of precipitation. The water table rose quickly, whereas the release of water was slow [Marty, 2021]. Factors that influenced the extent of the water table rise were precipitation and the antecedent water table, of which the first one had a positive and the latter a negative impact [Marty, 2021].

The knowledge gained by Marty [2021] will be used to build up a better understanding of water household of the raised bogs in Entlebuch. It is of high importance to gain a better understanding of the function of the raised bogs in Entlebuch, because also the Swiss government asserts the sponge effect of raised bogs [BUWAL, 2002]. They highlight their flood attenuation and the reduced risk of flood consequences [BUWAL, 2002]. This statement in combination with the examined varying effects of wetlands on floods by Acreman and Holden [2013] led to the aim of this study. It should be investigated if the raised bogs in the UNESCO Biosphere Reserve Entlebuch act like a sponge, and therefore absorb water during precipitation events and release it delayed to attenuate runoff peaks. To answer this question, four specific questions were asked:

1. How high are water tables in raised bogs in Entlebuch generally?
2. What happens in case of precipitation to the water table?
3. When do the raised bogs release water?
4. How does the state of a raised bog influence the answers of the previous question?

For all research questions, a hypothesis was made based on literature. The enumeration follows the research questions.

1. The raised bogs have generally a high water table of about 5 cm below the surface with deviations up to 30 cm below the surface [Acreman and Holden, 2013; Daniels et al., 2008; Breeuwer et al., 2009; Romanov, 1968].
2. Precipitation will be taken up by the raised bogs [Marty, 2021]. But because of a general high water table [Acreman and Holden, 2013], there will not be enough space to take up all the water in cases of heavy rain events.
3. The raised bogs release water continuously through evapotranspiration and outflow, and when precipitation was high enough also through overland flow [Oosterwoud et al., 2017; Evans et al., 1999].
4. Degraded bogs will have a lower water table [Acreman and Holden, 2013] with higher water table fluctuations [Menberu et al., 2016].

To answer the research questions, the water tables of different raised bogs are analyzed over two years, which will allow the analysis of the storage processes [Acreman and Holden, 2013]. Additionally, weather data will be used to assess the influence of weather parameters on the water tables. The answering of the last research question will be done while answering the other questions to reduce redundancy.

Chapter 2

Background Knowledge

In this chapter, essential background information about raised bogs is summarized to give a better understanding of the results and discussion. First, raised bogs will be delimited from other types of peatlands. After that, the structure and function of raised bogs are described, followed by the hydrology of raised bogs. In the last part, different types of anthropogenic transformations and their are illustrated.

2.1 Terminology: peatlands, raised bogs and fens

The International Peatland Society defines peatlands as an ecosystem that is water saturated, and therefore consists of poorly decomposed plant material [IPS, n.d.]. Organic matter builds up faster than it decomposes, which leads to its accumulation [IPS, n.d.]. This accumulation of organic matter in a wet and oxygen-poor environment is the so-called peat [Rydin and Jeglum, 2013], which is the typical layer of a peatland.

Different peatlands have different ecological factors, like nutrient and moisture conditions, which influences the peat's characteristics [Rydin and Jeglum, 2013]. This leads to different types of peatlands like bogs, fens, swamps or marshes.

Raised bogs are a type of peatland with a thick layer of peat [EPA, n.d.]. They are typically dome-shaped with the highest layer separated from the ground-water level [BUWAL, 2002]. The disconnection of the groundwater has several consequences for the ecological conditions. First, precipitation is the only water source, therefore they are also called ombrogenous bogs [Rydin and Jeglum, 2013]. Because there is no groundwater that saturates the peat, the water table varies more than in other peatlands [Rydin and Jeglum, 2013]. Secondly, precipitation is the only source of nutrients in a raised bog, making the raised bogs ombrotrophic [Rydin and Jeglum, 2013]. Consequently, there is a low nutrient concentration in raised bogs [EPA, n.d.].

Next to raised bogs, fens are also a type of wetland [EPA, n.d.]. In contrast to bogs, the upper layer of fens is connected to the groundwater, so they have their water and nutrient supply not only from precipitation [Rydin and Jeglum, 2013]. They are mostly saturated with water, so the water table is just below, or even slightly above the surface [Rydin and Jeglum, 2013]. They are less acidic and have a higher nutrient content, which leads to a higher plant diversity compared to bogs [EPA, n.d.]. Over time, the accumulation of peat in a fen leads to the elevation of the surface, which at some can disconnect the surface layer from the ground water and makes the fen a bog [Küchler, 2018]

2.2 Composition

Raised bogs are mainly covered by Sphagnum moss [Rydin and Jeglum, 2013]. It is a bryophyte that is adapted to extreme conditions: high acidity, cold, low nutrients, and water-logged soils. The survival of the moss highly depends on the position of the water table [Menberu et al., 2016]. A small shift of the water table can have significant consequences for Sphagnum, and therefore the plant composition in general [Menberu et al., 2016]. In the tip, the Sphagnum keeps on growing, while the lower parts of the moss dies [Rydin and Jeglum, 2013]. The higher growth than decomposition rate leads to a rise of the surface of 1mm per year [SWO, n.d.].

This rise of the surface led to the disconnection of the upper layer oft he peat of the ground water and the consequently high variation of the water table. This upper part, where the water table fluctuates, is called the acrotelm and is limited to the lowest water table [Rydin and Jeglum, 2013]. The fluctuating water table allows air to enter the pores and provides organisms, like the peat vegetation, bacteria, and fungi, with oxygen [Evans and Warburton, 2010]. That is why the acrotelm is also called the 'active' layer [Rydin and Jeglum, 2013]. The acrotelm typically has a depth of 5 up to 50 cm [Rydin and Jeglum, 2013]. Under the acrotelm is the permanently water saturated peat, the so- called catotelm [Rydin and Jeglum, 2013]. The constant water saturation makes this layer anoxic [Rydin and Jeglum, 2013]. The peat here is humified and darker than in the acrotelm [Rydin and Jeglum, 2013]. The largest volume of the peat is taken up by the catotelm [Rydin and Jeglum, 2013].

2.3 Hydrology

Precipitation is the only factor that rises the water table in raised bogs, while water table lowering factors are evapotranspiration and outflow on the surface or through the peat in lateral direction or as seepage to the groundwater [Keane and Daly, 1994]. This leads to the following equation of the water balance of a raised bog [Price and Maloney, 1994; Acreman and Holden, 2013]:

$$\Delta S = P - ET - Q$$

ΔS: change in storage, P: precipitation, ET: evapotranspiration, Q: outflow

The difference between precipitation, and evapotranspiration and outflow causes a change in water storage [Rydin and Jeglum, 2013]. If precipitation is higher, the water table will rise, and if the water table lowering factors dominate, the water table will sink. Of the water table lowering factors, evapotranspiration is by far the most dominant factor [Price and Maloney, 1994].

This change in dominance of in- and outflow causes a change in water storage, and therefore a change in water table height. Water tables of raised bogs have annual fluctuations and remain mostly close to the surface, roughly 5 cm below the surface [Holden and Burt, 2003a; Evans et al., 1999; Rydin and Jeglum, 2013]. During dry periods, the water table can go down to 30 cm below the surface [Daniels et al., 2008; Breeuwer et al., 2009; Romanov, 1968] and in very extreme dry years, Romanov [1968] measured water tables of 55 cm below the surface. For peatlands, it is normal to have water tables above the surface, and Daniels et al. [2008] found water tables of up to 5 cm above the surface. The height of the water table depends on the location in the bog [Howie and van Meerveld, 2012]. Towards the margins of a bog, the water table is in general lower and fluctuates more [Howie and van Meerveld, 2012].

Water is stored in the void of the peat. The deeper in the peat, the more humified the organic matter, and therefore the smaller the pores [Quinton et al., 2000]. Pores that are interconnected and large enough contribute to water flow in the peat and are therefore called active pores [Hoag and Price, 1997; Quinton et al., 2008]. In a study performed by Quinton et al. [2008], in the upper 10 cm of the peat the active porosity was 0.47 - 0.69, and therefore higher than in the lower part (0.38 - 0.58).

How smooth the water flows through the pores is summarized in the hydraulic conductivity (K) of the peat, which mainly depends on the degree of humification [Rydin and Jeglum, 2013]. High humification leads to dense peat and therefore less large, active pores [Rydin and Jeglum, 2013]. The lower in the peat, the higher the humification, and therefore the lower K [Rydin and Jeglum, 2013]. This vertical gradient of K leads to a vertical gradient of speed in lateral water movement with the highest flux on top of the water table [Rydin and Jeglum, 2013]. Water does not only flow in the lateral direction but also vertically. However, vertical hydraulic conductivity (K_v) is vastly smaller compared to horizontal hydraulic conductivity (K_h) ($K_h >> K_v$), indicating that peat in raised bogs is anisotropic [Beckwith et al., 2003]. Lateral and vertical water flow can lead to outflow of the raised bog. The ways of outflow are enumerated in the following list and depicted in Fig. 2.1 [Exler, 2015, and references therein]:

Saturation-excess overland flow If the soil is completely saturated, precipitation cannot be taken up anymore [Holden and Burt, 2003a]. In studies by Holden and Burt [2003a,b], where runoff production was investigated in a blanket peat, it was found out that 80% of the runoff was due to saturation-excess overland flow [Holden and Burt, 2003a,b].

Infiltration-excess overland flow If rainfall intensity is greater than the infiltration rate in the soil, water runs off on the surface [Holden and Burt, 2003a]. This is often the case for soils with low infiltration capacity [Holden and Burt, 2003a].

Subsurface flow Water also flows below the surface in the pores of the peat [Rydin and Jeglum, 2013]. Water flow in macropores, made by roots of plants or cracks, is faster than in micorpores, made by the peat matrix [Beven and Germann, 1982]. The increasing K_h in depth induces the highest water flux on top of the water table [Rydin and Jeglum, 2013]. Compared to overland flow, the water flux in the pores is much slower [Rydin and Jeglum, 2013].

Pipeflow Soil pipes are regarded to have a diameter of at least 1 cm [Holden, 2009]. According to Holden and Burt [2002], 10% of discharge runs off in soil pipes.

Seepage Seepage highly depends on K_h, which is very low in the catotelm peat [Exler, 2015]. It is only 1% of the discharge of ombrotrophic bogs that runs off through seepage [Damman, 1986].

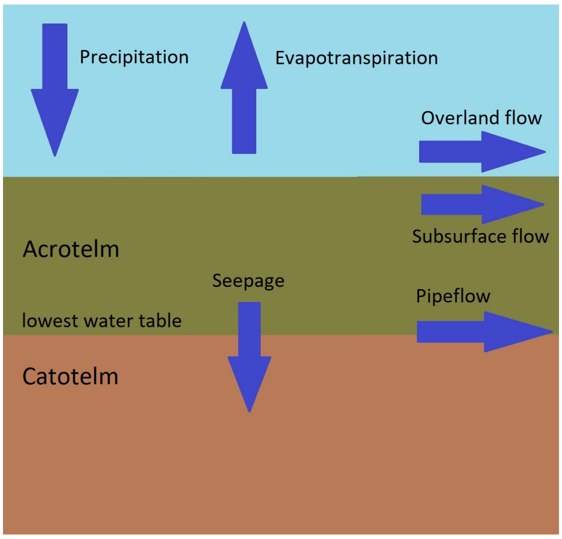


Figure 2.1: Overview of the two layers of the peat an the water balance components.

The discharge possibilities enumerated above should not be considered as separate phenomena [Exler, 2015; McDonnell, 2003]. Moreover, they are all well connected with surface water that infiltrates in the peat or water in the peat that goes back to the surface [Exler, 2015; McDonnell, 2003]. How much runs off and how much the different types contribute to runoff is highly influenced by the water table height [Daniels et al., 2008]. For example, a high discharge never occurs with a low water table [Emili and Price, 2006; Evans et al., 1999], or a high water table causes fast saturation of the soil and leads to saturation-excess overland flow [Evans et al., 1999].

When it rains, water goes in the peat and flows there laterally and vertically. Because of the low K, the flux is way slower compared to water on the surface. This low flux releases the water delayed in the stream and should alter downstream floods with a delayed peak flow and lower peak [Rydin and Jeglum, 2013; Keane and Daly, 1994; Gao et al., 2018]. Because water tables in wetlands are generally high, there is not much space left to take up precipitation [Gao et al., 2018]. After saturation, water runs off on the surface, where it flows much faster [Gao et al., 2018; Keane and Daly, 1994]. This overland flow causes a higher peak flow and a shorter lag time compared to the subsurface flow, but can be reduced by dense vegetation cover on the raised bog [Evans et al., 1999; Grayson et al., 2010; Gao et al., 2018].

2.4 Anthropogenic transformation

Even though peatlands have many valuable ecosystem services, their importance to humans is underrated [UNEPa, 2021]. In the past, many peatlands were destroyed and barely restored, which led to a present degradation of more than 25% of European's peatlands [UNEPb, 2021]. Drainage ditches were dug, so the water could run off, and the water table was artificially lowered to gain agricultural land or peat [Menberu et al., 2016]. Lowering the water table with drainage ditches has multiple consequences for the ecosystem. The lower water table cause more available space in the soil to take up water [Menberu et al., 2016]. The water storage capacity increase, but the drainage ditches also led to a faster runoff [Menberu et al., 2016]. This increased runoff is seen downstream with an increased peak flow [Acreman and Holden, 2013; Menberu et al., 2016]. Overall, the water table will fluctuate more, and consequently the water household of the raised bog will change [Menberu et al., 2016; Szajdak et al., 2020]. This change will also affect the main peat builder *Sphagnum*. It is very susceptible to high water table fluctuations and droughts [Rydin and Jeglum, 2013; Szajdak et al., 2020]. The changing water household has an immense impact on Sphagnum and therefore the plant composition, and biodiversity in general of the raised bog [Szajdak et al., 2020; Menberu et al., 2016].

However, in the more recent past, efforts have been put into the restoration of these valuable ecosystems. Drainage ditches have been blocked, so the water could not run off in the ditches [Menberu et al., 2016]. Consequently, the water tables rose and more favorable hydrological conditions were gained [Menberu et al., 2016]. These conditions include higher water tables and lower fluctuations. Water is stored again and runoff is reduced. This is seen in smaller down stream peaks and reduced flooding risk. However, restoration of a raised bog can take several years and some changes can be irreversible due to degradation [Menberu et al., 2016].

Besides drainage, raised bogs were also used for pastures [Von Wyl et al., 1995]. Cattle trampled the sensitive moss and destroy it [Von Wyl et al., 1995], This destruction led to changes in the water household of the soil and caused erosion [Von Wyl et al., 1995]. Pasturing of cows on raised bogs can lead to the complete destruction of the peat [Von Wyl et al., 1995].

Chapter 3
Methods

3.1 Study sites

The data for this study was collected in the UNESCO Biosphere Reserve Entlebuch in Switzerland (centre of the Biosphere is located at 46°57'N, 8°01'E, 733 m.a.s.l.). The biosphere has a mean annual temperature of +5.7 °C, an average yearly rainfall of 1717 mm and 148.6 days of precipitation [MeteoSchweiz, 2022]. The eleven piezometer were located in the raised bogs «Salwidili» (federal inventory No. 313), «Juchmoos» (federal inventory No. 400) and «Zwischen Glaubenberg und Rossalp» (federal inventory No. 257, hereinafter "Rossalp") [BAFUa, 2017]. A detailed map of the raised bogs and the weather station is shown in Fig. 3.1.

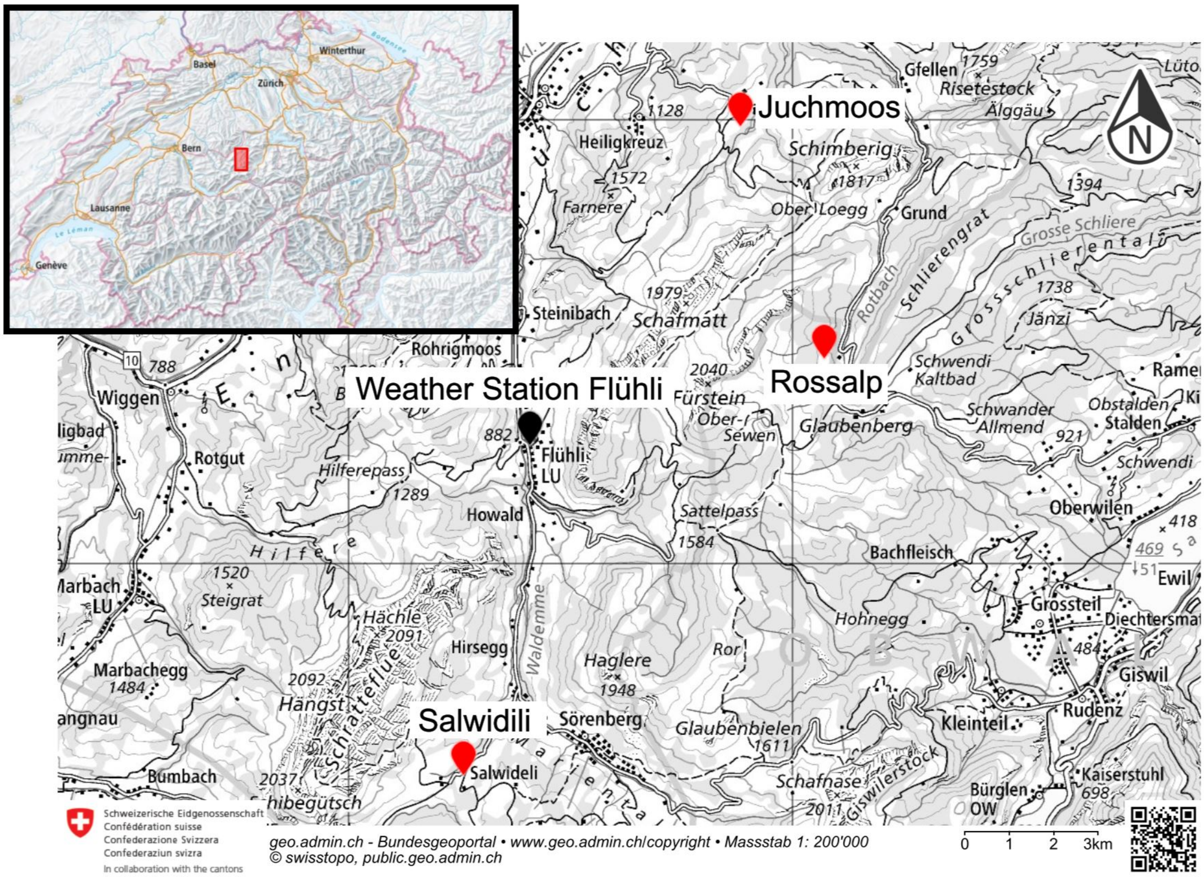


Figure 3.1: Small map: Location of the study site in Switzerland. Large map: Detailed locations of the sites and weather station in the UNESCO Biosphere Reserve Entlebuch [Swisstopo, 2022].

Juchmoos

The site Juchmoos is 1.50 ha large and is located 1040 m.a.s.l. [BAFUa, 2017]. The bog has been drained in the 1950s resulting in a large and deep drainage channel accompanied by a few smaller ones leading in to the large channel or running parallel to it. The four piezometers have been placed in a transect perpendicularly to the drainage channel: J1 is situated furthest away from the channel in the most intact part of the bog with an open vegetation but with *Frangula alnus* indicating disturbed hydrological properties. J2 is placed closer to the ditch in a vegetation transition zone that contains much more tree cover. J3 is placed just next to the large drainage ditch. J4 is placed at the start of the channel, very close to it but closer to agriculturally managed fens. The last piezometer was placed there in order to follow up the water table changes after the peatland restoration that took place after the study period of this study. Today, the bog is located in a pine forests (*Pinus montana*) with bilberry shrubs. Juchmoos was considered as a degraded bog [Knaus, 2022; BAFUa, 2017].

Rossalp

The second raised bog Rossalp has an area of 5.32 ha and is located 1520 m.a.s.l. [BAFUa, 2017]. In the past, cattle trampled the bog over decades before it was protected for conservation. As a consequence, the acrotelm and peat mosses are completely missing in most of the bog. The piezometers are placed as follows: R1 is situated next to a small natural channel that drains the eastern section of the bog. R2 stands close to a small water body within the bog from which end water drains towards the adjacent hill slope. R3 is situated in a large flat part of the bog where natural regrowth of peat mosses has started. The bog Rossalp was considered as degraded [Knaus, 2022; BAFUa, 2017].

Salwidili

The raised bog Salwidili has a size of 1.39 ha and is located 1330 m.a.s.l. [BAFUa, 2017]. There were four piezometers (S1 to S4) that measured the water table at different micro-sites: S1 is placed at the center of the bog, S2 at the north edge, where the acrotelm is partly missing,and peat is dense, most likely because of former cow trampling. S3 is standing in the vicinity of a forest edge, dominated by spruce (*Picea abies*), and is having a stronger cover of *Molinia caerulea*, indicating stronger water table fluctuations. S4 is placed next to a larger open water body within the bog. The bog was considered as non-degraded [Knaus, 2022; BAFUa, 2017].

Weather station

The weather data was taken from the weather station Flühli (8°01'/46°53'). It was located 939 m.a.s.l. and had a distance between 6.92 km and 8.61 km to the sites Swisstopo [2022].

3.2 Data analysis

The piezometers measured the water table automatically every hour from October 2019 until September 2020 for Rossalp, and until September 2021 for the other two sites. Because snow could have influenced the water table measurements, the periods with snow cover were excluded. It remained the period of May, 1 until September, 30. The weather data was taken from MeteoSwiss. To examine the function of the raised bogs, the data was transformed from hourly to daily, because an accuracy of an hour was too detailed to answer the research question.

To answer the research questions, it is first looked into the hydrographs of the piezometers. This allows it to make statements about the general water tables and their fluctuations. Additionally, the influencing weather factors on the water tables are investigated in a Linear Mixed Effects Model (LME). To answer the second research question, occurred precipitation events are used to compare the amount of precipitation, and the therefore needed space in the soil, with the available space in the soil. Previous events are used to represent the occurring combinations of available and needed space in the soil. This comparison allows to figure out if there was enough space in the soil for different amounts of precipitation. Additionally, the water table change is compared to the amount of precipitation and the therefore expected rise of water table. On this basis it is concluded if the raised bogs took up more water and acted like a sponge, or if runoff occurred. Finally, the water table change was compared to the length of dry and wet periods to investigate the water table change over time with the precipitation conditions. This was done in raised bogs that were considered as degraded and non-degraded to examine the influence of the state of the bog on all questions.

In the first step, variables were calculated with the given data of the piezometer and weather stations to do the further analysis. This resulted in the following variables, with day i (d_i) and day before i (d_{i-1}):

Site Raised bog Salwidili (S), Juchmoos (J) or Rossalp (R).

Piezometer Water table measuring tubes in the soil, 3 to 4 per site.

Water table Average per day; in cm above surface.

Precipitation Sum of d_i; in mm.

Temperature Average of day d_i; in °C.

Porosity Abbr. n; the porosity of the peat was unknown, so an assumption had to be made. According to Quinton et al. [2008], the active porosity of the near surface peat is between 0.47 and 0.69. To have one number for the calculations, the average 0.53 was used.

Water table change Change of water table of d_i compared to d_{i-1} (*water table* d_i - *water table* d_{i-1}); in cm.

Expected rise of water table When the soil takes up precipitation, the water table rises. Because precipitation runs only in the pores between the solid material, the water table rises more in height than the meteorological measured amount of precipitation. How much the water table rises depends on the porosity of the soil, a small porosity leads to a higher rise of the water table than larger pores. The expected rise of water table represents the water table change expected for the precipitation of d_{i-1} and is calculated by precipitation d_{i-1}, porosity of the soil and a conversion factor to convert the precipitation from millimeter to cm (*precipitation* d_{i-1}*/(10*n)*); in cm.

Available space The available space in the soil to take up precipitation is defined by the difference between the surface and the water table at a specific time; in cm.

Enough space The available space of d_{i-1} was compared to the amount of precipitation at d_i. If the available space was larger than the amount of precipitation needed, there was enough space. If the available space was smaller than the precipitation needed, there was not enough space.

Amount of dry / wet days in row Every day was defined as dry (no precipitation) or wet (with precipitation). This variable counts the days in a row before d_i with the same precipitation state. If there was no precipitation on d_i, the dry days in a row up to that day were counted. If there was precipitation on d_i, the same was done, but for wet days. For example, if it rained five days in a row, day number four gets for the variable «Amount of wet days in a row» a «4» and day number five gets «5».

The statistical analysis was done with R (version 4.1.3) with the packages ggplot2 and nlme. To examine which factors influence the water table of a raised bog, a Linear Mixed-Effects Model (LME) was made. Water table was the dependent variable, and the variables precipitation of that day and up to three days before (d_i, d_{i-1}, d_{i-2}, d_{i-3}), temperature and amount of dry and wet days in a row were the explanatory variables. The piezometers were defined to have as random effect on the water table. To make the subsequent processes easier applicable, the precipitation event with the strongest influence would be picked to continue the following calculations.

Because the water table of d_{i-1} influenced the water table of d_i, the data was not independent [Knaus, 2022]. To have an independent data set, 300 measurements (approx. 10% of the whole data set) were picked randomly by R [Knaus, 2022]. The LME was executed with those 300 random measurements. The whole process of picking 300 random measurements and calculating the LME with them was done 50 times. To summarize the 50 LMEs, the average of the estimated influencing values, p-values and standard deviations were calculated for all explanatory variables and put in a table. A level of significance of 0.05 was used.

Chapter 4

Results

4.1 Weather conditions and water tables

4.1.1 Course over time

Measurements were recorded at the weather station Flühli from May 1, 2020 to September 30, 2020 and May 1, 2021 to September 10, 2021, representing the local climate. During the study period, the average air temperature comprised 16.1°C with a maximum of 26.8°C on July 31, 2022, and a minimum of 3.3°C on May 12, 2020 (Fig. 4.1). The precipitation total during the study period comprised of 837.3mm in 2020, and 1021.4mm in 2021. The highest recorded rainfall was 52.9mm on July 8, 2021.

The water tables fluctuated strongly in every piezometer in the observation periods between May and September (Fig. 4.1). Fluctuations comprised both water tables above (maximum 10.4 cm) and below (maximum -42.9 cm) the surface. Fluctuations of the water tables at the different piezometers were parallel, and from the illustration it becomes clear that rain events generally lead to water table increases.

Of all examined influencing factors, «amount of dry days in a row» had the strongest influence (Fig. 4.1). Its negative correlation signifies that the longer the dry period, the lower the water table in the end. «Temperature» was the second strongest factor predicting the water table, indicating that the warmer the day, the lower the water table. Of the precipitation factors, the strongest influence was precipitation d_{i-1}. Precipitation of two and three days before also had a significant impact on the water table in contrast to the precipitation of that day.

The model assumptions of a LME were tested with a QQ-Plot and a Tukey Ascomb Plot (App. A.2). Both plots show a normal distribution, therefore the model assumptions were fulfilled.

Table 4.1: Summary of LMEs. The investigated factors with their estimated influencing value (Estimate) and its standard deviation (SD). * $P < 0.05$; *** $P < 0.001$.

Factor	Estimate	SD
Intercept	-5.46	2.82
Precipitation d_i	0.03	0.03
Precipitation d_{i-1}	0.10***	0.03
Precipitation d_{i-2}	0.08*	0.02
Precipitation d_{i-3}	0.09***	0.02
Temperature	-0.23***	0.06
Dry days in a row	-0.46*	0.13
Days of precipitation in a row	0.09	0.10

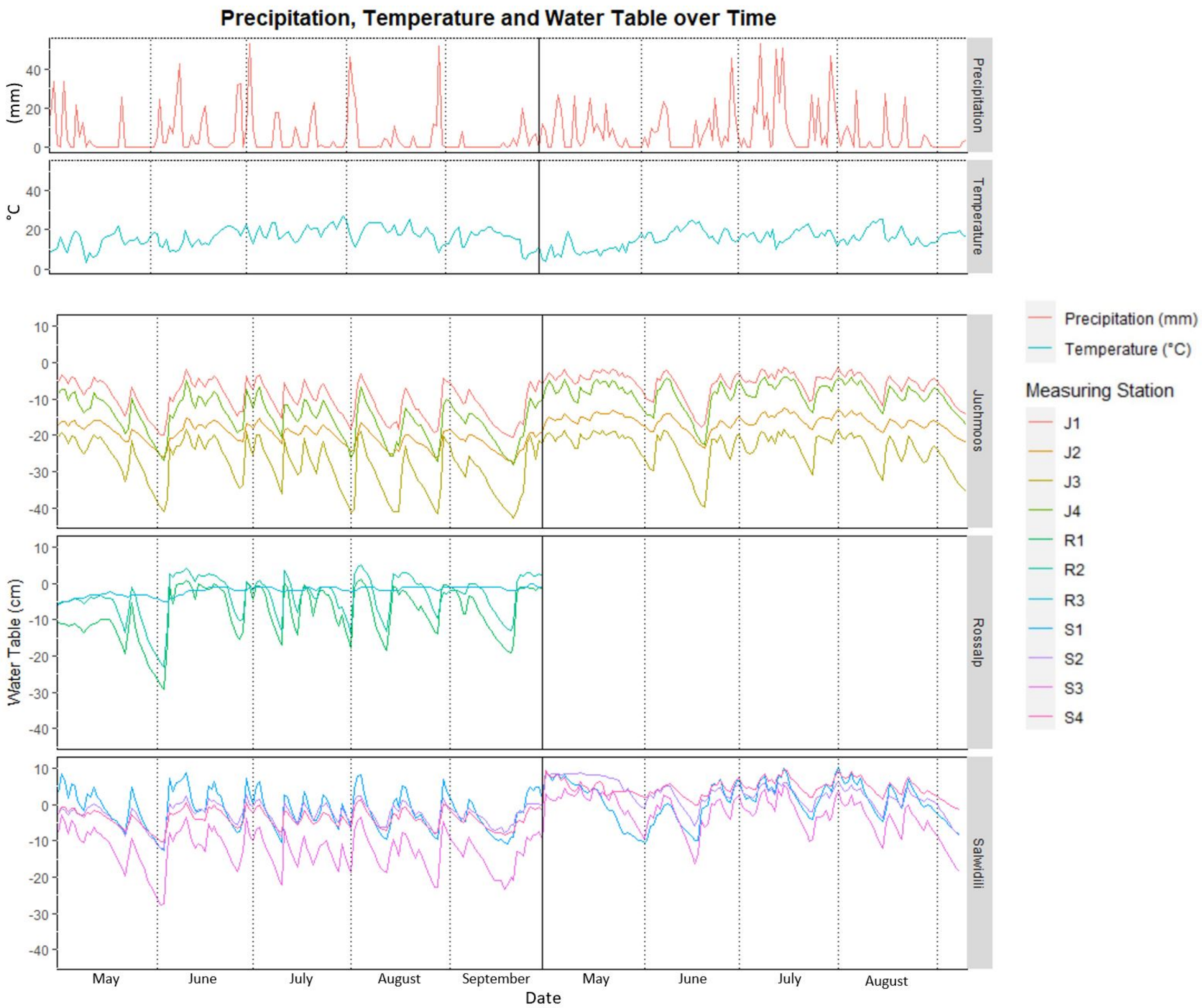


Figure 4.1: Precipitation (in mm), temperature (in °C) and water tables (in cm) over time during the study period. The water tables are sorted by site. The dashed lines mark the transitions between the months, the black solid line marks the transition between the years.

4.1.2 Water table summary

The average water table differed considerably between the different piezometers, both within and between the bogs (Fig. 4.2). The highest average water table was +0.01 cm at piezometer S4, located next to the large open water body. The second piezometer next to an open water body, R2, also had a relatively high average water table of -3.6 cm. Both of them showed a relatively medium to low difference between their highest and lowest water table (19.7 an 22.1 cm resp.). The lowest water table (on average -26.3 cm) was measured at J3, a piezometer next to a water channel, which also showed the third highest water table variation of 24.5 cm. Piezometer R1 is also next to a ditch and had a low water table (-8.1 cm) with high variations (30.4 cm), compared to the other piezometers at Rossalp. Additionally, piezometer J4 is also close to the drainage ditch but is influenced by the agricultural used fen. Its water table is relatively low compared to all the piezometers (-12.3 cm) and, also had high variation in its water table (-23.2 cm) between its maximum and minimum water table. The largest variation of the water table was 33 cm (average water table at -8.1 cm) measured at S3, the piezometer close to the forest. The second piezometer covered by woody plants was J2. The average water table was also low (-18.4 cm), but in contrary to S3 the water table variation was low (14.4 cm). The most stable water table with a variation of 5 cm and an average water table of -2 cm below the surface was at R3, the piezometer with the recovering acrotelm.

For the site Juchmoos, the average water table differed the most between the different piezometers. The further away from the drainage channel (J3 close to the channel, J2 in the middle, and J1 the furthest away), the higher the water table. For the other sites, the difference between the piezometer was not that high. At Salwidili, all piezometers had a similar water table average around 0 cm, except for S3, the site closest to the forest. The piezometer at the edge of the bog, S2, had a smaller variation of the water table compared to the piezometer in the centre of the bog, S1.

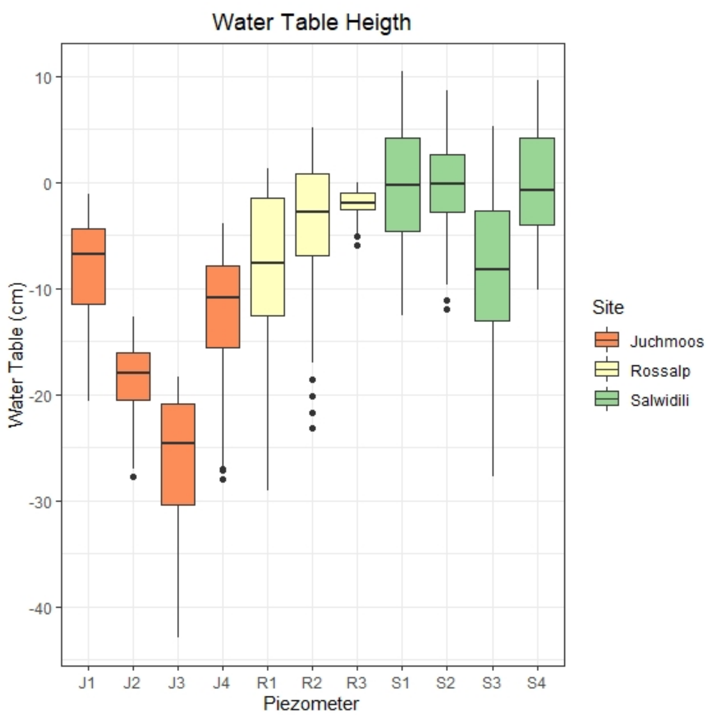


Figure 4.2: Box plots of the water tables of the different piezometers colored by the site.

4.1.3 Change of water table per day

How much the water table changed in one day differed between the piezometers (Fig. 4.3). The majority of water table changes lay within +3.5 and -4.3 cm, however, there were strong outliers in the positive direction. Changes per day had a larger extent in positive direction, indicating that the bogs could generally take up more water during one day than they could release in a day. The piezometer closest to the channel at Juchmoos, J3, had the highest water table change on one day of 20.1 cm. Likewise, R1 is also located next to a ditch and had very high water uptakes per day (maximum of 17.4 cm). It in addition, R1 had the largest reduction of the water table on one day, namely -6.3 cm. Also J3 and J4, two piezometer close to a drainage ditch, had medium to high releases of water per day (-4.1 and -3.0 cm resp.). The combination of the high water uptake and release per day gave J3 and R1 the highest range of water table changes per day (24.2 and 23.7 cm resp.).

It was R3, the piezometer with the regrowing moss, that had the smallest difference between the most negative and the most positive water table change per day of 1.6 cm. The second smallest water table range (6.5 cm) had J2, the piezometer with the second largest distance to the drainage ditch and the coverage of bilberry shrubs and pine trees. At Salwidili, it was S3, located close to the forest, with the largest difference in water table change per day of 20.1 cm. The piezometer at Salwidili that changed the least per day was S4, close to the open water, with a range between the most negative and most positive water table change per day of 9.6 cm. It was also R2 that was situated next to an open water body, but, in contrary to S4, it had a large range of water table changes per day, namely 19.9 cm. Piezometer S2 at the edge of the bog had smaller water table changes compared to piezometer S1 in the centre.

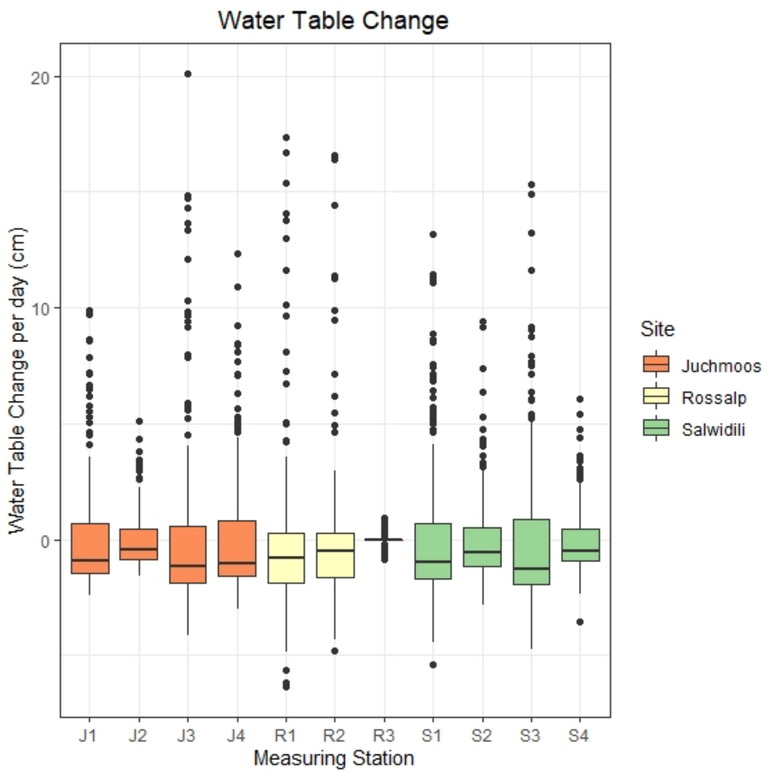


Figure 4.3: Box plots of the water table change per day of the different piezometers colored by the site.

4.2 Precipitation events

4.2.1 Was there enough space for the precipitation?

For all sites, there were precipitation events, where there was not enough space in the soil to take up the precipitation (Fig. 4.4), which was calculated with the porosity of the soil. For Juchmoos, this accounted for 8% of the precipitation events, for Rossalp it was in 53% of the cases and for Salwidili 69%. Not-enough-space-events occurred for all amounts of precipitation (Fig. 4.5), but for the smaller precipitation amounts they only appeared for Rossalp and Salwidili, not Juchmoos.

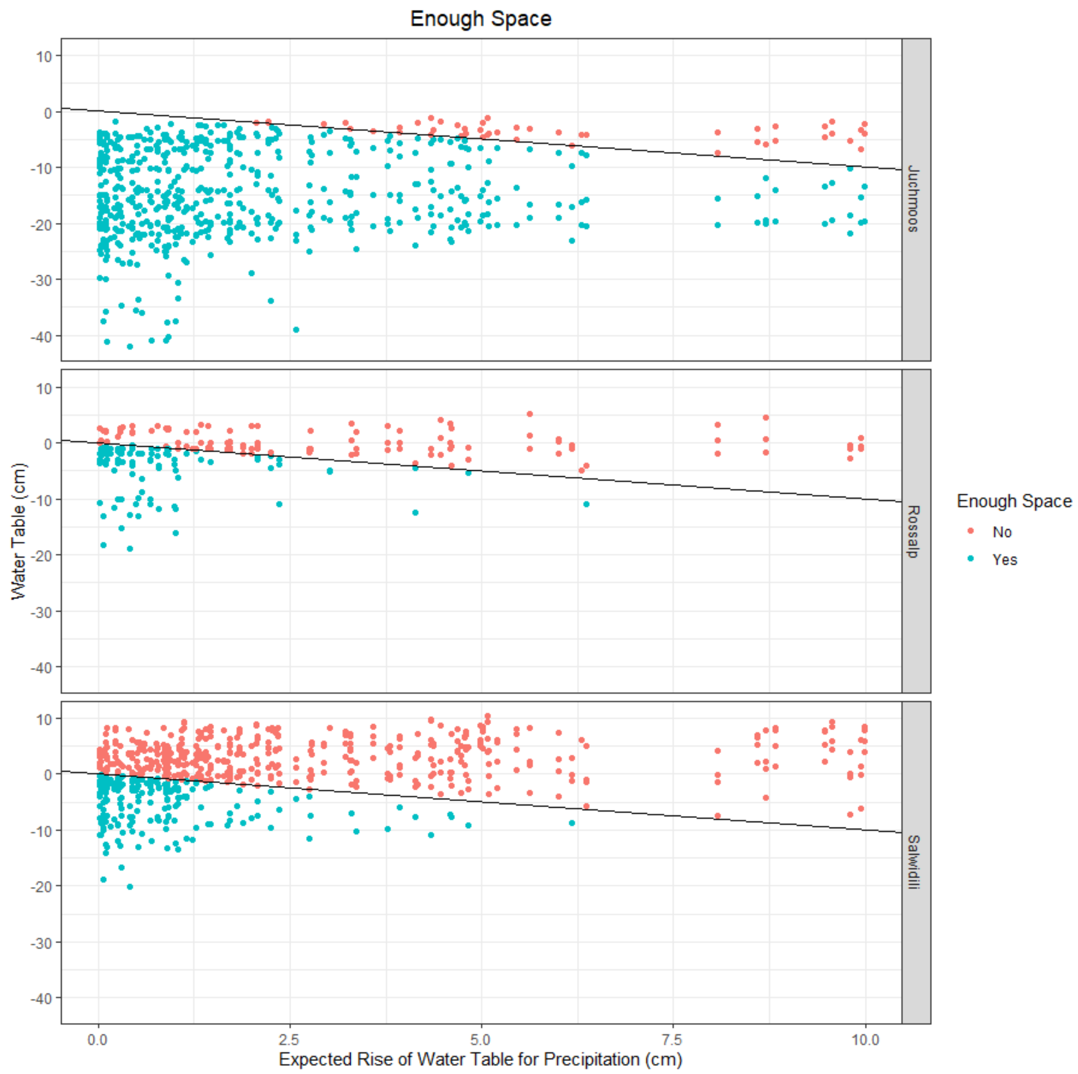
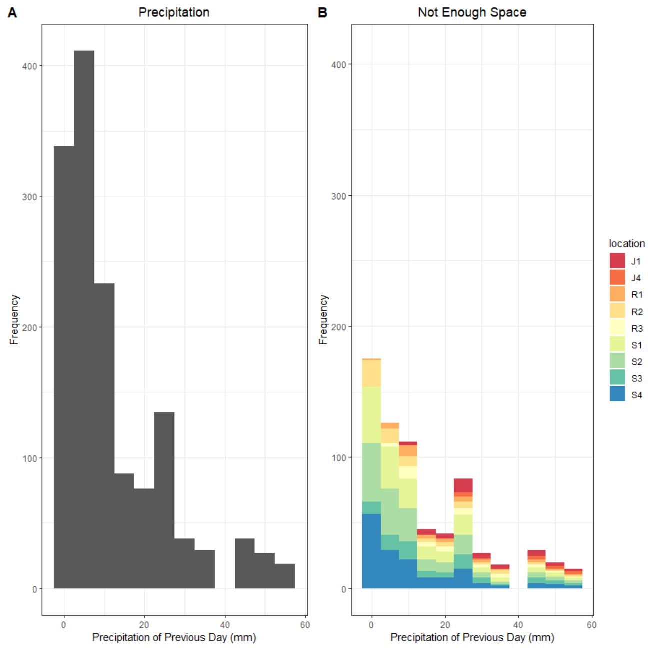
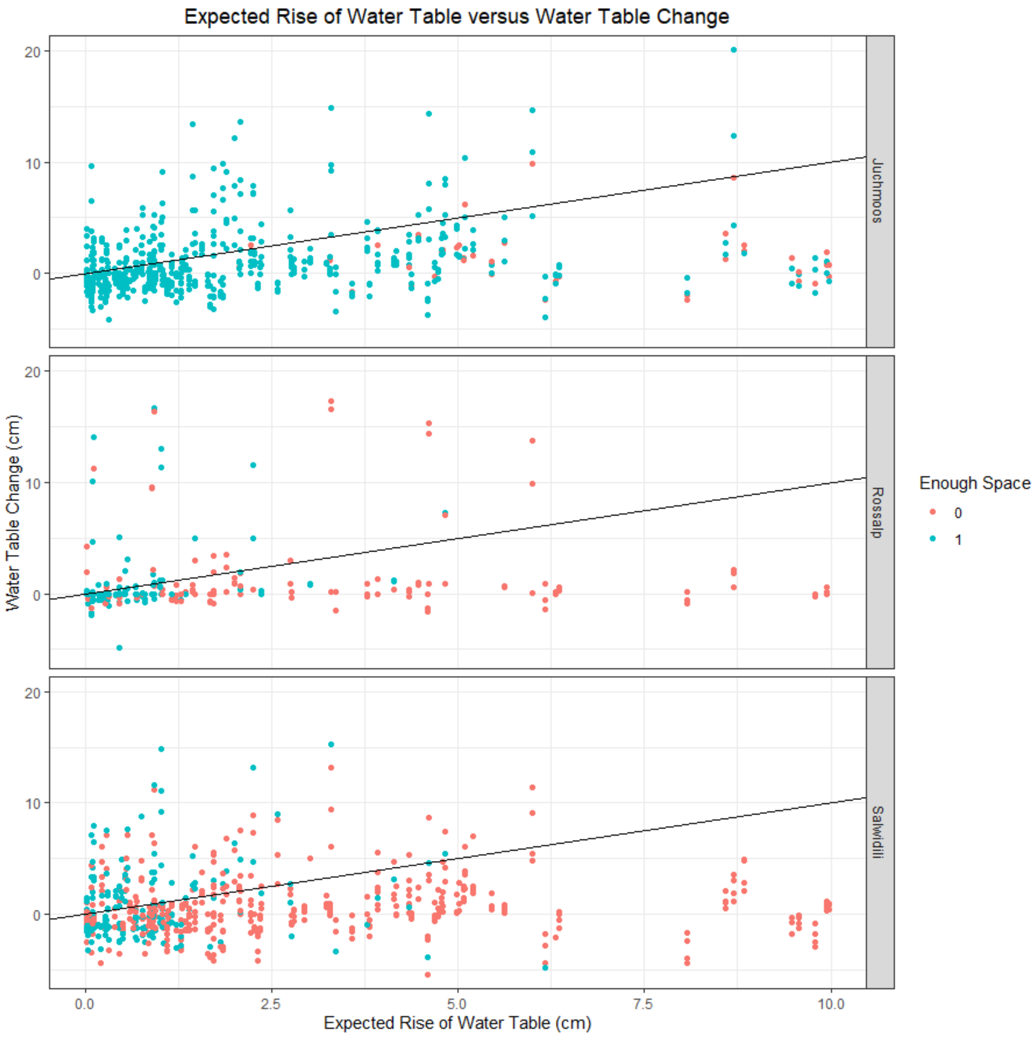


Figure 4.4: Dots mark precipitation events with on the x-axis the expected rise of water table of the rain for d_{i-1}, and on the y-axis the available space in the soil at the precipitation event. The black line marks the function $y = -x$, all the dots on this line mean that at that precipitation event, the needed space for the precipitation in the soil was equal to the available space. Dots above this line in blue represent events where the available space was larger than the expected rise, so there was enough space to take up the precipitation. Dots below the line in red mark not-enough-space-events with not enough space in the soil to take up the precipitation.

Figure 4.5 (right): Frequency of the different amounts of precipitation (A) and frequency of the not-enough-space-events for the different amounts of precipitation (B).

Figure 4.6 (bottom): Comparison of the expected rise of water table for precipitation d_{i-1} and the effective water table change. The black line marks the function $y = x$, dots on this line mark a change of water table that corresponds exactly to the expected rise of water table for precipitation d_{i-1}. Dots above this line mark events where the soil took up more water than expected. Dots under the black line mark events where the water table rose less than expected. The color of the points indicates if there was enough space for the precipitation d_{i-1}.





4.2.2 Water table change with precipitation

For all sites, there were events where the water table rose more than the precipitation d_{i-1} was expected to cause (Fig. 4.6). This was also the case when there was not enough space in the soil to take up the water (red dots above the black line). In total, the water table rose more than expected in 26% of the precipitation events for Juchmoos, for Rossalp 22%, and Salwidili 25%. These events mostly took place with low precipitation. On the contrary, there were also precipitation events were the water table rose less than expected, even though there was enough space (in Fig. 4.6 the blue dots under the black line). This was the case for 67% of the precipitation events in Juchmoos, 36% in Rossalp, and 20% in Salwidili. This occurred for little as well as large amounts of precipitation (Fig. 4.5). It is shown that for little precipitation, there was mostly enough space available, whereas for the larger amount of precipitation it was more the case that there was not enough space.

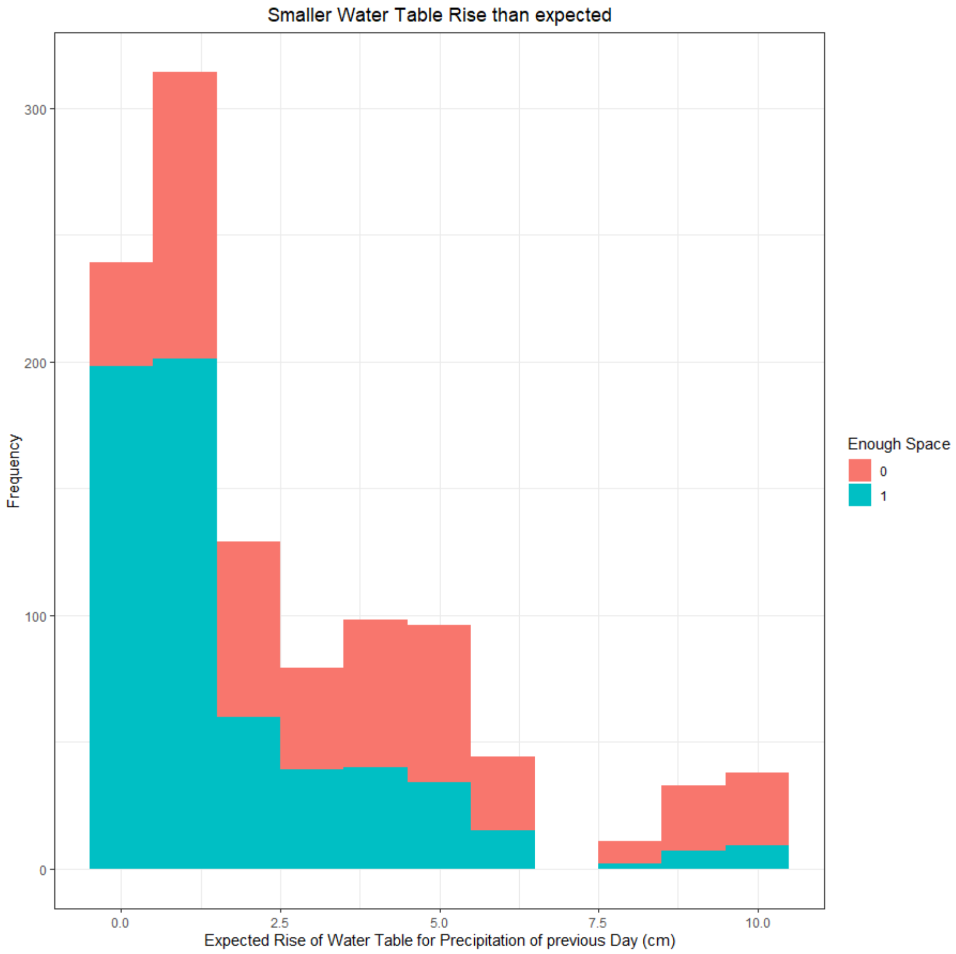


Figure 4.7: If the water table rose less than the expected for the precipitation d_{i-1}, the event is counted in this histogram. The events are sorted by the expected rise of the water table on the x-axis and the colors indicate if there was enough space in the soil.

4.2.3 Length of precipitation period

Independent from the amount of wet days in a row, the water tables could always sink, even though it rained (Fig. 4.8). There is a clear shift of the water table changes in positive direction at the second and third day, visualizing the delayed effect of precipitation on the water table calculated in the LME (Chpt. 4.1.1). The longer the precipitation period, the smaller was the variation of water table change.

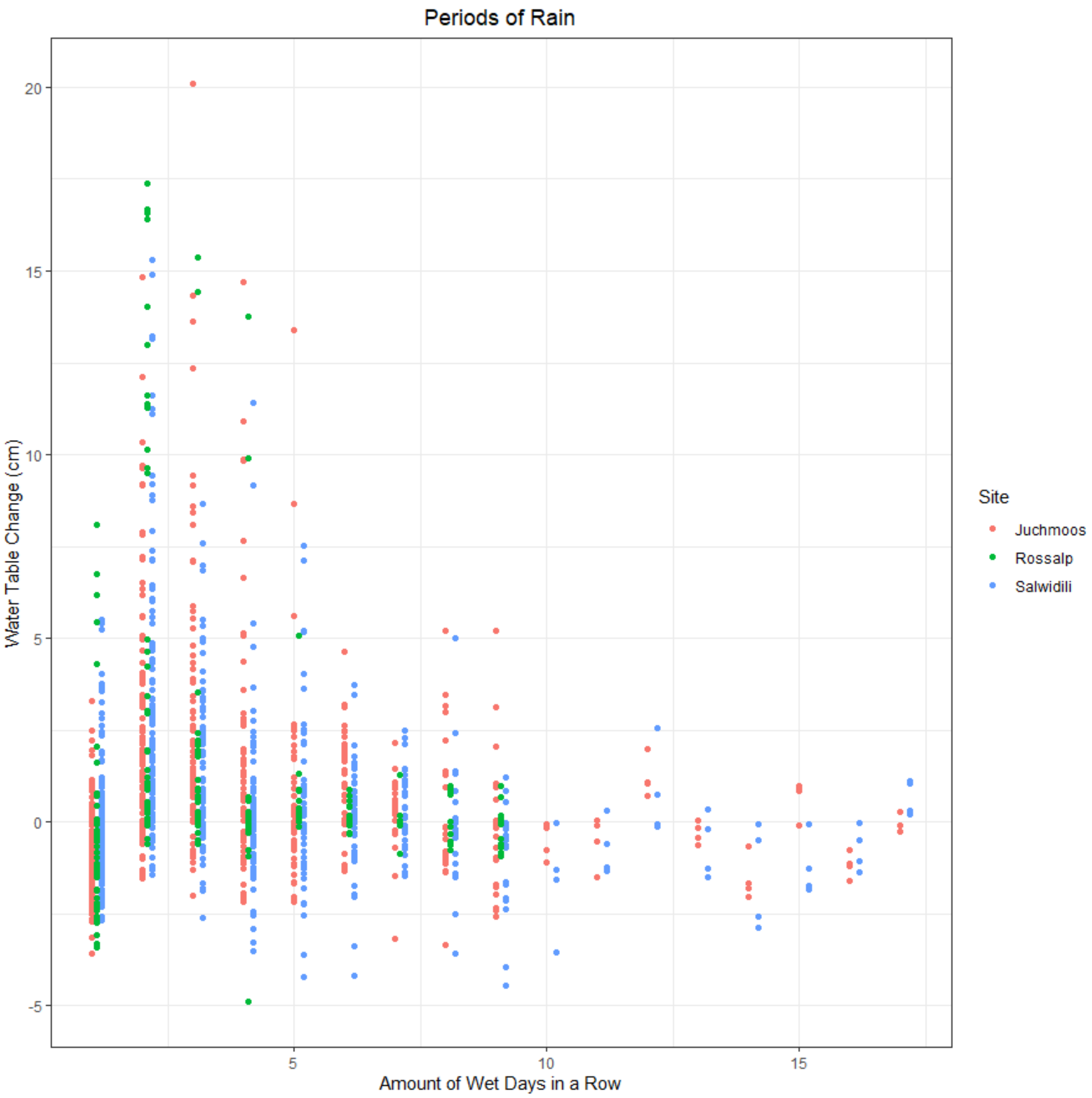


Figure 4.8: The change of water table is shown depending on the amount of wet days in a row. The different sites have different colors and are depicted slightly next to each other to avoid overlay.

4.3 Water release

Temperature and amount of dry days in a row had a negative effect on the water table, indicating that the warmer the air and the longer without precipitation, the lower the water table was. The effect of the amount of dry days in a row is shown in Fig. 4.9. The first day without precipitation could still have had a positive change of water table (Fig. 4.9). This matches the model of Chapter 4.1.1, which shows the influence of the precipitation of d_{i-1} on the water table. After the first dry day, the change of water table was mostly negative, and the later in a dry period the less the water table changed, similar to days with precipitation. This was the case for all sites.

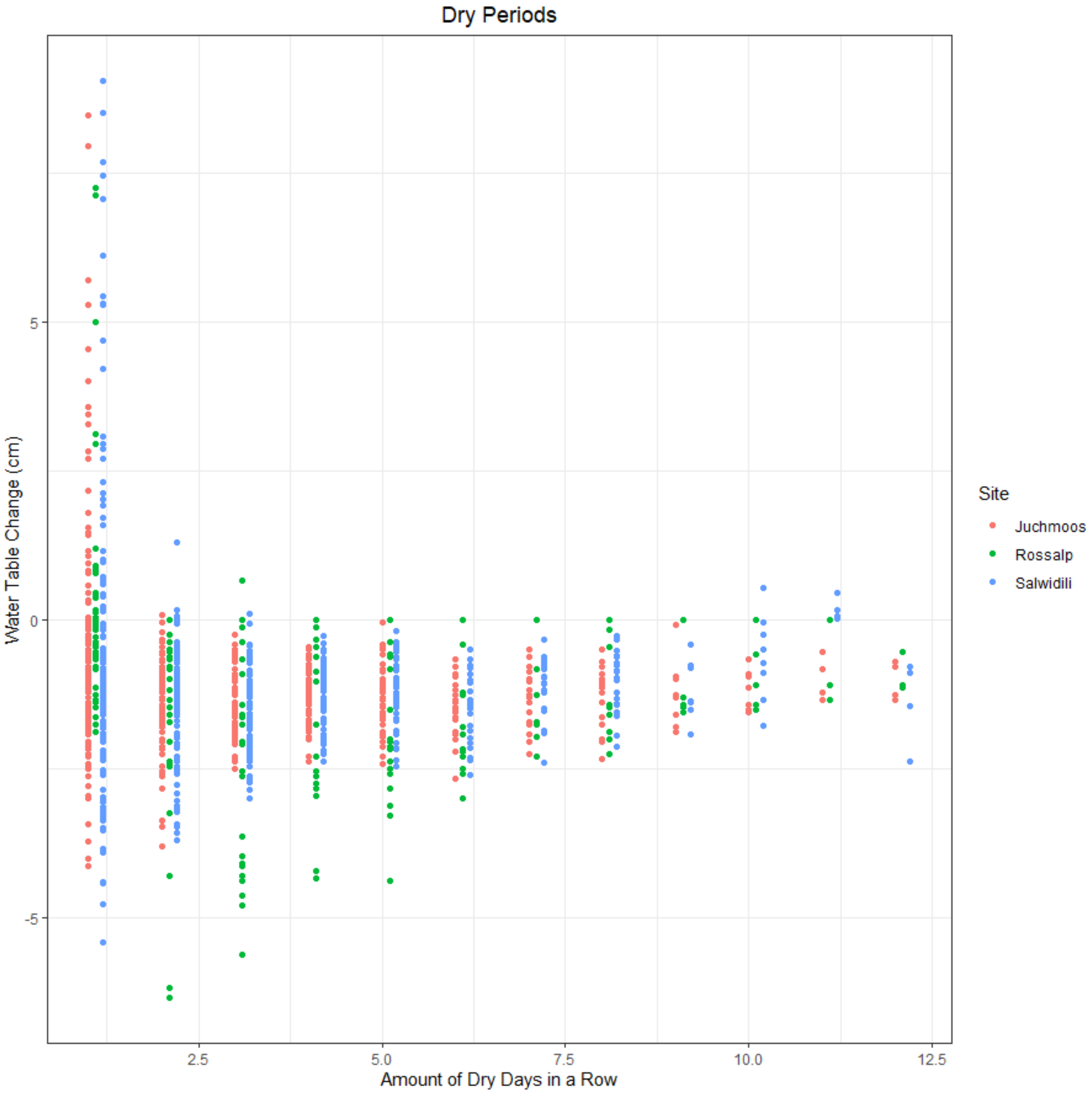


Figure 4.9: The change of water table is shown depending on the amount of dry days in a row. The sites have different colors and are slightly next to each other to avoid overlay.

Chapter 5

Discussion

5.1 Water table course

The water tables of all piezometers fluctuated and showed rises, which indicate recharges caused by precipitation, and recessions, which were a combination of outflow and evapotranspiration [Menberu et al., 2016]. The piezometers of the sites fluctuated similarly and reacted alike to the weather conditions, which is also observed in the previous study in Entlebuch [Marty, 2021]. This parallel fluctuation is also shown in studies by Słowińska et al. [2010] and Zarzycki et al. [2020]. Small dissimilarities between the piezometer can be explained by the effect of microhabitats [Wieder and Vitt, 2014]. Factors like vegetation, hydrology and topography influence the extremely local climate, the so-called microclimate [Wieder and Vitt, 2014; Davis et al., 2019]. This microclimate has a significant impact on the water table and its fluctuations [Zarzycki et al., 2020; Davis et al., 2019]. In addition to the microclimate, the porosity varied between the different sites [Knaus, 2022]. Because porosity influences hydraulic conductivity, the hydraulic conductivity differed as well for the sites. Therefore, water flow, and with that re- and discharge of the water tables, occurred at a different speed [Knaus, 2022]. Altogether, the microclimate and varying porosity caused small variations in the reaction of the water tables on precipitation, evapotranspiration and outflow.

Of the influencing factors on the water table, two factors were identified that lower the water table: temperature and dry days in a row. The negative correlation means that warmer temperatures lower the water table more than colder temperatures. In the previous study in the same study area executed by Marty [2021], no influence of temperature on the water table was found. But Marty [2021] only looked into water table elevations, and not water table lowering events. Because evapotranspiration is stronger during dry periods [Bourgault et al., 2017] and has a lowering effect on the water table, it is clear that Marty [2021] did not find an influence of temperature on the water table. In contrary to the findings of Marty [2021], other studies found an water table lowering influence of temperature [Zarzycki et al., 2020; Słowińska et al., 2010; Bridgham et al., 1999], which is in line with the findings of this examination. A thorough search of the relevant literature yielded only related articles about the influence of temperature but not about dry periods. The effects of dry periods on the water table are further discussed in chpt. 5.3.

Besides the water table lowering effects, factors that rose the water table were analyzed. Precipitation of the day itself (d_i) did not have a significant influence on the water table. Other studies on raised bogs in Poland by Zarzycki et al. [2020] and Słowińska et al. [2010] also found no or low correlation of precipitation d_i with the water table. Słowińska et al. [2010] investigated a higher influence of precipitation at the border of the bog, probably because the peat at the border receives runoff from the surrounding, and therefore was greater influenced by precipitation. In this study, precipitation d_{i-1} had a significant impact on the water table, indicating a delayed influence of the precipitation on the water table in raised bogs in Entlebuch. As well as for the dry period, no comparable studies were found where the influence of precipitation of previous day was investigated.

The previously discussed factors had a significant influence on the water tables of the raised bogs in Entlebuch. However, there exists a considerable disparity between the sites regarding topography, degradation, and coverage. In the following sections, it is more looked into the single sites and their water table behaviour.

Juchmoos

The water tables in Juchmoos were the lowest compared to the other sites. Normally, water tables are mostly around -5 cm [Daniels et al., 2008; Breeuwer et al., 2009], but at Juchmoos most water tables did rarely rise above -9 cm. During dry periods, water tables can sink up to -30 cm, but at Juchmoos, the water table at J3 even dropped to -42.9 cm. This low water tables were mainly caused by the drainage channel, which also caused a gradient in water table height from the lowest at J3, the piezometer the closest to the channel, over J2 in the middle to J1, the furthest away from the channel [Menberu et al., 2016]. J3 and J4 were both close to the drainage channel and their water tables were affected the strongest by it. This was seen in a very low water table, high variation of the water table height and high releases of water per day [Menberu et al., 2016; Price, 2003]. These higher fluctuations caused by the drainage channel induced steeper slopes in the hydrographs, which display quick runoff and high runoff peaks in the streams below [Menberu et al., 2016]. This fast runoff with high runoff peaks could cause downstream floods [Acreman and Holden, 2013], which is the contrary of the expected flood attenuation effect of bogs.

Piezometer J2 was also influenced by the drainage channel, but less than J3 and J4. At J2, the roots of pine trees and bilberry shrubs had probably a larger influence on the water table. They absorb water from greater depth than *Sphagnum* and extract water of micropores [Schouwenaars, 1993]. The woody plants also explain the low variation of the water table at J2. The coverage reduced the access of precipitation to the ground, which caused smaller water infiltration [Zarzycki et al., 2020; Rydin and Jeglum, 2013]. The shadow of the vegetation reduced evaporation from the peat surface [Zarzycki et al., 2020]. The combination of the rainfall interception and the shadow reduced water table fluctuations at J2. The vegetation is the main factor controlling the water table, but according to Tembata et al. [2020], coniferous trees do not attenuate floods, indicating that the pine trees at J2 do not prevent floods. However, shrubs attenuate floods [Kong et al., 2022], which implies that the area around J2 prevents floodings. Tembata et al. 2020

In contrary to the piezometer discussed so far, J1 is located in peat with a reasonable good state. However, the average water table of J1 is relatively low with its -8.2 cm compared the findings of Daniels et al. [2008], where 70% of the measured water tables were within 5 cm below the surface. This slightly lower water table could have been caused by the coverage of the deciduous shrub *Frangula alnus*, which has the same effect on the water table and floods as the bilberry shrubs at J2. Because the roots of shrubs are not as deep as the roots of the deep-rooted pine trees, the water table is not lowered as much as at J2.

At Juchmoos, the water table differs between the piezometer. The drainage channel is the main influencing factor on the water tables at J3 and J4 and supports fast runoff, and therefore enhances floods. On the other hand, the water tables at J1 and J2 are mainly influenced by the vegetation, but depending on the type of vegetation, the effect on floods differs.

Rossalp

At Rossalp, the water tables are mainly just below 0, probably because of the acrotelm destruction and soil compaction [Knaus, 2022]. Former trampling of cattle damaged the moss, which led to a destruction of the acrotelm and compaction of the catotelm [Knaus, 2022]. Because of the compaction, the pores are smaller, and consequently the capillary forces are high and hydraulic conductivity is low. Water is held back in the peat and water flow is impeded [Rydin and Jeglum, 2013]. Consequently, the water table stayed high.

The most remarkable at Rossalp is the large difference of water table fluctuations between R1 and R2, and R3. R1 and R2 had exceedingly high water table fluctuations, whereas R3 fluctuated to a minimal extend. In contrast to the other sites, the acrotelm is missing at Rossalp because of former trampling damage by cattle. It is in the acrotelm, where the water table fluctuates [Rydin and Jeglum, 2013], but because of this missing layer, the fluctuations are reduced to a minimal extent. Furthermore, recolonization of *Sphagnum* at R3 increases the resistance of the surface water flow [Gao et al., 2018]. This in combination with the flat topography lead to impeded water runoff on the surface. The high water table and the low fluctuations in R3 are necessary for the recovery of *Sphagnum*, however, it can take years for the acrotelm to recover, and in some cases, damage is even irreversible [Menberu et al., 2016]. In contrast to the positive effect on the recolonization of *Sphagnum*, the water infiltrates at a low speed and to a minimal extent, which is why the peat around R3 does not attenuate floods.

Not only R3 but also the areas at Rossalp did not have acrotelm. But in contrary to R3, R1 was close to a small natural ditch. Such ditches cause higher fluctuations [Menberu et al., 2016], which was already seen at Juchmoos. The difference with Juchmoos is that the water table at R1 was on average higher, but this is explained by the former trampling of cattle [Knaus, 2022].

Furthermore, piezometer R2 also showed high fluctuations of the water table, even though the soil was trampled. This piezometer was located close to an open water body that is drained by a slope. This adjacent slope facilitated runoff and caused high water table changes. Also this high runoff speed does not attenuate floods.

To conclude, the main influencing factors on the water table and its fluctuations at Rossalp were the degradation by trampling, the natural ditch and an adjacent slope. All factors did not contribute to slower runoff, which is why the raised bog at Rossalp did not attenuate floods.

Salwidili

At Salwidili, the water tables were around the surface. This was expected for a non-degraded bog [Rydin and Jeglum, 2013; Daniels et al., 2008]. Piezometer S3 had compared to the others a low water table. This is mainly explained by the spruce forest nearby. The roots of the spruces extract water from a greater depth compared to *Sphagnum* and draw water that is kept in the peat with a higher tension [Kettridge et al., 2013; Schouwenaars, 1993]. Therefore, they lower the water table to a greater extent than *Sphagnum* [Schouwenaars, 1993; Kettridge et al., 2013; Zarzycki et al., 2020]. But because spruces are shallow-rooted [Catoja, 2021], they do not lower the water table as much as the pine trees at Juchmoos, which are deep-rooted.

Towards the margin of a bog, it es expected to see lower water tables with higher fluctuations [Howie and van Meerveld, 2012]. This was not observed between S2 and S1. It is assumed that the former trampling at S2 overpowered this effect. It namely caused a compaction of the soil and consequently, the water table was higher and the fluctuations lower, as already seen in R3. The compaction caused the same effect as at R3, namely the water infiltrated at a low speed, which is a disadvantage to reduce floods.

For piezometer S4, the open water body and its influx stabilized the water table and reduced its fluctuation [Marty, 2021]. The constant high water table prevented high infiltration rates and caused low water absorption by the peat. However, a high water absorption is crucial to attenuate floods.

Overall, there were tree main influencing factors on the water table at Salwidili. This includes the water table lowering effect of spruce trees, the compacted peat because of former trampling, and a constantly high water table because of steady influx. The latter two reduce water infiltration and therefore foster saturation-excess overland flow.

To summarize the water tables and their influencing factors of the raised bogs in Entlebuch, it can be stated that the water tables reacted alike to the weather parameters temperature, amount of dry days in a row and precipitation of d_{i-1}. The water table heights and their fluctuations varied between the piezometer and were influenced by different environmental and man-made factors. Rossalp and Salwidili had generally high water tables in contrast to Juchmoos. At Juchmoos, the water tables were low for a raised bog, which is why the first hypothesis has to be rejected. Additionally, the degradation influenced the water table, but depending on the type of degradation, the water table was influenced in a different way. Only Juchmoos, where degradation was caused by a drainage channel, had a lower water table. Rossalp, which was the degraded bog because of trampling, did not have a lower water table. Not only the water table but also the fluctuations differed between the types of degradation. The drainage ditch caused higher water table fluctuations, while the trampling did the opposite. Therefore, the fourth hypothesis also has to be rejected.

5.2 Precipitation events

5.2.1 Enough space

Next to the general water tables in the bog, it was investigated how the bogs reacted on precipitation. It was first looked into the not-enough-space-events, which occurred for all sites but with different frequencies. The low occurrence at Juchmoos (8%) can be explained by its generally low water tables at all measuring stations caused by the drainage channel and shrub coverage [Menberu et al., 2016; Acreman and Holden, 2013]. At Rossalp, there was not enough space to take up the fallen rain for 53% of the time, mainly triggered by the generally high water table in the bog, caused by the acrotelm destruction and soil compaction because of former trampling [Knaus, 2022]. The even higher water table at Salwidili gave the bog the highest frequency of not-enough-space-events with 69%, which was expected because non-degraded bogs have high water tables [Rydin and Jeglum, 2013; Daniels et al., 2008]. All sites had for all amounts of precipitation at some point not enough space. The reasons differed from site to site, but all are related to the state of the bog.

5.2.2 Water table change with precipitation

At days with precipitation, the water tables rose in some cases more, in some cases less than expected. And sometimes the water table rose more than the precipitation was expected to cause, even though there was not enough space in the soil. In the following section, different explanations are discussed, why the water tables rose more or less than expected.

For 20% of the precipitation events, the water tables of the raised bogs rose higher than expected, mostly for smaller precipitation amounts. This higher rise of the water table could have been caused by water influx from the surrounding, what again means that the bog functioned as a sponge [Acreman and Holden, 2013]. On the other hand, there were some cases, where there was not enough space in the soil to take up all the rain, and the water table still rose more than the precipitation was expected to cause. This was often the case for the sites Rossalp and

Salwidili, probably caused by water accumulation on the peat surface due to the saturation of the soil and low runoff rates. It was expected that water would run off as soon as the water table rose to a larger extent above the peat, this means that the water table would not rise much above 0 cm (up to 5 cm above surface was measured by Daniels et al. [2008]). But at some locations, the water accumulated on the peat instead of running of, causing positive water tables up to 10 cm above to surface. Therefore the water tables rose higher than expected, which caused higher water table rises. Additionally, not only precipitation of d_{i-1} had an influence on the water table but also of d_{i-2} and d_{i-3}, but they were neglected in subsequent calculations. They probably also caused higher water table rises than expected for precipitation of d_{i-1}.

For most precipitation events, the water table rose less than expected for the fallen precipitation. This occurred often at Rossalp and Salwidili. The reason was probably often the already high water table, which led to a fast saturation of the soil. Consequently, saturation-excess overland flow, but also subsurface flow occurred independently of the precipitation intensity [Evans et al., 1999; Daniels et al., 2008; Emili and Price, 2006], which both are the most common outflows of bogs and have a high water flux, whereby the saturation-excess overland flow is clearly faster compared to the subsurface flow [Holden et al., 2008]. This fast water runoff is not in alignment with the expected sponge effect raised bog should have. On the other hand, some water tables rose less than expected, even though there was enough space in the soil. Not saturation, but other water table lowering mechanisms led to a smaller rise than expected. It was often the case for low precipitations that there was enough space but the water table rose less than expected. For days with high temperatures and low precipitation, it was expected that more water evaporates on such days than it rained. Alternatively, other outflow processes could have dominated like infiltration-excess overland flow or pipeflow, whereby the former only occurs with high precipitation intensities [Daniels et al., 2008; Acreman and Holden, 2013]. The former is a rather infrequent assumed process for raised bogs, but causes fast overland water flux, while the latter has an estimated frequency of 10 - 30% [Holden et al., 2001; Daniels et al., 2008; Cunliffe et al., 2013]. For pipeflow, the water is taken up by the soil and runs of in a slower speed than on the surface. Therefore, this mechanisms contributes to a sponge effect of the raised bogs.

However, these numbers should be interpreted with caution, taking into account that this percentages depend on the porosity of the soil, which in turn was assumed to be 0.53 according to the findings of Quinton et al. [2008], but porosity was never measured at the study sites. If the effective porosity was smaller than estimated, the calculated ratio of how many times the bogs acted like a sponge would have been smaller. It would have been the contrary if the effective porosity was larger than assumed.

Not only the expected water table rise was investigated, but also the change of water tables with the length of wet period. The longer the rain period, the smaller the water table change. The slower rise with time can firstly be explained by the higher porosity in the upper part of the soil. Consequently. the higher the water table the slower the rise of the water table [Price and Schlotzhauer, 1999]. Secondly, the higher in the soil the higher the hydraulic conductivity and the more subsurface flow, which leads to a constant lowering of the water table [Holden and Burt, 2003b]. Finally, the high water tables probably led to saturation of the soil, and consequently water table rises were not possible anymore [Acreman and Holden, 2013].

To summarize the reaction of the raised bogs when it rained, it can be stated the sites had different ratios of not-enough-space-events. Juchmoos with a generally low water table often had enough space in contrast to Rossalp and Salwidili. Therefore, the second hypothesis has to be rejected. However, in 1/5 of the precipitation events, the raised bogs took up more precipitation than expected. It was assumed that the bogs took up additional water from the surrounding, and they therefore acted as sponges. For all other days of precipitation, there are several reasons why the water table rose less than the precipitation would have caused. The reason mainly depended on the antecedent water table. High water tables could have caused that evapotranspiration rates exceeded the amount of precipitation, so the water table rose less than expected. Another reason could have been saturation of the soil and the limited space to take up precipitation, whereby saturation-excess overland flow occurred. Additionally, other outflow processes such us pipeflow or infiltration-excess overland flow caused the lowering of the water table. However, the uncertainty about the porosity should be taken into account. Therefore, it cannot be directly concluded that the bog was not acting as a sponge in these cases and circumstances.

5.3 Water release

After absorbing water of precipitation, the peat bogs release water through evapotranspiration and runoff. Temperature was used to measure the evapotranspiration rate, because it is the main influencing factor [Bridgham et al., 1999; Chen et al., 1999]. Oosterwoud et al. [2017] showed in their study of a raised bog in Estonia that evapotranspiration had a higher influence on the water table than discharge during summer months. However, in this study the water table did not only depend on temperature, but also on the amount of dry days in a row. The longer the dry period the lower the water table, which was also observed by Daniels et al. [2008] in a study in the UK. But the later in a dry period, the less the water table sank. This phenomenon can be explained with the sinking water table and the consequently lower evapotranspiration rates because of the higher capillary forces due to the smaller pores [Słowińska et al., 2010; Bourgault et al., 2017; Kettridge et al., 2013]. Along with that, the hydraulic conductivity is smaller in depth, for which reason the subsurface outflow is reduced with a lower water table [Evans et al., 1999]. In situations with very low water tables, it is even possible that seepage is the only discharge process [Exler, 2015].

How much of the water run off and what the dominant process was, depended on the height of the water table [Daniels et al., 2008; Evans et al., 1999]. High water tables mainly cause high evapotranspiration rates, saturation-excess overland flow and subsurface flow. Lower water tables in contrary have a higher proportion of pipeflow and seepage. Different processes of runoff have different speeds, but overland flow has by far the highest flux [Rydin and Jeglum, 2013]. Therefore, raised bogs release water constantly and with that, the third hypothesis can be accepted.

5.4 Future research

To gain a better understanding of the function of the raised bogs in Entlebuch, further research is of high importance. Additional measurements could improve the understanding of the water balance of the raised bogs. In the following sections, some of them are listed:

In this study, it was only looked into the water table. To understand the complete water household of the raised bogs in Entlebuch, additional measurements should be carried out. The different discharge types and evapotranspiration should be measured to make more precise statements about the release of water. Additionally, the hydrographs of the raised bogs should be compared to a hydrograph of a downstream river to analyse if there are delayed peak flows and reduced peaks.

A second important factor is the infiltration speed of water in the peat. This is namely important to know how fast precipitation infiltrates and if this is a limiting factor for the raised bogs in Entlebuch. In case of low infiltration, water would run off, even though the bog is not completely filled with water. This would be the contrary effect of a sponge. Furthermore, climate change will increase frequency of extreme weather events such as heavy precipitation [Tabari, 2020]. This could mean that the infiltration rate becomes a more limiting factor for water infiltration, and could therefore cause more overland flow.

5.5 Data limitation

To some extent, available data was insufficient or limited to answer the question precisely. The following enumeration includes some of the limitations:

The porosity and storage capacity of the peat were unknown, and assumptions had to be made. For more precise results, the porosity should be identified to calculate the storage capacity. This is essential to calculate the outflow and evaporation [Bourgault et al., 2017]. It is an advantage, to know the porosity of all sites to compare degraded with non-degraded raised bogs.

The weather data station was not exactly in the raised bogs but had a distance of 6 - 9km. It is unclear how precise the weather data described the conditions at the sites.

Chapter 6

Conclusion

There are multiple ways in which peatlands alter floods. This includes for example a delayed peak flow, a reduced peak or a decreased runoff volume. Because of their absorption and delayed release of water, it is assumed that they act as a sponge, absorbing water during wet periods and releasing water during dry periods.

In this study, it is found out that the raised bogs in Entlebuch take up water during precipitation. In 20% of the precipitation events, all the amount of rain or even more was absorbed by the raised bogs, indicating that the bogs acted like a sponge. This was mainly the case for low precipitation amounts.

During wet as well as dry days, the raised bogs lost water in form of evapotranspiration or outflow. Which process of outflow dominated depended on environmental as well as man-made factors and the antecedent water table. Different factors determined the water tables and its fluctuations at the different sites. These factors had with their influence on the water tables a direct or indirect effect on floods. The determining processes and their influence on floods are summarized in the following table:

Table 6.1: Summary of main water table influencing factors found for the raised bogs in Entlebuch. Observed factors are described with their mechanism of how they influence floods, where they were observed, and if the factor had a positive (+), negative (-) or a neutral (0) effect on floods.

Factor	Mechanism	Piezometer	Flood attenuation
Coniferous tree	unknown	J2, S3	0
Ditch	fast and high runoff causes increased peak flow	J3, J4, R1	-
Open water body	The constant high water table results in a low water take up capacity. The soil is rapidly saturated, which leads so saturation-excess overland flow	S4	-
Shrubs	unknown	J1, J2	+
Slope	fast runoff causes increased peak flow	R2	-
Trampling	Trampling by cattle causes acrotelm destruction and soil compaction. The consequently low hydraulic conductivity leads to a generally high water table, which causes fast saturation of the soil. As a consequence, saturation-excess overland flow occurs	R1, R2, R3, S2	-

The summary shows, that most factors influencing the water table and its fluctuations do not attenuate floods, they sometimes even have intensifying effects on floods. However, it is important to mention, that some knowledge is still missing to answer the question completely. In this study, it was only looked into the water tables and their reaction on weather variables.

This plays an important role in the flood alteration, but to get the whole picture, further research is of high importance. To understand if and how the raised bogs in Entlebuch alter floods, it is especially important to investigate the runoff timing and speed for different weather conditions.

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Appendix A

Appendix

A.1 Declaration of originality

ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Declaration of originality

The signed declaration of originality is a component of every semester paper, Bachelor's thesis, Master's thesis and any other degree paper undertaken during the course of studies, including the respective electronic versions.

Lecturers may also require a declaration of originality for other written papers compiled for their courses.

I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor.

Title of work (in block letters):

Flood Alteration of the Raised Bogs in Entlebuch, Switzerland

Authored by (in block letters):

For papers written by groups the names of all authors are required.

Name(s):	First name(s):
De Groote	Justine

With my signature I confirm that

- I have committed none of the forms of plagiarism described in the 'Citation etiquette' information sheet.
- I have documented all methods, data and processes truthfully.
- I have not manipulated any data.
- I have mentioned all persons who were significant facilitators of the work.

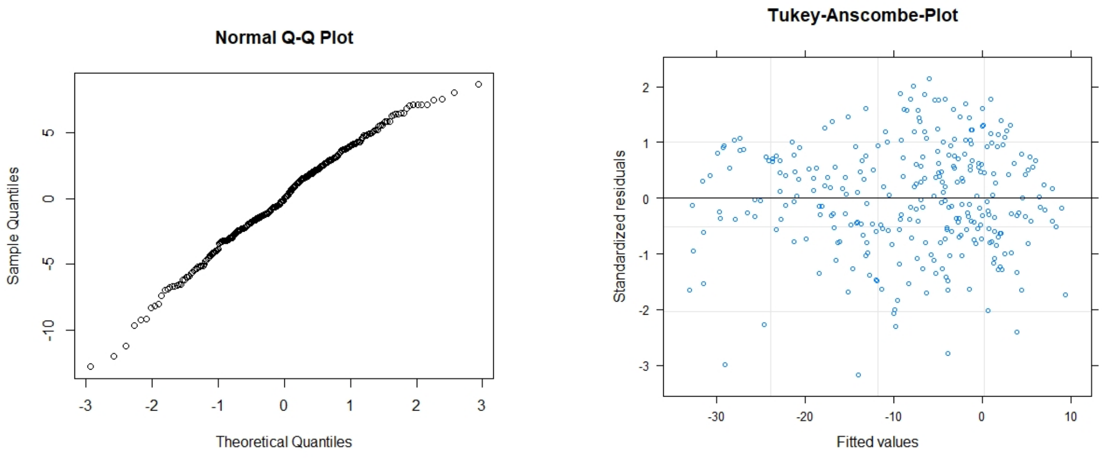
I am aware that the work may be screened electronically for plagiarism.

Place, date	Signature(s)
Zurich, 12.06.2022	

For papers written by groups the names of all authors are required. Their signatures collectively guarantee the entire content of the written paper.

Figure A.1: Declaration of originality

A.2 Linear Mixed-Effects Model



(a) QQ-Plot (b) Tukey

Figure A.2: (a) QQ-Plot of LME: The QQ-plot of the LME (a) show a linear correlation of the quantiles, indicating a normal distribution of the residuals. The Tukey Ascomb Plot of LME (b) shows the equally dispersed points around 0, indicating a normal distribution of the errors