Beaver impacts on the riverine carbon budget in a study area in Marthalen (CH)

Master thesis

Faculty of Science, University of Bern

handed in by

Raphael Fabrice, d'Epagnier

2023

Msc-Thesis Director: Prof. Dr. Bettina Schaefli, University of Bern

Msc-Thesis Co-director: Dr. Annegret Larsen, University of Wageningen

Acknowledgement

During my master's thesis, I was in constant communication with many different people who gave me suggestions, helped me with questions, assisted with data collection, and proofread my work at the end. Without this support, my master's thesis would not have been in the same quality, for which I am very grateful. Therefore, I would like to express my sincere gratitude to the following people for their support:

Annegret Larsen

Joshua Larsen

Bettina Schaefli

Christoph Angst

Natalie Ceperley

Sarah Thurnheer

EAWAG-Team

Peter Leiser

Heinz Widmer

Carlos Pinto

Kaspar Berger

Tanja Schneider

Thank you very much!

Abstract

This master thesis was part of one of the two national beaver projects from 2021 to 2023 in Switzerland and investigated the potential of beavers to strengthen ecological infrastructure. The goal of this master's thesis was to calculate the carbon budget of a beaver-influenced area. The beaver wetland in Marthalen is the biggest impacted territory of beavers in Switzerland. To investigate the impact of the beaver wetland on the carbon balance, we measured DOC, DIC, and suspended sediment from inflowing and outflowing stream, and CO_2 and CH_4 emissions from the beaver pond and wetland soil at regular intervals throughout 2022. We also collected soil samples to determine the annual carbon stored in the soil and measured the water volume of the entire beaver pond. The analysis shows that more carbon is imported than exported and therefore the study area is a carbon sink. DIC imports and exports and CO_2 exports from the beaver pond and wetland had the biggest impact on the carbon balance, with CO_2 emissions from the wetland significantly higher than those from the pond. On average, 8.67 kg $CO_2/m^2/a$ is emitted from the wetland and 1.16 kg $CO_2/m^2/a$ from the beaver pond. In comparison, CH_4 emissions had little impact on the carbon balance. The findings from this master's thesis and additional research from national beaver projects should help decision makers reintegrate beaver as ecosystem engineers in the future.

Table of Content

List of Figures

List of Tables

1 Introduction

1.1 Context and relevance of the research field

There are two species of beaver in the world. The castor canadensis lives in North America and the castor fiber in Eurasia. Before man started hunting beavers, the population was estimated at 100 million European beavers and 60 million Canadian beavers. At the beginning of the 19th century, the beaver was extinct in Switzerland. The beavers were exterminated for their meat, fur and castoreum (CSCF, n.d.a). The castoreum is a glandular secretion similar in taste to valerian and was used in medicine against cramps and nervousness. Castoreum today has a significance only in homeopathy (Chemie.de, n.d.). The meat of the beaver was especially popular during Lent. In the Catholic faith, eating warm-blooded animals during Lent is forbidden. However, since the beaver lives in water and its scaly tail reminds of a fish, the beaver was declared to be a fish and could also be eaten during Lent. At the end of the 20th century, only about 1000 beavers lived in Europe. Due to reintroduction and specific protection in many European countries, populations have recovered to about 750,000 individuals. Since 1962, the beaver has been protected by federal law in Switzerland and may no longer be hunted (CSCF, n.d.a). In 1956, the first beavers were reintroduced to Switzerland. The reintroduction lasted from 1956 to 1977 and 141 animals were released. Three people, Morice Blanchet, Karl Rüedi and Anton Trösch, were mainly responsible for this. They considered the beaver as an important part of the aquatic ecosystem and therefore promoted the reintroduction in Switzerland (CSCF, n.d.b). According to the last Switzerland-wide beaver population survey from the winter of 2007 / 2008, 1,600 beavers again populated Switzerland. Since this population survey, the number has continued to increase. Some cantons have already conducted beaver counts since 2008. According to this, the number of beavers in 2019 was estimated at about 3500 individuals (see Figure 1) (CSCF, n.d.b) and the last count of the national beaver population survey in 2022 showed 4914 beavers.

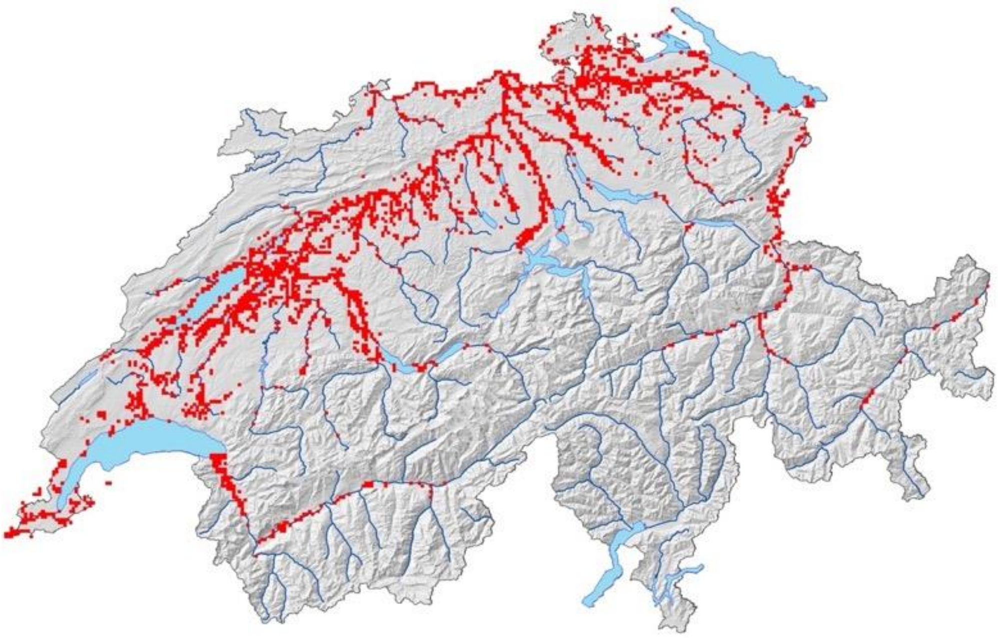

Figure 1: *Distribution of the beavers in Switzerland in 2019 (CSCF, n.d.c)*

Beavers are among the mammals that have the greatest influence on river system design, hydrology, geomorphology, nutrient cycling, and ecosystem (Larsen et al., 2021). Impoundment of the river system by beaver dams increases the extent of open water, which changes the limnology and also affects atmospheric fluxes. Damming river systems can affect water quality and ecosystem processes. Existing flow paths can be altered or new ones created, existing channels can be expanded, their velocity changed, and the interaction between flowing water and the river system can be influenced (e.g. hydraulic efficiency and residence time). These effects due to changing landscapes by beavers, have an essential impact on the carbon balance (Larsen et al., 2021). Due to the expanding beaver dam number across the headwater river network in Switzerland, it is important to understand if these influenced river systems act as net carbon sinks or sources in the future. Carbon that cannot be stored is released into the atmosphere either as carbon dioxide (CO_2) or methane (CH_4) (Roulet et al., 1997; Yavitt & Fahey, 1994). CO_2 and CH_4 are both greenhouse gases that contribute in large quantities to global warming by absorbing longwave radiation emitted from the earth into space. If more carbon could be stored than released, this could help to reduce the amount of CO_2 and CH_4 that is released to the atmosphere and so also have an impact on climate change. Therefore, measurements of the carbon balance changes in beaver influenced areas are essential information's for ecosystem managers and policy makers, to discuss the further reintegration of beavers as natural landscape architects in Switzerland.

1.2 State of the research

1.2.1 Hydrological Feedback

After colonizing a new section of river, beavers build dams to open up their territory for food, create water areas that do not freeze completely in winter, and to protect themselves from predators (Müller-Schwarze, 2011). The beaver dams reduce water velocities and increase the water depth and water surface behind beaver dams. Flooded areas can be created, with volume determined primarily by topography and stratigraphy and due to the infiltration in the flooded area, the connectivity between surface water and groundwater increases (see Figure 2) (Karran et al., 2018; Zahner, 1997).

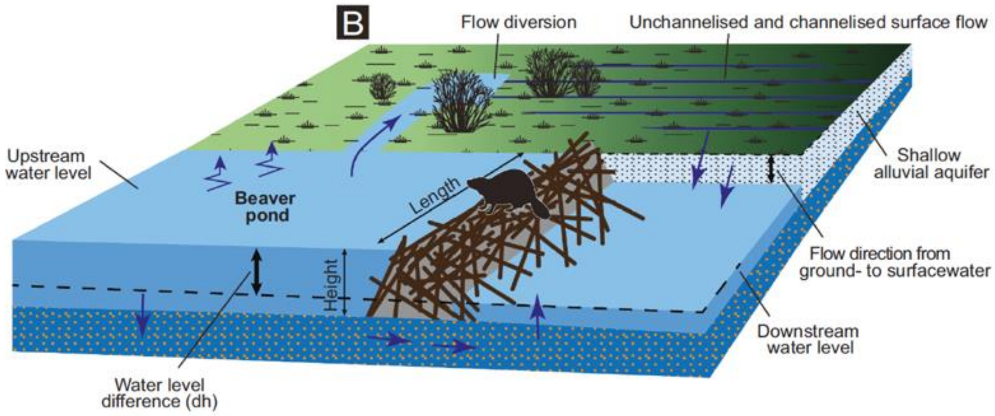

Figure 2: *Hydrological effects due to construction of beaver dams (Larsen et al., 2021).*

The dams are made of sediment, stones and branches and cause water to be dammed upstream, but are not completely impermeable to water. The dam height is often only slightly higher than the water surface upstream of the dam. This allows water to flow over the dam during a flood event. A certain amount of water also flows through the beaver dam. Depending on the construction of the dam or if the dam is damaged, the water flows through gaps and can also flow below the dam (Figure 3). By retaining the water, it causes the downstream discharge to have lower and delayed discharge peaks than upstream (Nyssen et al., 2011). Nyssen et al. (2011) focused their study on a beaver area in Belgium. The attenuation impacts happen due to the cumulative storage and flow diversions processes (Larsen et al., 2021). According to a 2D hydrometric model experiment by Neumayer et al. (2020), significant attenuation occurs only for smaller discharge events and additionally was stronger for low slopes and high floodplain connectivity. For flood events with a return period of two years or more, only a small attenuation and delay of the flood peak could be detected (Neumayer et al., 2020). In summary, beaver dammed areas only have an impact when the flood event is not too large. In addition, the floodplain roughness can also have an impact on attenuation of flood events. If the presence of the beaver leads to a higher density of shrubs vegetation, then the roughness in floodplain area increases and causes higher attenuation of flood events. If beaver presence results in lower shrub density, roughness decreases (Larsen et al., 2021; Thomas & Nisbet, 2007), and if extreme flood events damage beaver dams, discharge may be increased further downstream. In principle, further studies are needed to fully understand the effects of beaver on flood events.

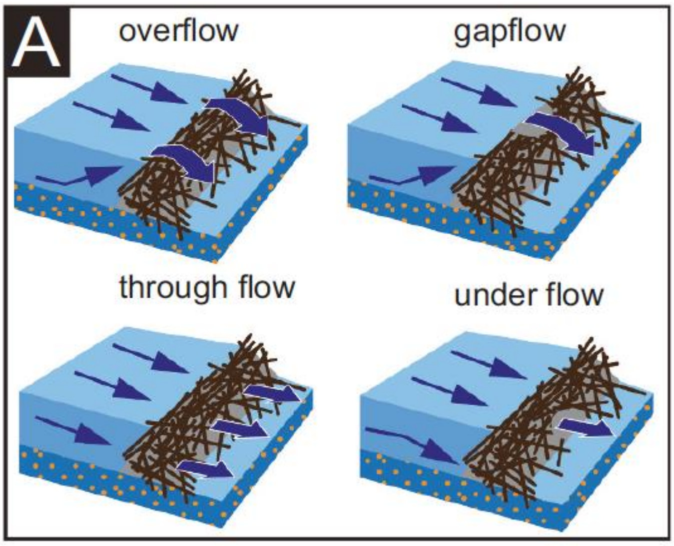

Figure 3*: Different types of flow through a beaver dam (Woo & Waddington, 1990).*

The areas behind the dams are called beaver ponds (Larsen et al., 2021). Beside the beaver ponds a floodplain can develop and with increasing ground water table a wetland areas can emerge (Chaubey and Ward, 2006; Karran et al., 2018; Naiman et al., 1988; Zahner, 1997). As water levels rise behind the beaver dam, the floodplain may be permanently inundated, increasing open water areas. As a result, the flow velocity decreases. In addition to the additional water storage in the flooded areas, the water content in the floodplain soil also increases and is permanently or seasonally saturated (Larsen et al., 2021) and fine sediment is deposited in the pond (Johnston, 2017). This allows wetland vegetation to develop that provides food supply for the beavers (Larsen et al., 2021). The landscape changes and a mosaic of aquatic and terrestrial habitats emerges. The increasing open water areas due to the beaver dams, have an influence on the water balance, biogeochemical processes and ecosystems (Jones et al., 2020). For example, surface water storage behind beaver dams increases and has an impact on greater residence time of carbon (Larsen et al., 2021). Figure 4 shows these different effects of the beavers on the river network as a function of valley shape, which is dependent of the valley slope and has an impact on the lateral connectivity. The lateral connectivity of river systems is highest with decreasing valley slope. After Beaver settled in these valleys, the longitudinal connectivity gets lower, due to the damming effect which reduce the flow velocities. In addition, rivers ponded by beavers are changing from a lotic to lentic ecosystem. Open water surfaces are created, which in turn translates into a higher vertical exchange gradient (Larsen et al., 2021). More water molecules can be evaporated and transported from the water surface to the atmosphere, but also more sediments and chemical compounds can be deposited in the water due to the lower turbulence. There is also a higher exchange between the surface water and groundwater, known as hyporheic exchange. This, in turn, leads to higher storage and residence time of water, sediments, and chemical elements such as carbon, nitrogen, and phosphorus. According to NAWA (National Surface Water Quality Monitoring), nitrogen and phosphorus levels in Swiss waters have improved in many places since 1970 (BAFU, 2013). However, some reduction targets have not yet been achieved. Especially in small streams where treated wastewater is discharged, there is little mixing, which leads to high nitrogen and phosphorus levels (BAFU, 2021). By altering the river section, the beaver can contribute to improving water quality, thus increasing the importance of the beaver as a landscape creator.

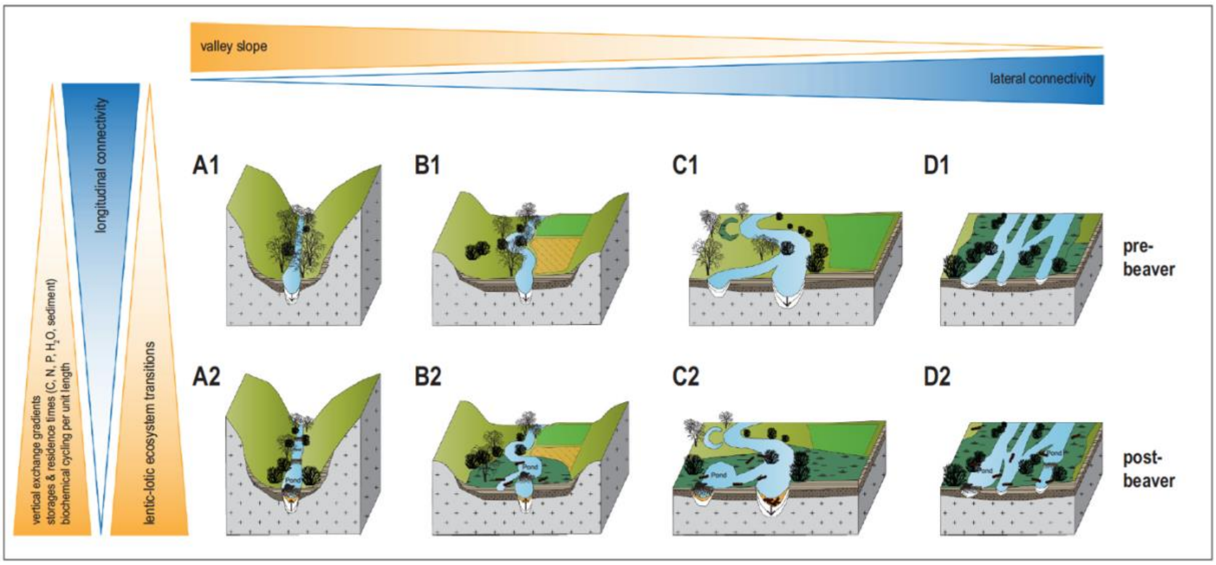

Figure 4: *Change of riverine systems due to beavers (1-2) shown on different type of river systems (Larsen et al., 2021).*

1.2.2 Carbon balance

After the beaver settles in a new area, besides hydrological changes, there are also influences on the carbon balance of the area. Carbon is stored in the sediments (blue arrow), transported in the river system to and out of the beaver impacted area (red arrows) and exported from the sediments to the atmosphere as CO_2 and CH_4 (violet & light violet arrow) (see Figure 5).

Figure 5: *Different carbon fluxes which contribute to the calculation of the carbon balance of a specific area (CSCF, n.d.d)*

1.2.3 Corg

Due to floodplains and rising water tables, woody biomass decreases when floodplains are located in forested areas. Additionally beaver fell trees which also reduce carbon stored in woody biomass (Naiman et al., 1994). But in the lentic water behind the beaver dams anaerobic conditions emerge, which slow the organic matter cycle (Naiman et al., 1994). Slower decomposition rates of woody carbon therefore favor long-term carbon storage (Larsen et al., 2021). Woody biomass from the fluvial network, which enters in the beaver system also increase the carbon storage (Hodkinson, 1975). Beaver influence creates lentic anaerobic conditions. Therefore, the amount of carbon stored in woody biomass decreases but is transferred to carbon stored in herbaceous and grassy biomass; furthermore carbon storage in sediment increases (Johnston, 2014; Naiman & Melillo, 1984; Wohl, 2013). Coarse wood and floodplain sediments are important organic carbon storage over time spans of 10^2-10^3 years. In the wetland areas dissolved inorganic (DIC) and organic (DOC) and particulate organic carbon (POC) is deposited by the river network (Wohl et al., 2012). Due to the infiltration and therefore high riparian water table, the soil in this area is saturated. This reduces microbial decomposition by organic matter and enables that DIC, DOC and POC can be deposited in the floodplain sediments (Trumbore & Czimczik, 2008). Carbon stored in the O horizons can be lost to oxidation and fire as beavers leave the area and flooded areas dry out. In comparison, carbon stored deeper in the soil is less exposed to oxidation and can be stored long-term (Johnston, 2014). So, the vertical deposition of carbon in beaver meadows have implication to the longtime storage (Johnston, 2014).

1.2.4 DOC, DIC & POC

Carbon can be transported in water as DOC, DIC or POC. DOC is the percentage of carbon that is smaller than 0.45µm. Often 0.22µm is also taken as a limit value (Cheremisinoff & Davletshin, 2015). DOC occurs as a natural component in water, but can also be increased by anthropogenic factors. Examples of this are the rain discharge from wastewater treatment plants during rain events or organic fertilizers entering the water body through erosion of the soil. This can increase not only DOC but also POC levels. However, natural factors such as, runoff from peatlands can also increase DOC concentrations. According to the Water Protection Ordinance, a DOC value between 1 and 4 mg/l is to be aimed for. However, this assessment class is problematic, because DOC is divided into easily degradable and hardly degradable and therefore high DOC values can be measured, which do not have bad effects for the water body (BAFU, 2010). DOC generally interacts most strongly with organic carbon storages in flooded areas (Regnier et al., 2013). There are already several studies existing to the behavior of beaver impacted area to the DOC concentration. The measurements were made upstream and downstream of the beaver impacted area. Most studies measured an increase in DOC concentration downstream compared to the concentration upstream (see Figure 6). This is mainly related to increased carbon production, and residence time of the water in the beaver pond (Larsen et al., 2021). Lakes and wetlands without the presence of beaver have similar effects on downstream DOC concentrations (Kalinin et al., 2016). However, according to Catalàn et al. (2016), the measured DOC concentration may also depend on the age of the beaver system studied. The proportion of labile carbon is assumed to increase in the early years of beaver influence and decrease later (Ecke et al., 2017) as stable carbon can be stored deeper in the soil. Seasonality can also have effects on DOC and DIC exports from the floodplain (Mann & Wetzel, 1995). In summer, algal biomass production and decomposition is higher, which increase DOC exports (Mann & Wetzel, 1995).

DIC is like DOC the fraction smaller than 0.45 respectively 0.22µm but consists of inorganic carbonate. DIC mainly contains the three aqueous species HCO_{3-} (Hydrogen carbonate), CO_2 (Carbon dioxide) and CO_3^{2-} (Carbonate) (Mackenzie &. Lerman, 2006). DIC concentrations in rivers are mainly influenced by rock weathering and are higher in karst areas. (Chen et al., 2017). Compared to DOC there are no clear evidence on how DIC concentrations relate to the beaver impacted area. Therefore, further research is needed.

Compared to DOC and DIC, POC is the fraction of total organic carbon (TOC) that does not pass through the filter. POC in river systems originates from vegetation, soils, and bedrock (Leithold et al., 2006). But as mentioned earlier, POC concentrations can also be altered by anthropogenic factors. Based on Naiman et al. (1986) there is no significant change of POC concentration downstream compared to upstream. This is unusual compared to results of different studies. Most studies found a decrease of suspended sediment concentration, what can be bring in relation with POC, downstream compared to upstream (Larsen et al., 2021). According to Larsen et al. (2021) there is evidence beaver impacted areas act as POC sinks, but still further research is needed to understand the effects of POC to the whole carbon balance.

According to Figure 6 there is a clear evidence that the nitrate- (NO_3^-) concentration is lower downstream compared to upstream. For ammonium (NH_4^+), this is exactly the opposite of the NO_3^- concentration. In most studies, the NH_4^+ concentration was higher downstream than upstream. For phosphorus (PO_4^{3-}), there is no clear indication of whether the beaver impacted area results in an increase or decrease in concentration (Larsen et al., 2021). As noted above, most studies have measured lower discharge downstream than upstream due to beaver dams and the associated longer residence time of water (Larsen et al., 2021).

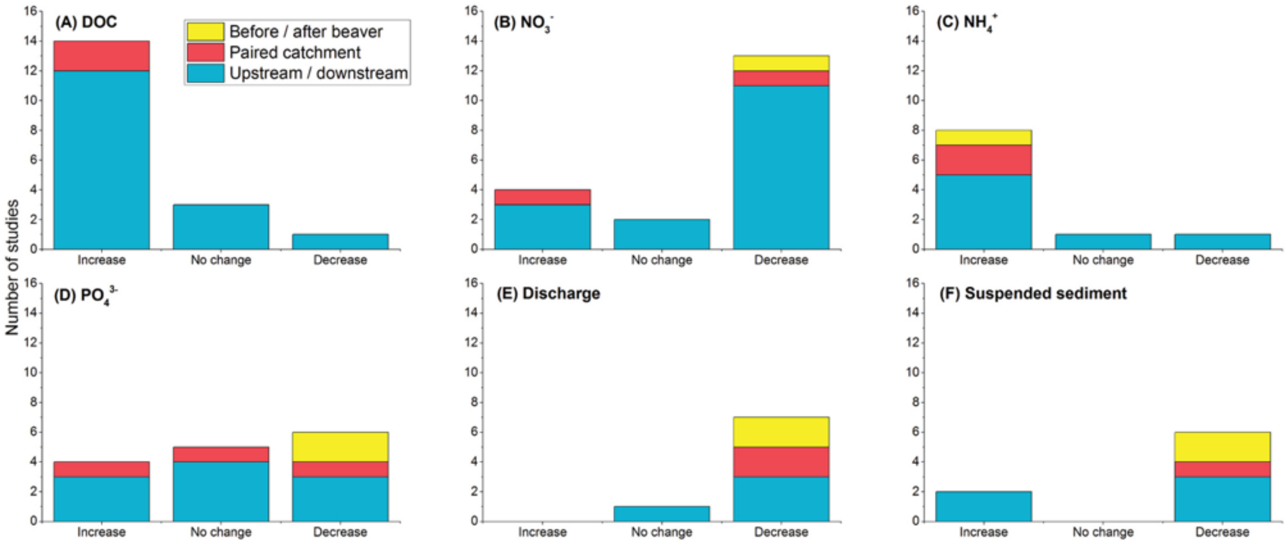

Figure 6: *Summary of results of studies examined on the influence of beaver dammed areas on DOC, NO_3^-, NH_4^-, PO_4^{3-}, Discharge and Suspended sediment (POC) (Larsen et al., 2021).Based on data from: (Błędzki et al., 2011; Burns and McDonnell, 1998; Cirmo and Driscoll, 1993; Correll et al., 2000; Dahm et al., 1987; Devito and Dillon, 1993; Dillon et al., 1991; Driscoll et al., 1998; Fuller and Peckarsky, 2011; Green and Westbrook, 2009; Hillman et al., 2004; Klotz, 1998; Klotz, 2010; Koschorreck et al., 2016; Kothawala et al., 2006; Law et al., 2016; Levanoni et al., 2015; Maret et al., 1987; Margolis et al., 2001a, b; Muskopf, 2007; Naiman, 1982; Naiman et al., 1986; Puttock et al., 2017; Roy et al., 2009; Smith et al., 1991; Wegener et al., in press; Woo and Waddington, 1990).*

1.2.5 CO_2 & CH_4

The higher carbon storage and the anaerobic conditions in the beaver impacted areas have important implications how the carbon is exported out of these areas. The additional mass of organic matter in the wetland, is available for aerobic and anaerobic microbial metabolic pathways (Larsen et al., 2021). This may result in a higher flux of carbon dioxide (CO_2) from the water surface to the atmosphere due to the presence of beavers than in the same area without beavers. Compared to the surrounding riverine network, beaver ponds are very large net sources CO_2 fluxes (Roulet et al., 1997; Yavitt & Fahey, 1994). In addition, high HCO_3^- can contribute to the outgazing of CO_2. According to a review from Nummi et al., (2018) CO_2 flux from beaver ponds where around 0.1 to 11.2 g/m^2/d. In addition to CO_2 emissions, CO_2 is also absorbed in a beaver wetland through plant photosynthesis. He et al. (2023) found that water level in a beaver pond may be important in determining whether a beaver wetland is acting as a CO_2 sink or source when comparing CO_2 emissions and CO_2 uptake through photosynthesis. The lower the water table, the more likely a beaver wetland will respond as a source of CO_2 (He et al., 2023).

Besides the increased CO_2, methane fluxes (CH_4) are also elevated in beaver influenced areas compared to similar water bodies with their absence (Ford and Naiman, 1998). CH_4 in beaver pond is released molecular diffusion or via gas bubbles. Weyhenmeyer (1999) measured CH_4 fluxes per year of 5.8 g per m^2 for a beaver pond in Ontario, Canada. 65% of the CH_4 emissions in this study area originated from gas bubbles. In the study of Naiman et al., (1986) they measured CH_4 fluxes of 7.4 g per m^2. Emission of CH_4 depends on the production and consumption of CH_4 (Weyhenmeyer, 1999). The production of CH_4 is mainly related to the number of microbial activity, temperature, water level and redox conditions (Baker-Blocker et al., 1977; Harriss & Sebacher, 1981; Moore et al., 1990; Svenson & Rosswall, 1984; Westermann, 1993; Westermann & Ahring, 1987). On the other hand, it is assumed that the consumption of CH_4 depends on the transport mechanism from the sediments to the atmosphere and on the redox potential of the water column and the sediments (Barber et al., 1988; Burke et al.,1988; Rudd & Hamilton, 1978). According to Yavitt and Fahey (1994) the CH_4 amount inclines to be higher in beaver ponds with lower water depths. In addition, CH_4 fluxes in stream segments between beaver ponds may be higher than in the beaver ponds themselves (Yavitt et al., 1990). This is due the higher turbulence in the stream segments compared to the beaver ponds, but this depends on the CH_4 input from upstream (Larsen et al., 2021). However, results on CH_4 fluxes currently come only from study areas at higher elevations in North America (Nummi et al., 2018). Additionally, results varied regionally (Nummi et al., 2018; Whitfield et al., 2015), locally (Bubier et al., 1993; Lazar et al., 2015), and even within beaver ponds (Weyhenmeyer, 1999; Yavitt et al., 1992). It is not clear if the higher CH_4 fluxes emerge due to the higher methane production rates, due to different oxidation rates in sediments and water column or both of it and needs therefore further research (Weyhenmeyer, 1999).

For CO_2 it is important to understand that some anaerobic pathways produce, and others consume CO_2. Therefore, it is not possible to make a general statement of how much CO_2 fluxes develop with increasing anaerobic conditions. Nevertheless, it can be said that floodplains created by beavers contribute disproportionately to natural CO_2 and CH_4 fluxes. As these areas will continue to increase in the future, it is important to understand the contribution of these areas to regional and global CO_2 and CH_4 fluxes. (Larsen et al., 2021).

On the one hand, more carbon is stored due to the activity of the beaver, but higher CO_2 and CH_4 fluxes are also produced (Nummi et al., 2018). All these information from previous studies investigated each separate impacts of beaver dams on the various carbon fluxes and did not analyze the whole carbon balance. Only one study from Naiman et al. (1986) investigated a full carbon balance of one specific beaver system. The results indicated that in areas affected by beaver, more carbon is stored than exported downstream. To determine the carbon balance, the import and export of carbon to and from the floodplain was measured, and the accumulation in the floodplain was estimated. In addition, primary production and response, insect occurrence, and methane flux in the floodplain and adjacent river system were considered for determination of the carbon balance. However, the beaver dams in the study areas were over 30 years old and were located downstream of a watershed where on average already 10 other beaver dams existed. Therefore, the results could only be analyzed very vaguely, since the carbon budget was already strongly influenced by the upstream beaver dams.

1.3 Research objectives

Except for the study by Naiman et al. (1986), the influence of beaver on the carbon balance has not been studied. Furthermore, the study areas where the influence of beaver wetlands on individual carbon fluxes has been investigated are often located in North America and only rarely in Europe. This master thesis is therefore intended to help close this research gap. The goal of this project is to assess the relative importance of key carbon cycle components in a river system impacted by beaver dams. From this, I will calculate whether this beaver-influenced river reach behaves as carbon sinks or carbon sources and determine a first carbon balance. Additionally, the role of wetlands and hydrology on altered carbon fluxes will be determined. These findings should provide information for ecosystem managers and policy makers to plan for the reintegration of beavers as ecosystem engineers. From these objectives, I formulated the following research question:

What is the carbon balance in a river system impacted by beaver dams in Marthalen and what is the role of the wetland and hydrology in altering the carbon cycle?

Beaver dams create a floodplain that increases the storage capacity and residence time of water and sediment. According to Wohl et al. (2012), DOC DIC and POC are continuously imported through the upstream river system in the floodplain area. Due to the anaerobic conditions in the floodplain area a slower organic matter cycle emerge (Naiman et al., 1994), which has an impact on carbon long-term storage (Larsen et al., 2021). Additionally due to the high primary production in floodplain area, more DOC is exported out than imported in the study area (Larsen et al., 2021). But there are also higher CO_2 and CH_4 emissions from the floodplain compared to the adjacent river systems (Roulet et al., 1997; Yavitt and Fahey, 1994), and all different carbon fluxes are also dependent on the season (Mann & Wetzel, 1995). Therefore, the following main and three sub-hypotheses were made:

H1: Due to the impact of the beaver dams on the Mederbach in Marthalen, more carbon is stored than released.

H1.1: There are higher DOC values downstream than upstream in the Mederbach.

H1.2: There are higher CO_2 and CH_4 fluxes out of the floodplain compared the adjacent riverine network.

H1.3: There are higher carbon fluxes in summer compared to other seasons in the study area.

2 Case study

2.1 Project set-up

In 2021, two national beaver projects have been commissioned by the BAFU (Bundesamt für Umwelt), which are coordinated by the Swiss Beaver Agency (Biberfachstelle Schweiz). These projects will illustrate the impact of beavers in strengthening ecological infrastructure, with the goal of increasing beaver involvement in future conservation projects to strengthen biodiversity and ecological infrastructure. The first project will analyze the impact of beavers on fish diversity and fish migration (CSCF, n.d.e). This master thesis is part of the second national beaver project which investigate the functionality of beaver damming activity in the landscape and is divided into five different modules:

- **National beaver population survey**
  - The National Beaver Survey aims to find out how many and where beavers currently live in Switzerland. The aim is to show how the beaver population has changed since the last population survey in 2007/2008. The survey forms the basis for two national beaver projects and future beaver management (CSCF, n.d.e).
- **Impact of beavers on biodiversity**
  - In this module the influences of the beavers on the different groups of organisms by the change of the river formation will be investigated. This will be studied over two years in 16 beaver territories in different types of water bodies (CSCF, n.d.e).
- **Generate a beaver floodplain model**
  - Based on the current and potential future distribution of the beaver, water retention for beaver floodplains is modeled. This model will be used as a planning basis for future beaver management and will form the basis for the last two modules to develop Switzerland-wide forecasts (CSCF, n.d.e).
- **First assessment of the impact of beaver ponds on the carbon budget in Switzerland**
  - During 12 months, periodic measurements are made in an area to determine the carbon balance. The aim is to find out whether the area is developing as a carbon sink or carbon source due to the influence of the beaver. Together with the floodplain model, these findings should be applicable to other areas in Switzerland.
- **Analyze the spatial variation of nitrogen and phosphorus concentrations in Swiss rivers**
  - In contrast to the Beaver Carbon Module, Switzerland-wide measurements are carried out in this module. Two measurement campaigns (winter & summer) will be conducted to find out the influence of beaver territories on different water quality parameters.

The latter two modules are developed in form of master theses integrated in a project team consisting of scientists from the Universities of Bern, Wageningen (Netherlands) and Birmingham (UK). This master thesis refers to the development of the carbon budget. Both modules are in an exchange with EAWAG (Eidgenössische Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz) and CSCF (Centre Suisse de Cartographie de la Faune). The project is led by Dr. Annegret Larsen from the University of Wageningen and the entire project was commissioned by the BAFU (Bundesamt für Umwelt).

2.2 Study area

The study area is located in a beaver wetland near Marthalen (Canton of Zurich) and belongs to the catchment area of the Rhine. The river which flows through the investigated wetland area is called Mederbach. This stream starts upstream of Oerlingen (ZH) and subsequently flows into the Thur. 1.7km after the confluence of the Mederbach with the Thur, the Thur flows into the Rhine. The Mederbach unites the Burggbach, which flows from the Husmersee and the Türlikerbach, which begins in Trüllikon (ZH). In Marthalen, the Abistbach flows into the Mederbach, which also has beaver territories upstream. After flowing through Marthalen, the Mederbach flows into a forested area (Niederholz) southwest of Marthalen, where the investigated beaver wetland is located (see Figure 7).

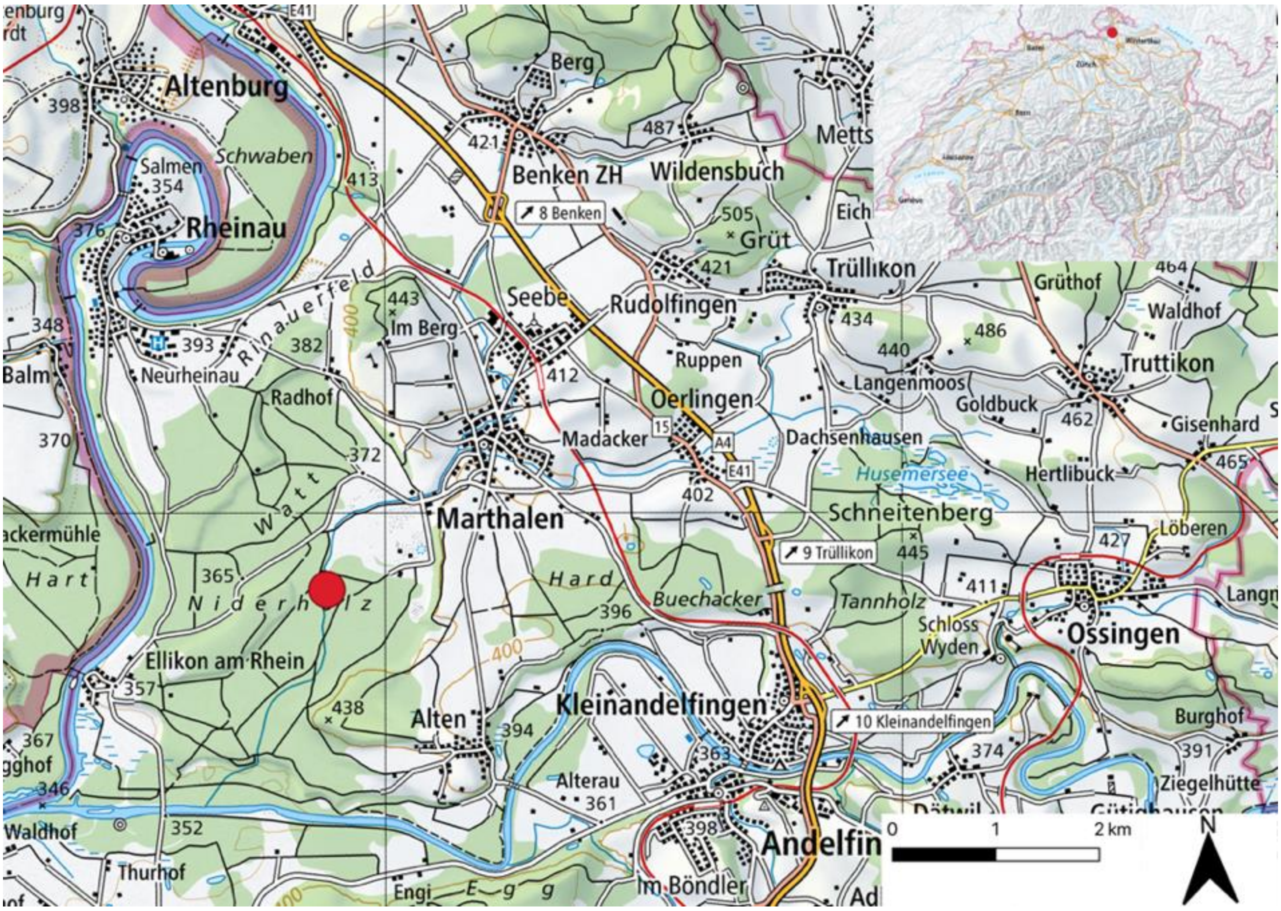

Figure 7: *Map of the investigated area in Marthalen (Swisstopo, 2022a).*

Until 1955, the Mederbach flowed into the Niederholz, where the water seeped away. After the 2nd World War more water meadows were converted into farmland, and therefore the discharge in the Mederbach increased (Nägeli, 2020). As a result, the runoff could no longer seep away completely, but formed a pond and caused the trees to be damaged. Therefore, in 1955 / 1956 a 3 km long canal was built, which flowed into the Thur (Nägeli, 2020).

In 2007 a beaver family colonized a part of the Mederbach in the Niederholz and began damming the stream (Pro natura, n.d). Temporary and permanent flooded areas were created and over time the landscape changed from a forest to a wetland area. In 2013, the canton of Zurich, the municipality of Marthalen and Pro Natura jointly concluded a forest protection contract for the wetland under study for the next 50 years. The area protected by this contract is about 10 hectares. Figure 8 shows this transformation from forest area to wetland area.

Figure 8: *Two orthophotos of the study area. On the left side from 2006 and on the right side from 2022 (Swisstopo, 2023).*

Before the beaver family colonized this area, the landscape consisted of a dense forest. 14 years later, a clear change is evident. Due to the activity of the beaver family, flooded areas developed on the left side of the channel, which is about 90m wide and 630m long. Almost all the trees in the flooding area died due to the high water level and fell down or were cut by the beavers. Instead of the forest, a beaver meadow has developed over the years, which serves as a food source for the beavers.

The study area can be divided in five different sections. The first section is located above the fishpond, where the Mederbach flows into the study area from the direction of Marthalen and is described as upstream in this master thesis (see Figure 9). In this section the water in the Mederbach still flows in the stream and is not affected by the activities of the beavers downstream. In 2019, the Mederbach was relocated and renaturalized over a length of 1.2 km directly above the study area (Spalinger, 2019) so that the company Toggenburger AG could enlarge the gravel extraction area in Niedermarthalen (Kantonaler Gestaltungsplan, 2004). As result the channel changed from a straightened stream to a meandering channel.

Figure 9: *Mederbach upstream of the beaver wetland area (own illustration, Background; Swisstopo, 2022b).*

In the second section below the fish pond, the wetland begins. The orographic upper part of the wetland consists of a heterogeneous landscape with a majority of beaver meadows, a few open water areas, and small channels made by beavers. The soil in this area is water saturated and consists of organic material up to 1 m deep. Depending on the amount of runoff, the water surfaces are more or less interconnected. Compared to winter, biomass increases rapidly in warm months. The vegetation, which consists of stinging nettles (Urtica dioica) in the upper part and then mainly of various reed species (Phragmites, Typha) grows up to 2m high. This section is described as upper pond in this thesis. Almost no trees are still standing in this area (see Figure 10).

Figure 10: *Section 2 of the study area, described as upper pond (own illustration, Background; Swisstopo, 2022b)*

In the third section is the middle part of the wetland. This section consists of a connected open water area, which is described as middle pond in this thesis. As in the upper pond almost no trees still standing in the middle pond. Many trees have fallen and therefore lie in the open water area. Compared to the second section, there are more open water areas in the third section. In the orographic upper part of the third section the first beaver dam is located. This dam leads to the fact that the water in the channel is dammed the level is increased, and therefore permanently also drained into the floodplain (see Figure 11). This drainage contributes to the preservation of the open water areas in the middle and lower pond. In the center of the middle pond the beaver lodge is located, which serves the beavers as a safe and dry sleeping place. As in the second section there is also a rapidly increase of biomass in this section. Besides the reed specious there are also algae's and other water plants in the open water areas.

Figure 11: *Third section, described as middle pond* (*own illustration, Background; Swisstopo, 2022b).*

In the fourth section the lower pond is located. In this area many pine trees from the former forest are still standing. It is the only tree species that have not yet fallen due to the high water level. As well as in the middle pond, in lower pond there is also a connected open water area. In addition to the open water area, the second and third beaver dams are located in the fourth section, with the last dam constructed during the study period. As the first beaver dam, the second bever dam cause water from the former creek to be impounded and directed into the floodplain. Compared to upper and middle pond, the lower pond is permanently flooded, which is about 200 m long and 30 m wide (see Figure 12). The subsoil consists of fine sediment, which is saturated with water. A lot of methane is stored in this subsurface, which is released to the atmosphere as bubbles by disturbances.

Figure 12: *Permanently flooded section four, described as lower pond (own illustration, Background; Swisstopo, 2022b).*

Below the last beaver dam, water flows from the floodplain back into the stream channel, which is referred to as the beginning of the last and fifth section of the study area. This section is located downstream of the wetland area and the water flows within the stream, where it subsequently flows into the Thur (see Figure 13). This is not a natural watercourse, but a straightened channel which is always between 2.5 and 3.5 m wide until it enters the Thur. In 1956, this channel was built because a lake was formed in the Armenfeld (name of the study area), damaging the trees in this forest area. Before the construction of the channel, the water from the Mederbach had seeped into the Armenfeld and drained underground into the Rhine (Lee, n.d). This section is described as downstream in this master thesis.

Figure 13: *Mederbach downstream of the study area, which flows into the Thur river (own illustration, Background; Swisstopo, 2022b).*

3 Data

For this master thesis, I used additional data besides the data we collected ourselves (see chapter 4). In order to determine the meteorological conditions while the measurement period I downloaded data from IDAweb. IDAweb is a data portal from meteoSwiss for teaching and researching and gives universities, technical colleges and schools the possibility to obtain ground station weather data (MeteoSchweiz, 2023). In this project I analyzed monthly total precipitation values from 2013 to 2022 from a ground station in Andelfingen, which is around 3.3 km away from the study area (see Figure 14).

In addition, I obtained discharge data from the Zurich Civil Engineering Office to verify discharge measurements I made myself (see chapter 4.3). The measuring station is located about 1.5 km upstream from the study area. The data, which I requested monthly from the Civil Engineering Office, were unchecked raw data with a temporal resolution of five minutes.

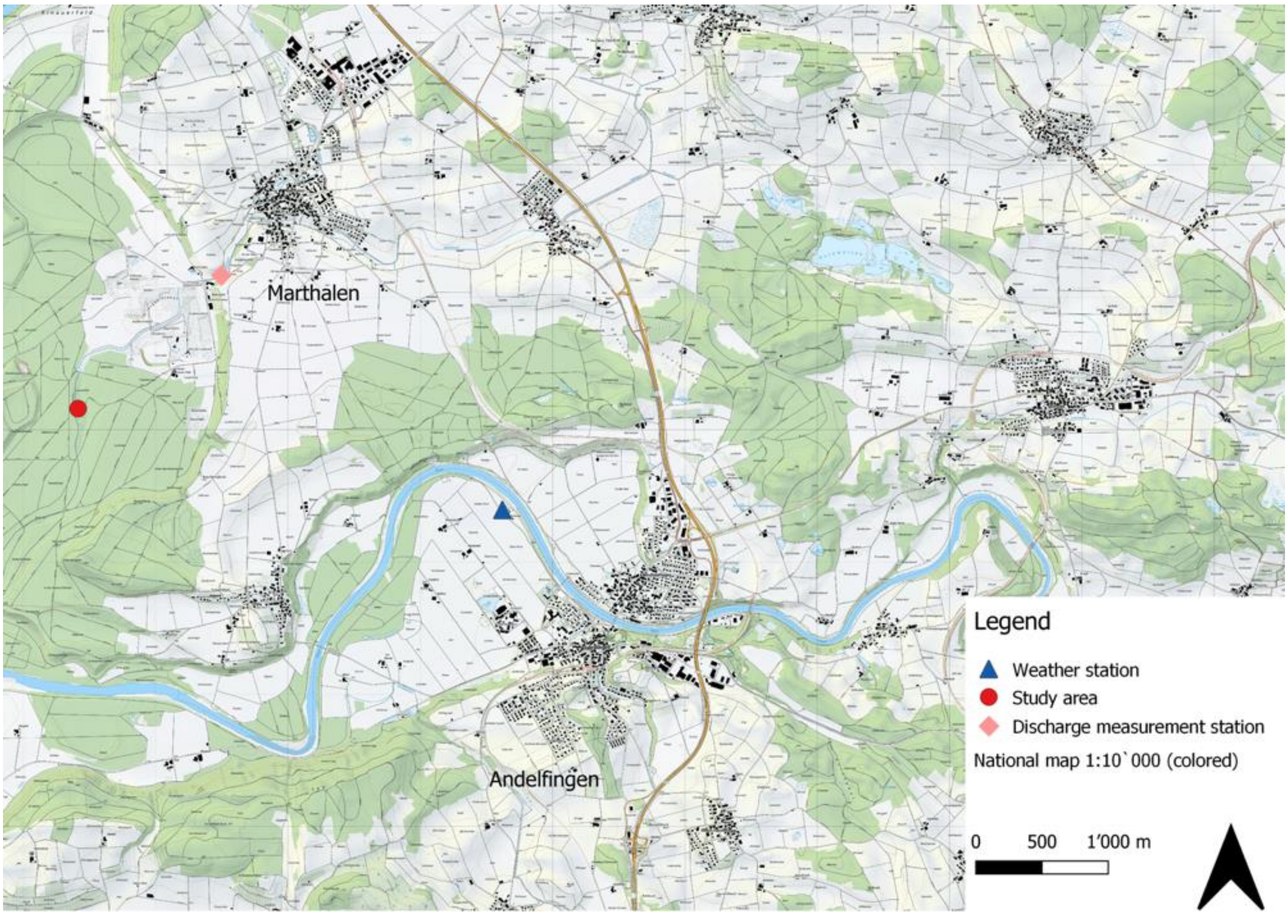

Figure 14: *This figure to show the localisation of the weather and discharge measurement stations (own illustration, Background; Swisstopo, 2022c).*

4 Methodology

As mentioned above, this project aims to make the first assessment of the carbon budget of an area affected by beaver in Switzerland. For this purpose, measurements were made throughout the year to include seasonal influences. Samples were collected upstream of the beaver wetland, in the wetland itself, and downstream of the beaver wetland (see Figure 15). In addition, the effect of land cover change from forested areas to wetlands and its influence on carbon balance was examined, and hydrologic changes and their effects on carbon balance were also considered. Specifically, this was done as follows:

- Take sampling of the most important inputs and outputs of the riverine carbon balance to and from the beaver wetland every two weeks. This means sampling of dissolved organic (DOC), dissolved inorganic (DIC) and particulate organic carbon (POC).
- Point measurements of water quality measurements including ammonium, nutrients, stable isotopes and fluorescence to and from the wetland area all two weeks and continuous measurements of the riverine electrical conductivity.
- Continuous measurements of inflow and outflow and including point measurements of discharge.
- Conduct two field campaigns in summer and winter on carbon storage and lability in sediments.
- Take measurements of CO_2 and CH_4 fluxes in the wetland area all two weeks. This means measurements from the water surface, from the soil and from trees in and out of the wetland area to the atmosphere.
- Measurements to estimate the water storage capacity of wetland and its influence on the regulation of the carbon budget.
- Monthly drone pictures of the study area, to record landscape changes over the whole measurement period.

For all samples and measurements, it was important to choose the optimal locations to represent the various processes in the study area as well as possible (see Figure 15). For this purpose, before the measurement period began, we carried out a field visit with the corresponding project members to determine the measurement- and sample sites. All water quality measurements, carbon measurements in the river (DOC, DIC & POC), stable isotopes, electrical conductivity and water level measurements were always carried out at the same two sites for the entire measurement period. A wetland leads to a backwater effect and thus influences the hydrological processes of the channel upstream. Therefore, for the first monitoring site upstream of the wetland, we chose a location in the stream that was not impacted by the wetland and where the water flowed undisturbed in the channel. For the second monitoring site downstream of the watershed, we chosen a location that was downstream of the last beaver dam and downstream of any bypass channels.

As already mentioned in the case study (see chapter 2.2) we divided the beaver made wetland area in three different sections called lower-, middle and upper pond. Additionally, we have referred to the two sections outside the wetland as downstream and upstream. For all measurements in the study area, we selected sites to represent these five areas as well as possible. Figure 15 shows the locations, where all measurements and samples were taken and the classification of the study area. All carbon measurements in the river, stable isotopes, ammonium, nutrients and fluorescence measurements are collectively referred as water samples and all different measurements with HOBO sensors (electrical conductivity, water level, temperature & air pressure) are collectively referred as HOBO measurements in this figure.

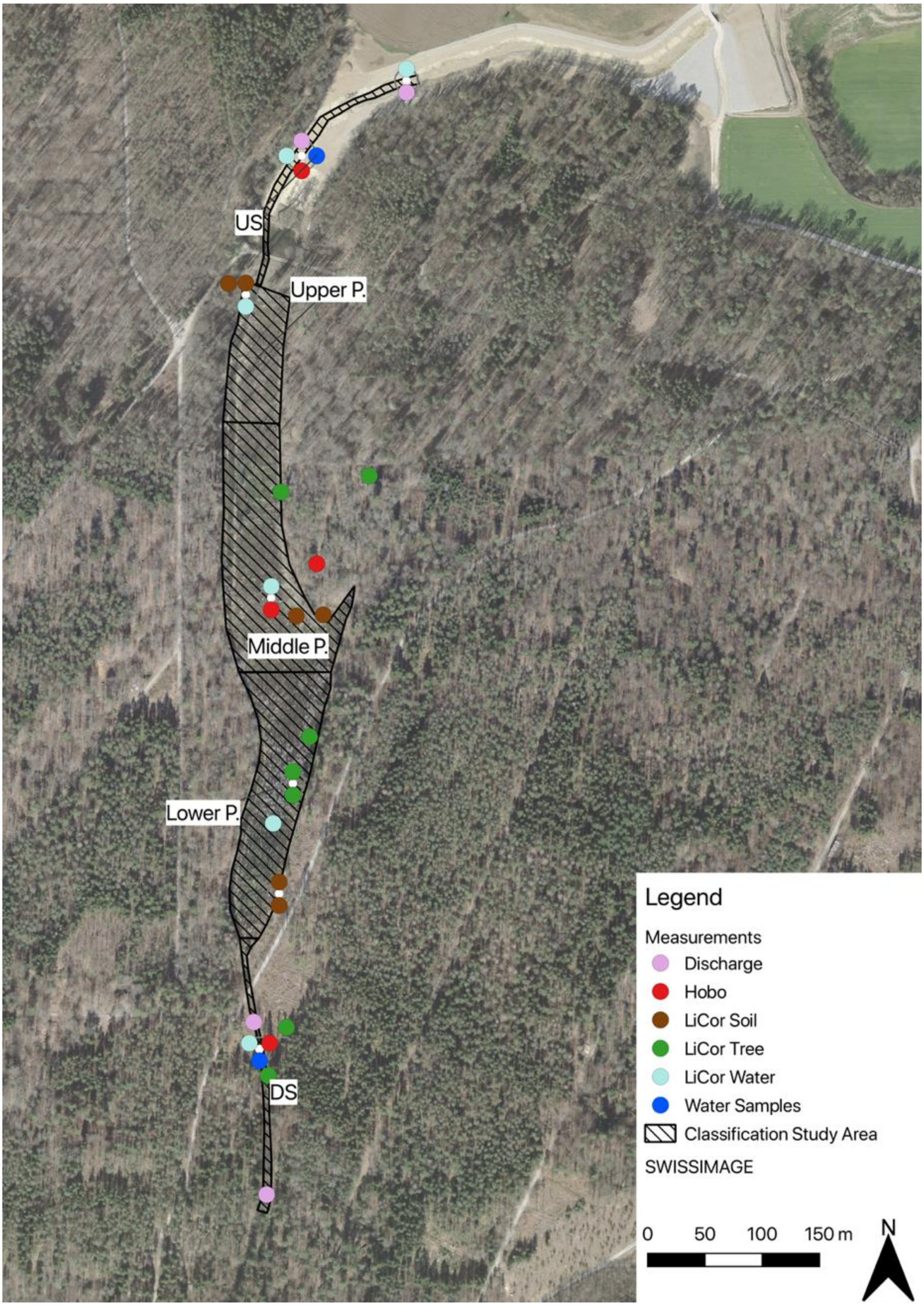

Figure 15: *Locations of different measurements and classification of study area (own illustration; Background: Swisstopo, 2019).*

Every two weeks I was in Marthalen together with Sarah Thurnheer (project collaborator) and collected the data. Due to the large number of different measurements, we split up for time reasons, which is why I could not be involved in the collection of all measurements. My main focus of data collection was to take water quality data and discharge measurements. In addition, together we measured CO_2 and CH_4 from the water surfaces and soils. The CO_2 and CH_4 measurements from the trees were performed by Sarah Thurnheer. Besides the periodic measurements, I did the bathymetry measurements with Carlos Pinto (Geomatician) and was involved in both field campaigns.

4.1 Drone

While the measurement period a total of nine orthophotos of the study area were made with the rtk phantom 4 multispectral drone. Drone images were taken at regular intervals to map seasonal effects and changes in the water surface. Due to the multispectral resolution, the images could be used to calculate indices such as the NDWI (Normalized Difference Water Index) and NDVI (Normalized Difference Vegetation Index). The calculation of these indexes was done by Emanuel Rey from Info Fauna Switzerland (CSCF).

4.2 Bathymetry

On March 26, 2022, we performed the measurements to determine the bathymetry. The aim of the bathymetry was to obtain information about the water volume in the study area. It was important that we carried out the measurements before the vegetation period in order to simplify the measurements in the field, on the one hand, and to make the water surfaces easily visible on the drone images, on the other hand. To determine bathymetry, we attached a folding rule to the pole of the GPS device. To prevent the stick from sinking into fine sediment during the measurement, we attached a plate-shaped foot to the end of the stick. We recorded a total of 596 GPS points in the study area. In addition to recording the water depths in the flooded area, we recorded seven cross sections at regular intervals to calculate the volume of water in the channel. For each recording, we read the water level on the folding stick and recorded it on the smartphone and on waterproof paper as a backup.

Figure 16: *GPS recording and reading of water depth in the middle pond to calculate the volume of water stored in the study area (photo courtesy: Carlos Pinto).*

As mentioned before, the NDWI could be calculated from the orthophotos of the drone images. In combination with GPS-points and measured water depths, I could calculate the water volume stored in study area. I have done this as follows:

- NDWI rasterfile, orthophoto from 15.03.2022 and GPS points with water depths loaded together into a new QGIS project (QGIS Development Team, 2022).
- Set a threshold for NDWI calculation with the "Raster Calculator" function to create a new raster file with the separation in water areas (1) and no water areas (0) named "Water Areas Raster".
- Created a new polygon named "Study Area", with limited spatial extent to the beaver wetland.
- Used the "Clip raster by mask layer" function to clip the "Water Areas Raster" with the "Study Area" to reduce the spatial and data size and named it as "Cut Water Areas".
- Converted "Cut Water Area" layer in a vector layer with the function "Raster to Vector" and named it as "Vector Water Areas".

- Deleted All non-water areas (0) and calculated area in m^2 for each object.
- Joined "Vector Water Areas" with GPS point by "Join attributes by location" function and named it as "joined Water Areas".
- Exported "joined Water Areas" as csv.file and calculated mean water depth [m] for each object, multiplied it with Area [m^2] and summed the volume [m^3] for all objects for the flooded area.
- Calculated water area of channel by calculating area of each cross section and multiplied with the length between each cross section.
- Summed calculation of flooded area and channel to get water volume of whole study area.

After calculating the water volume for a specific time, I determined the water areas for the other orthophotos. Then I was able to use the HOBO U20L Water Level Logger installed in middle Pond to determine the water depth for the time of each drone picture. Then I calculated the difference between the water level at the time of the GPS recording on 15.03.2022 and the water level of each drone recording, multiplied it by the water area, and added or subtracted the additional volume with the calculated water volume of 15.03.2022.

4.3 Discharge & water level

Discharge measurements were essential in this project to calculate how much mass of DOC, DIC, POC and other water quality parameters are transported into and out of the study area throughout the measurement period. In addition, the discharge data provided information on the impact of the wetland on the behavior of the discharge downstream.

4.3.1 Measuring process Discharge

I conducted the discharge measurements upstream and downstream of the study area (see Figure 15) using the salt dilution method. This method is very suitable for discharge rates up to 1 m^3/s. For higher discharge rates, another discharge method, such as fluorescence tracer measurement, should be selected (BWG, 2002). In this method, salt is dissolved in the water by mixing in a container and then rapidly injected into the channel. This is referred to as slug injection (Moore, 2005). In this process, the dissolved salt mixes in the channel in both depth and width. Since not all water in a river flows at the same velocity, the dissolved salt spreads out downstream, which is called longitudinal dispersion (Moore, 2005). After injection, the change in conductivity downstream could be measured with the WTW Multi 3510 IDS meter. Electrical conductivity can be measured in microsiemens per centimeter (µS/cm) and is determined by the number of free electrons and indicates how well electrical current can be conducted. The higher the number of free electrons in water, the higher the conductivity. When salt (NaCl) is added to the water, the conductivity increases. This property can be used for discharge measurement. I chose the distance between the measurement site and the injection site so that the tracer (dissolved NaCl) could mix completely across the width of the channel (Moore, 2005). This could be verified by taking measurements with several sensors distributed across the channel width and then comparing the values with each other. Because of the difference in channel width, we chose a mixing distance of 75 m upstream and 150 m downstream. The change in electrical conductivity could be automatically recorded and stored with the instrument used. Afterwards, I could import the data set into an Excel file via an add-in (WTW-MultiLab Importer) to calculate the discharge.

4.3.2 Calculation

With the integration method the discharge could be calculated. For this purpose, the calibration coefficient for the Mederbach had to be determined first. To do this, I took a water sample of 0.5 l from the Mederbach. and added 0.5 ml of calibration solution to the water sample ten times with a micropipette and noted the electrical conductivity in each case. The calibration solution consisted of distilled water and NaCl in a ratio of 10 g/l. I then determined the slope of the change in electrical conductivity and then divided by the slope (1/slope) to calculate the calibration coefficient. A realistic range of values for the calibration coefficient is between 0.4-0.6 (mg/l)/(µs/cm). Together with the salt input quantity V, the integration of the curve $\Delta t \sum_n [EC(t) - EC_{bg}]$ and the calibration coefficient k the discharge Q could be calculated (Moore, 2005). The formula of the integration method is as follows:

$$Q = \frac{V}{k\Delta t \sum_n [EC(t) - EC_{bg}]}$$

For the discharge measurement, salt input quantity is of high importance. If too less NaCl is introduced into the stream under investigation, the success of the experiment may be jeopardized because the change in conductivity is too small and no discharge curve can be recorded. If too much salt is injected into the channel, then on the one hand the run-through time and thus also the measurement time is increased and unnecessary water contamination occurs (BWG, 2002). According to Wernli (2011) between 4-5kg salt must be injected for 1 cubic meter per second (m^3/s).

4.3.3 Water level

Upstream and downstream of the study area, we installed "U20L Water Level Logger" before the start of the measurement period (see Figure 15) to measure the water level. In addition to water level, temperature and barometric pressure could also be measured with this logger. To do this, we placed a reinforcing bar in the stream bottom and inserted the sensor into a plastic tube to protect it from environmental influences during the measurement period. We then attached the plastic tube to the reinforcing bar so that the sensor was only a few centimeters above the streambed. The sensors were programmed to measure an absolute pressure value every 15 minutes. To measure the water depth, we first had to install HOBOware Pro software to use the measured water column pressure to determine the water depth (HOBOware Pro, n.d.). Since we could not install the logger downstream at the deepest point in the middle of the stream, we calculated the difference between the measurement point and the deepest point in the stream and then added it to the measured data. The storage capacity of the U20L water level logger is 64 KB, which is equivalent to approximately 21,700 pressure and temperature samples (HOBO U20L Manual, n.d.). If measured every 15 minutes, this storage capacity would be sufficient for approximately 226 days. However, for this project, data were downloaded from the logger every month and exported for continuous analysis. To transfer the data from the logger to the computer, an intermediate piece called a "coupler" was needed. By connecting the coupler to the logger, we were able to transfer the data to the coupler and then transfer it to the computer via a USB cable (HOBO U20L Manual, n.d.). This process was the same for all the HOBO loggers we used in this project.

4.3.4 Water Level & Discharge Relation

To calculate a level-discharge relationship, I compared the discharge measurements and the water level data. This relationship allowed us to determine discharge over the entire measurement period with a temporal resolution of fifteen minutes. However, it was important to measure effective discharge over a wide range from low to high water in order to establish the best possible relationship between discharge and water level. Since I only conducted the discharge measurements every second week and the study area was about 2.5 hours from Bern, I introduced a person living in Marthalen to the discharge measurement so that measurements could be made quickly during low water or high-water events. In addition, data from a discharge measuring station of the Zurich Civil Engineering Office, which was located about 1.5 km above the study area, could be included in the calculations. However, this was raw data and should be treated with caution. In addition, I was only able to use the Civil Engineering Office discharge data to calculate the upstream discharge-level ratio. I calculated the discharge-level ratio using the power function based on the master's thesis by Binkert (2022) in RStudio (RStudio Team, 2022).

4.4 Water samples

I collected all water samples every two weeks throughout the measurement period. In total, I had to take 16 water samples (8 per site) per field day in different sample vials for this purpose. For illustration see Table 1.

Table 1: *Information on water quality sampling*

	Type of sampling	**Labelling**	**Amount (per site)**	**Type of vial**	**Type of storage**
Ammonium	filtered	A	40ml	falcon tubes	Freezer (-20°C)
Nutrients	filtered	N	45ml	falcon tubes	fridge (4°C)
Dissolved Organic Carbon	filtered	DOC	45ml	falcon tubes	fridge (4°C)
Alkalinity	filtered	Alkalinity*	100ml	falcon tubes	fridge (4°C)
Fluorescence	filtered	F	¾ vial	dark glass vials	fridge (4°C)
Stable Isotopes	unfiltered	SI	whole vial	dark glass vials	fridge (4°C)
Sediment transport	unfiltered	Sediment	1L	big plastic bottle	cellar

*Note.*Two falcon tubes per measurement site*

Figure 17: *Different type of vials (from left to right: falcon tube, big plastic bottle & dark glass vials)*

4.4.1 Sample preparation

In order to distinguish the samples from each other, I had to label the different vials before each sampling. The labelling was provided by the project, as the majority of the water samples were analyzed by EAWAG. It had to be indicated which water sample it was, where it was taken and on which date and time it was carried out. An example of labelling looked like this:

DOC
US_ZH_NB03_1_1
07.06.2022
14:00

Before sampling, the syringes needed for filtration, the large plastic bottles and the dark glass vials had to be cleaned from contamination at each measurement site. To do this, I rinsed the syringe three times with water from the stream before taking the final sample. It was important that the water was directed back downstream into the stream when rinsing the syringe to avoid disturbance for the final sample. I had to do the same for the large plastic bottles and the dark glass vial to clean the sample vessel and lid. I did not have to clean the falcon tubes because they were sterile. I also cleaned each filter before sampling by filtering in drops of river water to remove any residue from the filter before sampling.

4.5 DOC, DIC & Suspended Sediment

To determine the total amount of carbon imported and exported through the river network, I collected DOC, DIC, and suspended sediment samples in Mederbach upstream and downstream of the beaver wetland. In order to take DOC samples, the water must be filtered. In this study, I used filters with a membrane of 0.22µm. We applied the same filter size for other water quality parameters too. The fraction that passed through the filter could later be used to measure the amount of DOC. For DOC I collected a water sample by filtering approximately 45ml per site into a falcon tube. I used the same procedure for the DIC measurement, with the only difference being that I took one sample of 100 ml per site (see Table 1). During data collection, it was determined that for EAWAG, one measurement sample for DOC and nutrients per site of 50ml is also sufficient for analysis. Already in the field after sampling, I stored all water samples expect the sediment, fluorescence and stable Isotopes samples in a cool box, since several hours passed from sampling to storage in the fridge or freezer.

Figure 18: *Filtration of a water quality sample while the winter field campaign in Marthalen (photo courtesy: Kaspar Berger).*

One week after sampling, I sent the DOC and DIC by post to EAWAG in Dübendorf for analysis, together with other water quality samples (see chapter 4.6). All DOC samples were analyzed by the “TOC-L CSH” measurement device (see Figure 19). The sample is oxidized, the resulting CO_2 concentration is measured and from this the carbon content in the water sample is determined (DIN EN 1484, 1997). Because the sample was filtered, the measured value corresponded already to the DOC and not the TOC content. With this measuring method, the DOC value is given in mg/l. The determination limit is 0.5, the measuring range is 0.5 - 10.0 and the measuring error is 0.1 mg/l.

Figure 19: *Measuring instrument at EAWAG for the determination of TOC and DOC in water samples (own photo, 2022).*

Since DIC is not sampled as a common parameter by EAWAG, alkalinity was measured instead of DIC. The alkalinity was measured with the "809 Titrando" (see Figure 20). This is done by titration with a standard acid solution up to 8.3 and 4.5 pH. Here, the pH value 8.3 corresponds to the equivalent concentration of carbonate and carbon dioxide and the pH value 4.5 is used to determine the total alkalinity of the sample (DIN ENISO 9963-1, 1995). Alkalinity is measured in mmol/l with this measurement method. The determination limit is 0.2 and the measurement error is 0.1 mmol/l. To convert alkalinity in mmol/l to TIC in mg/l, the measured value must be multiplied by 12.011 (molar mass of carbon). the TIC corresponded to the DIC value, since I had filtered the sample in the field.

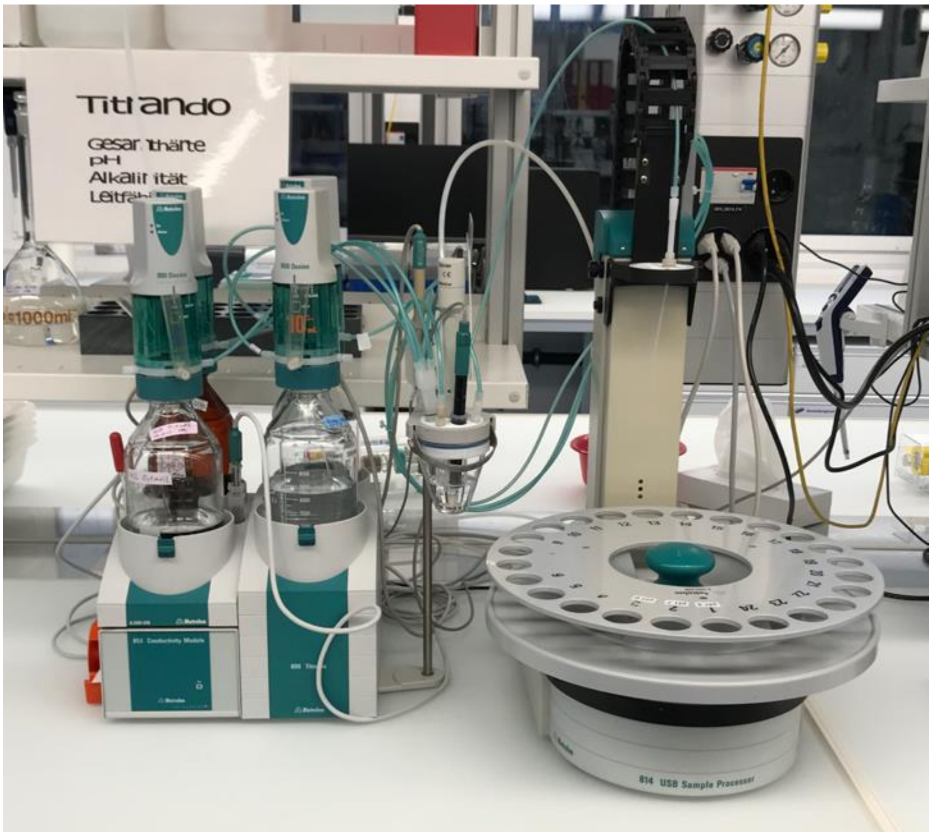

Figure 20: *Measurement device at EAWAG to determine the alkalinity value of water samples (own photo, 2022)*

The amount of carbon which was bigger than 0.22µm could then be used to determine the suspended sediment in the Mederbach. For this purpose, I collected an unfiltered water sample of one liter at each of the two sites. During the measurement, I stood in the riverbed and had to make sure that no additional sediment was stirred up for the final sampling. Particular care was needed at the downstream sampling site because the flow velocities were low.

After I took the samples, they were analyzed at the Geographical Institute in Bern. The water sample was filtered through a filter (0.22µm). A vacuum pump was used to reduce the filtration time (see Figure 21). All residues on the filter could then be analyzed as suspended sediment. Each filter was weighed with a high precision balance before and after the measurement including residues. For this purpose, the filter had to be dried in order to avoid the influence of the water. The difference in weight of the filter could then be analyzed as suspended sediment. To calculate a concentration in mg/l, the empty and full sediment bottle was also weighed for each sample to calculate the amount of water for each sample.

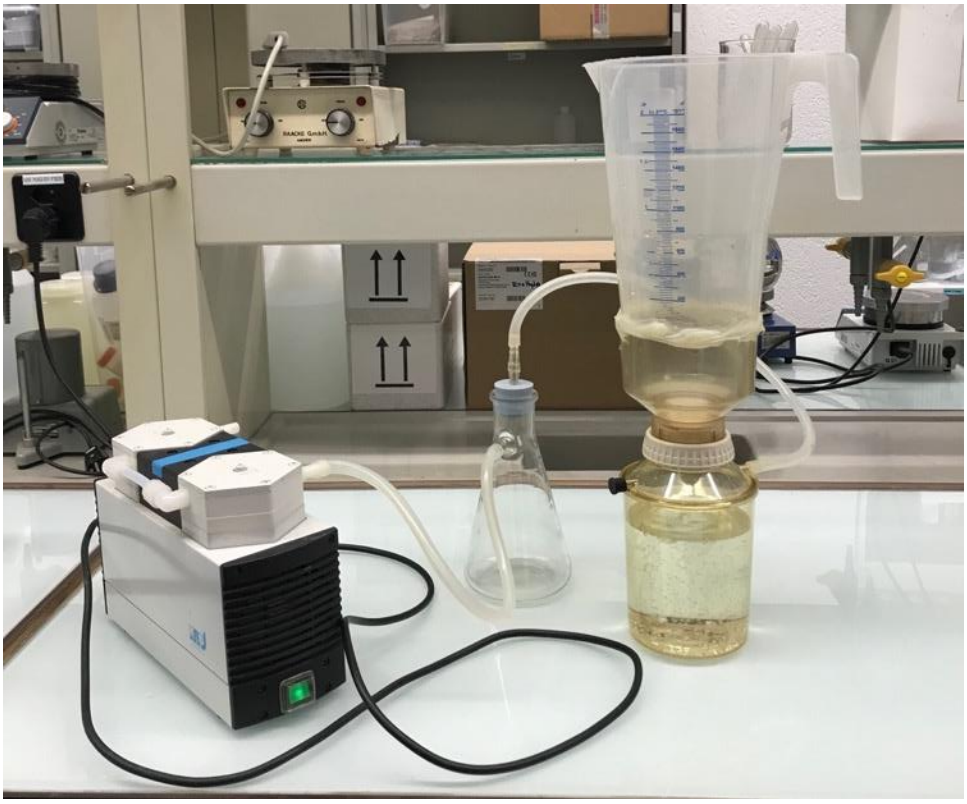

Figure 21: *Filtration of water sample together with a vacuum pump, to analyse the suspended sediment (own photo, 2023).*

4.6 Water Quality

Water quality was also recorded as part of this project but is not described in detail and not presented in the results as it is not the focus of this master's thesis. I collected the water quality samples like DOC, DIC & POC every two weeks throughout the measurement period upstream and downstream of the beaver wetland area. The measured water quality parameters can be seen in Table 1.

After one week at the latest, I sent the nutrient samples together with the DOC and alkalinity samples to EAWAG for analysis. Every three months, I sent the ammonium samples in a cool box together with dry ice, in a frozen state, or brought them directly after measurements. With the nutrient water sample, the sodium, magnesium, calcium, potassium, fluoride, chloride, bromide, nitrate and sulfate concentrations were analyzed.

To measure electrical conductivity, I took sample measurements at the same monitoring locations as the discharge measurement using the WTW Multi 3500 meter. In addition, we installed a HOBO U24 conductivity logger (U24-002C) upstream and downstream in the streambed throughout the measurement period. This sensor was used to measure the conductivity and temperature of the water every 15 minutes. Beginning in June, we also took water quality measurements with the YSI meter (ProDSS Multiparameter Digital Water Quality Meter) at all monitoring sites where we also took measurements to atmospheric fluxes. Since multiple sensors can be connected to the YSI meter, we were able to take simultaneous measurements of pH and dissolved oxygen in addition to electrical conductivity. We were not able to carry out the measurements with the YSI meter until mid-June due to delivery delays.

4.7 Infiltration

In addition to the amount of DOC and DIC exported downstream of the Beaver Wetland, we calculated infiltration to complete the carbon export fluxes. For this purpose, we selected comparable beaver dammed areas from the existing literature and applied their findings on infiltration to the study area in Marthalen.

4.8 CO_2 & CH_4

In order to cover the CO_2 and CH_4 fluxes, we made measurements from the water surface, from dead trees and from the soil to the atmosphere throughout the year in the study area. In addition, we measured the gas fluxes from aquatic plants during the summer months. To get an idea about the diversity of the emerging gas fluxes, we distributed the measurements throughout the study area (see Figure 15). In total, we measured atmospheric fluxes from the water surface at 6 sites, from dead trees at 7 sites, and from the soil at 6 sites. In each case we did effective and reference measurements. The tree flux and the fluxes from aquatic plants are described shortly in this method and will not be part of the results and discussion in this master thesis, since I did not measure or only partly by myself. In addition, these fluxes contributed only slightly to the total CO_2 and CH_4 emissions.

4.8.1 LiCor

All gas flux measurements we caried out “LI-7810 CH_4/CO_2/H_2O Trace Gas Analyzer”. In this thesis this measurement device is described as LiCor. The LiCor is a laser-based gas analyzer, which uses optical feedback to measure gases in the air. Its internal memory stores the dry mole fraction of CO_2 and CH_4 in air, corrected for spectroscopic interference and dilution by H_2O (LI-7810 CH_4/CO_2/H_2O Trace Gas Analyzer, 2021). During a measurement with the LiCor, laser light is injected into a V-shaped cavity. Through the mirrors 1, 2 & 3 the photons are reflected several times, which increases the path length and thus also the sensitivity so that the sample gas has many opportunities to absorb the light (see Figure 22) (LI-7810 CH_4/CO_2/H_2O Trace Gas Analyzer, 2021).

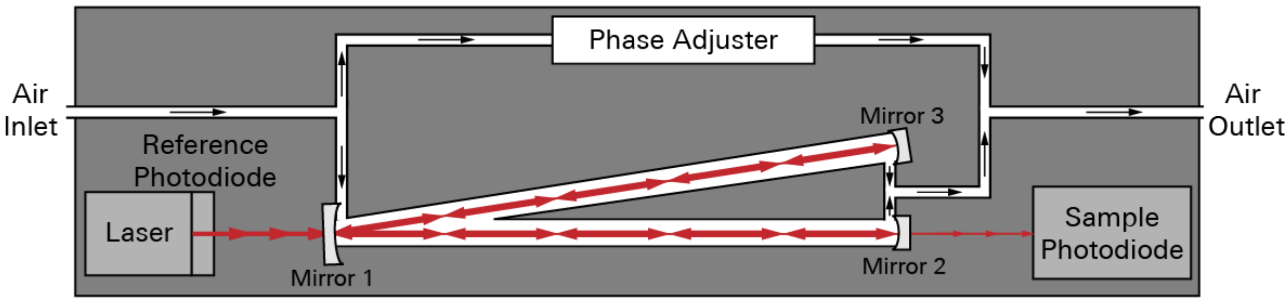

Figure 22: *Construction of the LiCor measuring device (LI-7810 CH_4/CO_2/H_2O Trace Gas Analyzer, 2021).*

Through the instrument, the laser drive current is controlled to sample a wavelength range corresponding to the absorption characteristics of CO_2, CH_4 & H_2O. To measure all three gases, the LiCor meter takes about 0.25 seconds for the laser frequency to scan through the corresponding spectral range. A fitting algorithm determines gas concentrations by comparing the measured absorption spectrum with the internally stored spectrum (LI-7810 CH_4/CO_2/H_2O Trace Gas Analyzer, 2021). Since the instrument is equipped with a Wireless Local Area Network (WLAN), it is possible to connect to the IP address in order to follow the measurements directly on the smartphone or computer and export them as a text (txt) file. To perform the measurements at a specific location, we connected the LiCor to a chamber at the "Air Inlet" and "Air Outlet" with tubing. The air from the chamber was directed via the "Air Inlet" into the measuring device, where the corresponding gas concentrations were analyzed and then directed again via the "Air Outlet" into the chamber. Since the measurements via the chamber took place in a closed system, the gas concentrations increased over the measurement time, because the air could not escape from the chamber. For illustration, Figure 23 shows the measurement of CH_4 in the upper pond on Aug. 29, 2022.

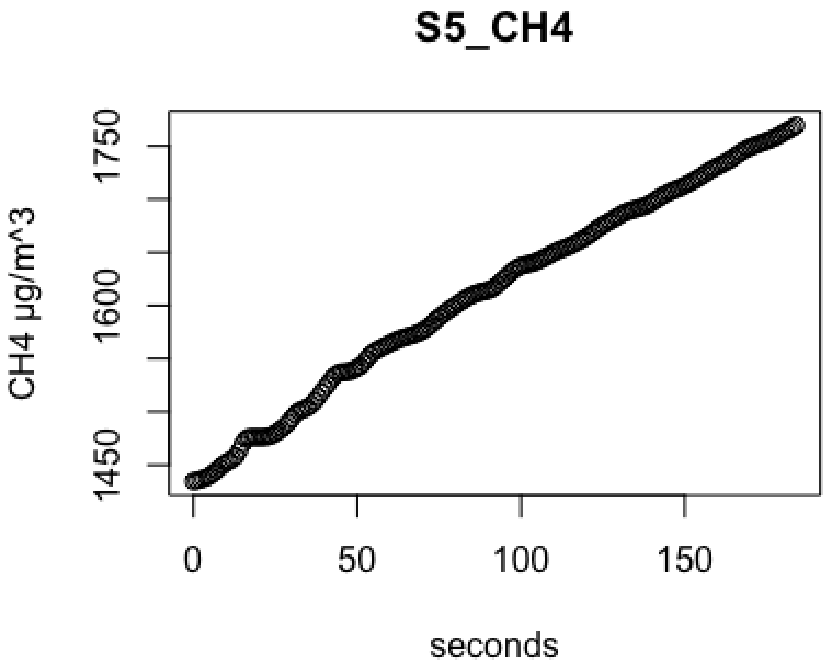

Figure 23: *Measurement of CH_4 in the upper pond on 29.08.2022 over a measurement time of 185 seconds.*

Using the package "gasfluxes" from Fuss (2020) in R-Studio, we were able to calculate the gas flux in µg/m^2/s for individual measurements. Based on the measurement data, the package was used to calculate a robust linear approximation, where the flux was determined from the slope of the approximation line. For each measurement, the volume of the chamber and the water or air temperature for each measurement had to be known in order to calculate the gas fluxes. We measured the water or air temperature using the HOBO U20L Water Level Logger.

4.8.2 Water flux

To measure CO_2 and CH_4 fluxes from the water surface to the atmosphere, we made three effective and three reference measurements per measurement day from January 18, 2022 to December 06, 2022. For the effective measurements, we made one measurement in the lower pond, one in the middle pond, and one in the upper pond. For the reference measurements, we took one downstream in Mederbach near the downstream water quality and HOBO measurements and two upstream in Mederbach, one near the upstream water quality and HOBO measurements and one near the discharge point of the discharge measurement. Throughout the series of measurements, we always took the measurements at the same locations so that we could compare the data.

In lower pond and, depending on water levels, in middle Pond, we mounted LiCor meter on a rubber boat to protect it from the water. Two pool noodles were attached to the edge of the chamber to ensure buoyancy of the chamber during the measurement and two holes were bored in the top of the chamber to connect the chamber to the LiCor meter via the tubes (see Figure 24).

Figure 24: *Measurement of atmospheric fluxes from the water surface in the lower pond on March 29, 2022 (photo courtesy: Sarah Thurnheer).*

During the measurements, we had to be careful to move as little as possible to not create additional CO_2 and CH_4 fluxes. In the wetland, a particularly large amount of CH_4 is stored in the soil, which is released even at low levels of disturbance and could thus influence the measurements.

4.8.3 Soil flux

To measure the CO_2 and CH_4 fluxes from the soil in the study area, we performed a total of three effective and three reference measurements. We distinguished between wet and dry soils. The wet soils are located within the beaver wetland and are also inundated depending on the water level. The dry soils are located outside the floodplain in the adjacent forested area and are unaffected by beaver activity. We conducted the soil flux measurements during the period from March 9, 2022 to December 06, 2022. The start of the soil flow measurements took longer because of the complexity of fabricating and installing the chambers.

The soil chambers could be divided into two parts. The lower part consisted of a plastic pipe with holes that was permanently installed in the ground, and the upper part of the soil chamber also consisted of a plastic pipe with a closed lid that was placed on top of the lower part for the measurements. As with all chambers, there were two ports on the top of the chamber that we could connect to the LiCor meter via plastic tubes for the measurements.

Figure 25: *Soil chamber upper and lower part on the left and on the right the measurement of the gas flux in the wet soil in mid-October (own photo, 2022).*

4.8.4 Tree & vegetation flux

Due to the flood plains and the wet soil, all trees in the flooded area died. To determine the influence of the dead trees on the carbon balance, we did CO_2 and CH_4 measurements throughout the study area. For this purpose, four effective measurements were made in the floodplain and 3 reference measurements in the adjacent forest (see Figure 15). The tree flux measurements were caried out over the time span from the 2nd of February 2022 till 6th of December 2022. For the effective measurements, those trees were selected that were in water for the whole period. For the reference measurements, trees were selected in the forest where the soil was unaffected by the floodplain and as close as possible to the effective tree measurements. For all measurements, two chambers were installed per tree, which measured the vertical and the horizontal gas flux. The chamber for measuring horizontal gas fluxes was installed on the side of the log and the chamber for measuring vertical gas fluxes was installed above the end of the trunk (see Figure 26). To ensure that the chambers were airtight on the trunk, they were attached to the trunk with tree wax from the Landi (Baumwachs Bärtschi) and secured with tension ropes.

While the summer months gas flux measurements of different aquatic plants were made in the lower and middle pond. For this purpose, samples of the main aquatic plants were first collected in the study area to understand which have the main influence on gas flux measurements. In total we made five vegetation flux measurements.

Figure 26: *Effective horizontal tree flux measurements at the end of April 2022 (photo courtesy: Sarah Thurnheer).*

5 Results

In this chapter, the results are presented based on the methods chapter. Chapters 5.1 and 5.2 present results on meteorological conditions and bathymetry to provide an overview of weather influences in the study area for the measurement period and to show the stored water volume in the study area. Chapter 5.3 presents the discharge calculations and the discharge-water level relation and is used to derive the DOC, DIC and suspended sediment calculations in Chapter 5.4. Chapters 5.4 and 5.5 show the fluvial and atmospheric carbon imports and exports of the study area, and Chapter 5.6 presents the carbon balance for the study area.

5.1 Meteorological conditions

To get a better knowledge about meteorological conditions while the measurement period and how this could have an impact on the results, specific on the discharge, I analyzed the precipitation data from a ground weather station in Andelfingen (see Figure 14) and the air temperature data of a HOBO logger permanently installed in the study area.

According to this measuring station, a total of 732 mm of precipitation fell in the surrounding of the study area in 2022. Compared to the last nine years, this was the smallest value measured (see Figure 27). The average annual precipitation reading from 2013 - 2022 was 902 mm. Figure 28 shows the monthly precipitation distribution of the year 2022. The months with the highest precipitation were June, August and September and the months with the least precipitation in 2022 were February, March and July (MeteoSchweiz, 2023).

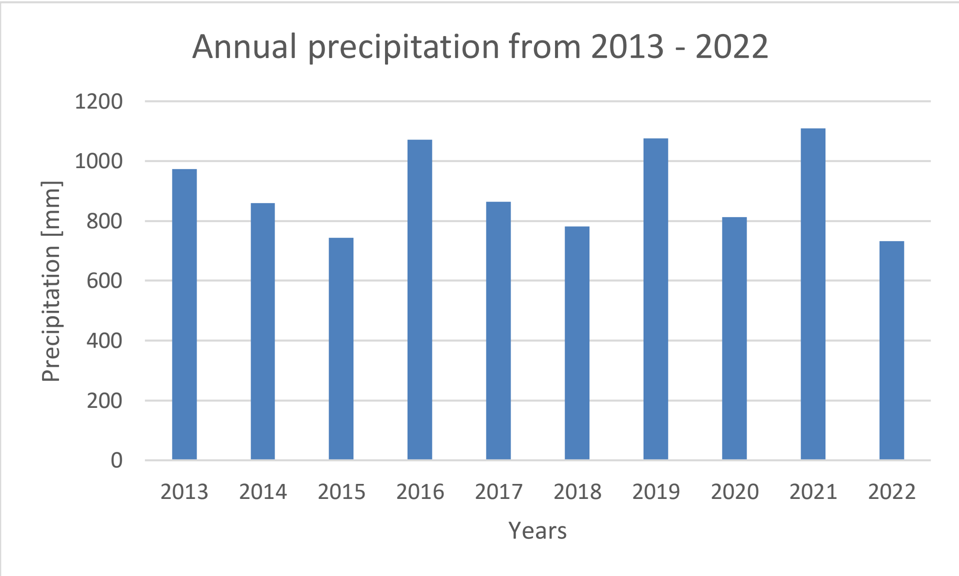

Figure 27: *Measured precipitation in the years 2013 to 2022 at the ground weather station in Andelfingen (Data from: MeteoSchweiz, 2023).*

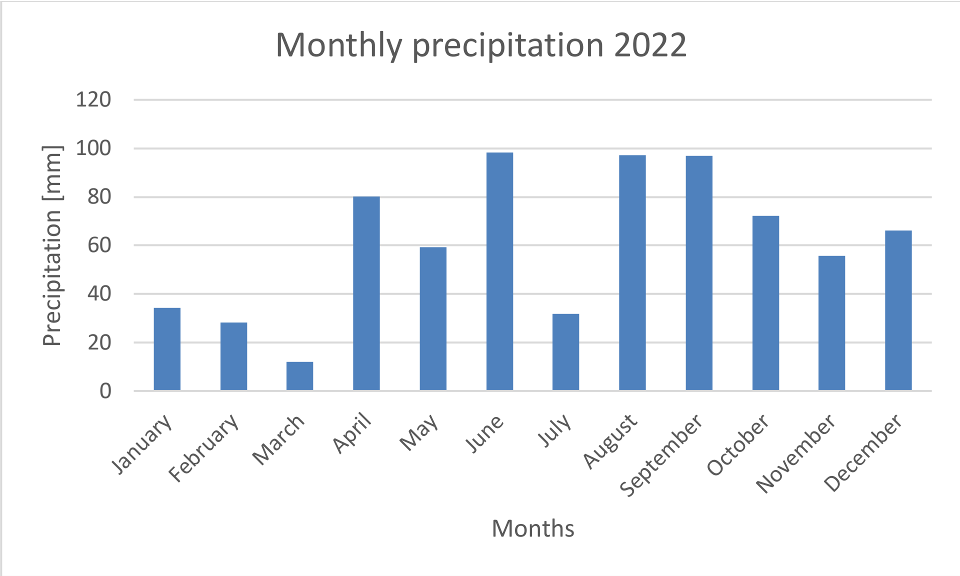

Figure 28: *Monthly precipitation in 2022 measured with the ground weather station in Andelfingen (Data from: MeteoSchweiz, 2023).*

Additionally, to the precipitation data I calculated the mean temperatures per month based on the temperature logger installed in the study area in Marthalen. July was the hottest (20.6°C) and January the coldest (0.6°C) month in 2022. The annual mean value in 2022 in the study area was 7.7°C.

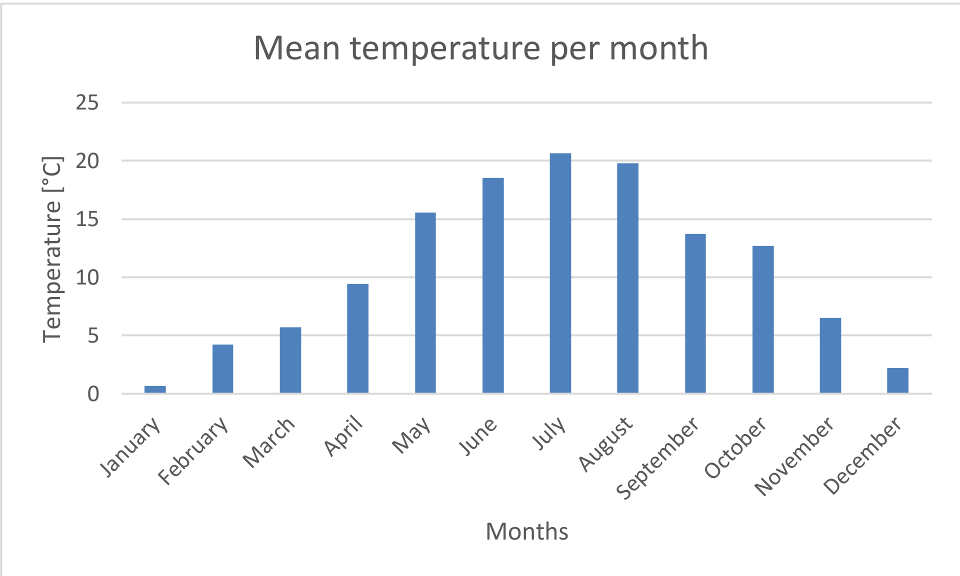

Figure 29: *Mean temperature per month in 2022 based on a temperature logger in the study area.*

5.2 Bathymetry

To calculate the water volume stored in beaver wetland area, I divided the water areas in channel and floodplain area. By joining the water areas with GPS points, I obtained 97 individual water areas that were in the floodplain, for which I individually calculated the water volume with the average water depth. By summing up the volume calculation of the 97 water areas I got the total water volume in the flooded area for the situation on 26.03.2022. According to these calculations, 3221 m^3 of water was stored in the flooded area. To calculate the volume in the channel within the beaver wetland, I used the seven cross sections by multiplying the area of each cross section by the length between cross sections. A total of 1507 m^3 of water was stored in the channel on 26.03.2022 (see Figure 30). This resulted in a total water volume of 4728 m^3, with about 30% stored in the lower pond.

	Geometry cross section (CS)	Area cross section	Distance between cross section
CS1	2.9m	1.256 m^2	109.3 m
CS2	2.4m	0.9 m^2	50 m
CS3	3.1m	1.513 m^2	25.5 m
CS4	3.6m	1.03 m^2	80.2 m
CS5	4.4m	2.44 m^2	47.5 m
CS6	5.4m	3.011 m^2	193.7 m
CS7	6.4m	4.068 m^2	124 m
Total volume of channel		1507.012 m^3	

Figure 30: *Calculation for stored water volume in the channel based on the cross sections for the situation on 26.03.2022.*

Of the total nine drone images, I could calculate the water volume for four of them. For the remaining five images, the water areas could only be evaluated to a limited extent because they were covered by vegetation, or the solar irradiance was too low for multispectral resolution of the images and calculation of the NDWI. As mentioned in chapter 4.2, those calculations were based on the water HOBO level logger installed in the middle pond. This logger was permanently installed while the whole measurement period (04.01.2022 – 04.01.2023) and measured the water level with a temporal resolution of 15 minutes. This allowed me to calculate the water volume at a resolution of 15 minutes throughout the measurement period using the power function and determine the relationship between water level and water volume (see Figure 31). The mean calculated water volume was 5383 m^3 with a standard deviation of 403 m^3 and most of the volume calculations over the whole year were between 5000 and 5500 m^3 (see Figure 32).

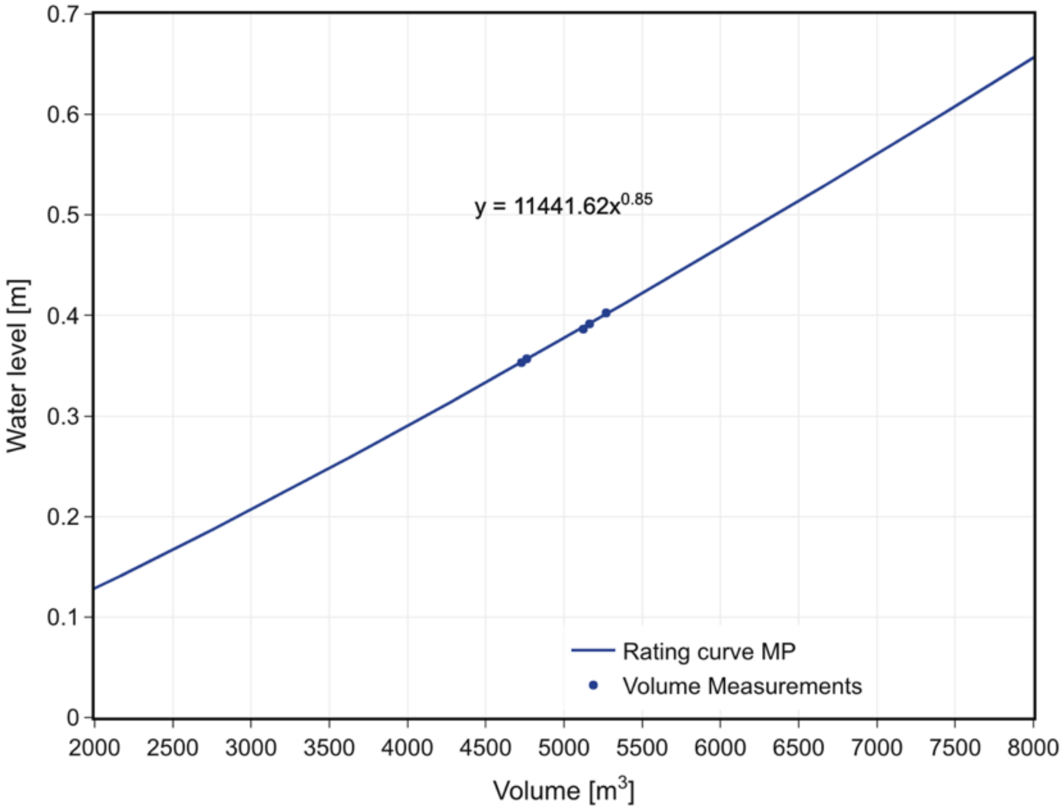

Figure 31: *Calculated water level and water volume relation.*

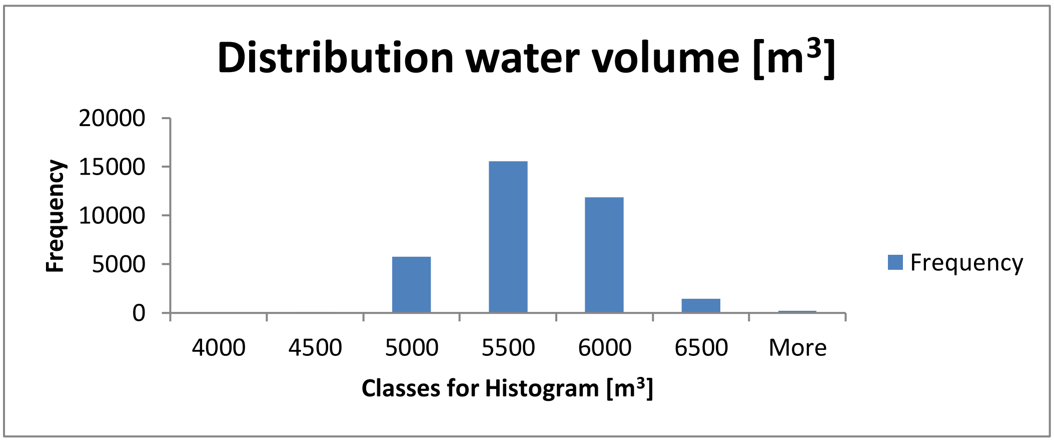

Figure 32: *Distribution of water volume in the beaver wetland area, while the measurement period from 04.01.2022 - 04.01.2023.*

5.3 Discharge & water level

To calculate the total amount of DOC, DIC, and suspended sediment that flowed into or out of the study area, I had to include the discharge calculations. In total, we performed 33 downstream and 33 upstream measurements (see Appendix A). The largest measured discharge value for upstream was 430 l/s and the smallest was 50 l/s. For Downstream the measured range was between 220 l/s and 30 l/s. Combined with the water level measurements, I was able to calculate the PQ relation (water level – discharge relation) for downstream and upstream (see Figure 33 & Figure 34).

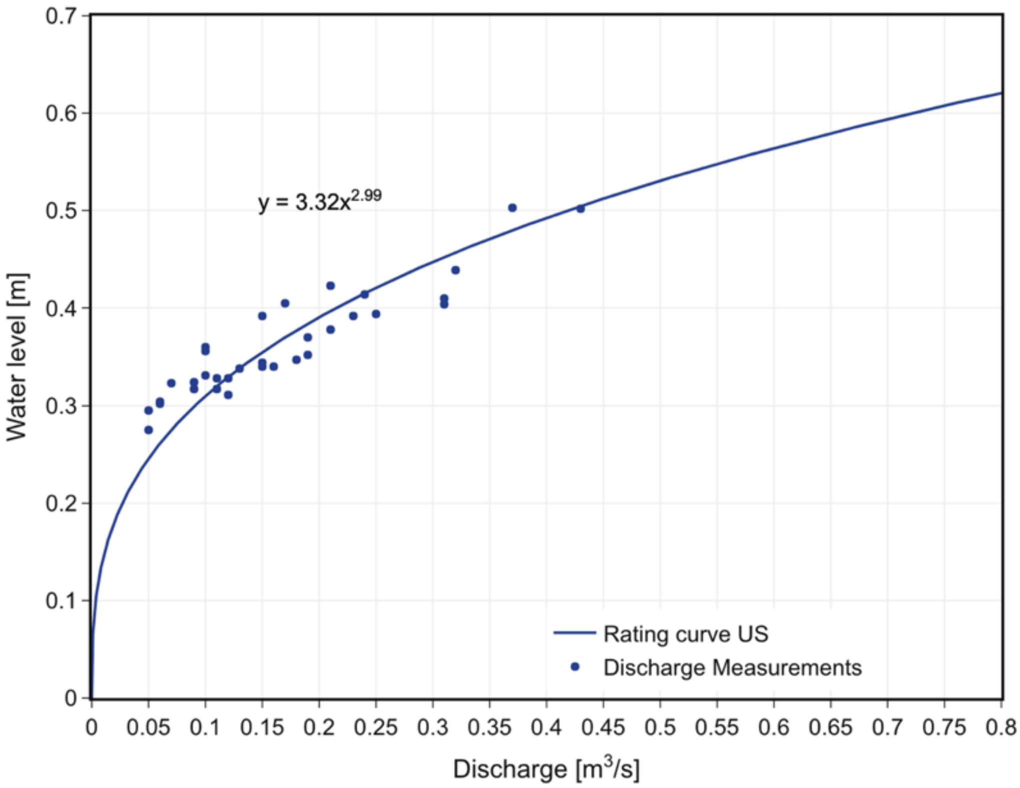

Figure 33: *Calculated PQ-relation for upstream.*

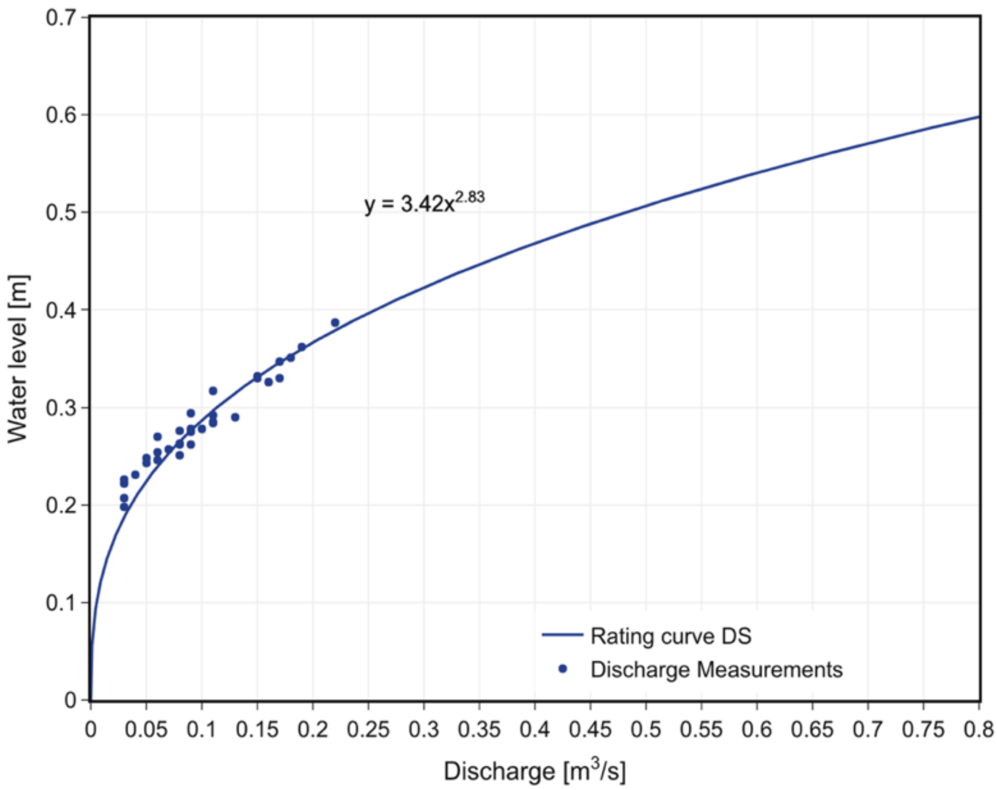

Figure 34: *Calculated PQ-relation for downstream.*

By calculating the rating curve, I determined the discharge of upstream and downstream with a temporal resolution of 15 min over the entire measurement period (04.01.2022 - 04.01.2023). The mean discharge for upstream was 173 l/s and for downstream 100 l/s. This corresponds to a difference of 42.3 %. Most discharges for upstream downstream were between 70 and 140 l/s (see Figure 35 & Figure 36).

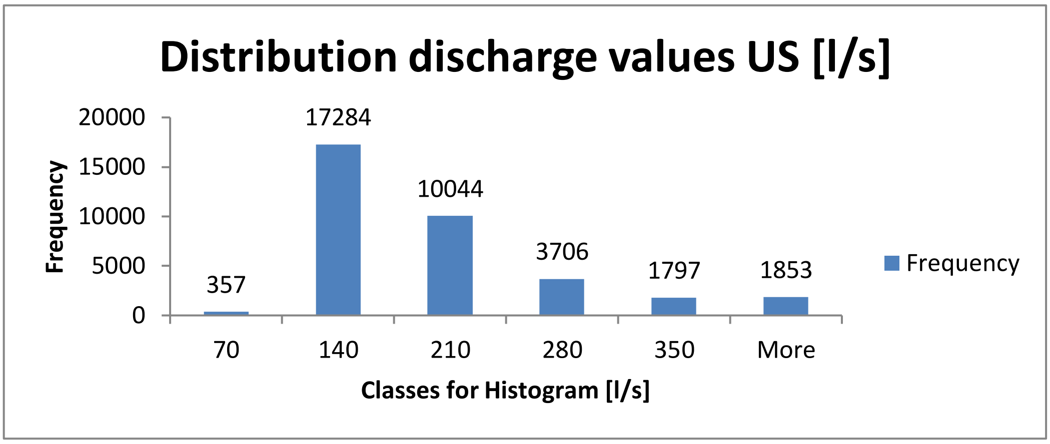

Figure 35: *Distribution of upstream discharge during the measurement period from 04.01.2022 - 04.01.2023.*

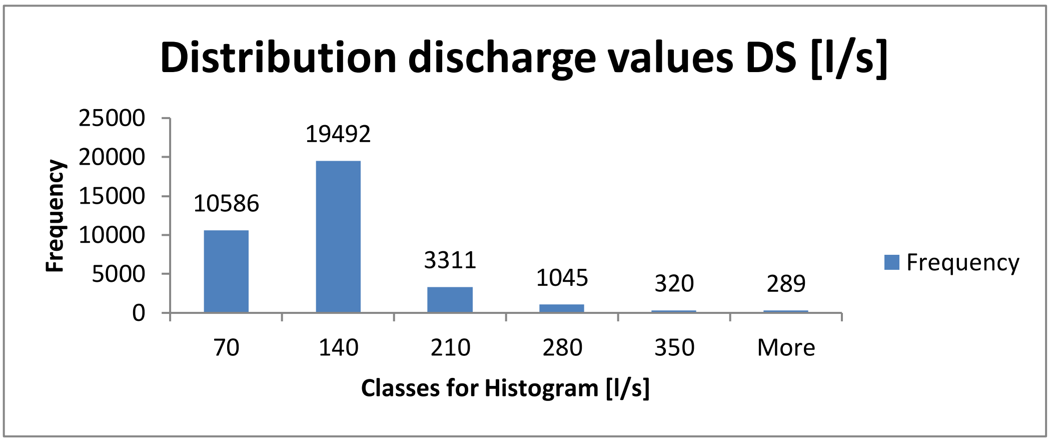

Figure 36: *Distribution of downstream discharge during the measurement period from 04.01.2022 - 04.01.2023.*

5.4 DOC, DIC & Suspended Sediment

We did a total of 25 DOC and suspended sediment and 23 DIC measurements in the Mederbach upstream and downstream of the beaver wetland area (see Figure 37, Figure 38 & Figure 39). The mean value for DOC was 4.3 mg/l upstream and 4.6 mg/l downstream. For 21 of the 25 measurements, DOC concentrations were higher downstream than upstream. Compared to DOC, DIC values upstream and downstream differed only slightly. The mean value of DIC was 66.2 mg/l upstream and 65.8 mg/l downstream. For 9 of the 23 measurements, DIC concentrations were higher downstream than upstream. The opposite was found for suspended sediment compared to DOC measurements. For 5 of the 25 measurements, suspended sediment concentrations were higher downstream than upstream. In addition, upstream and downstream concentrations are significantly lower in the second half of the year than in the first half.

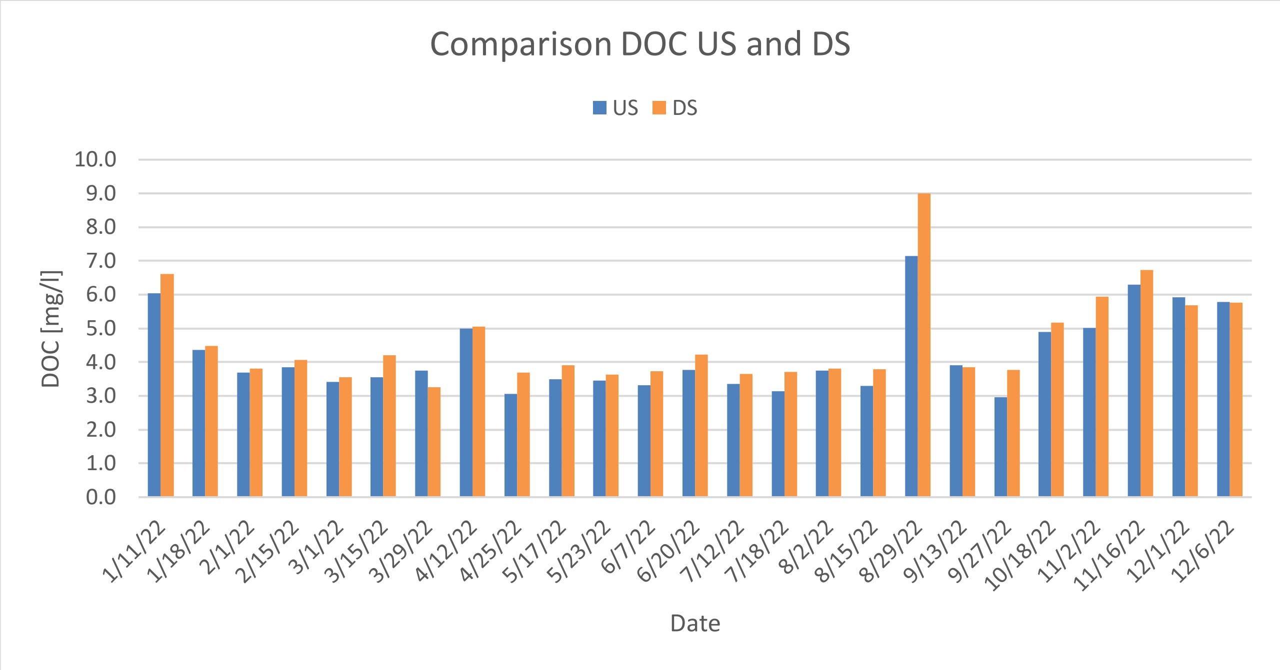

Figure 37: *DOC measurements in the Mederbach upstream and downstream of the beaver wetland, during the time period of 11.01.2022 and 06.12.2022.*

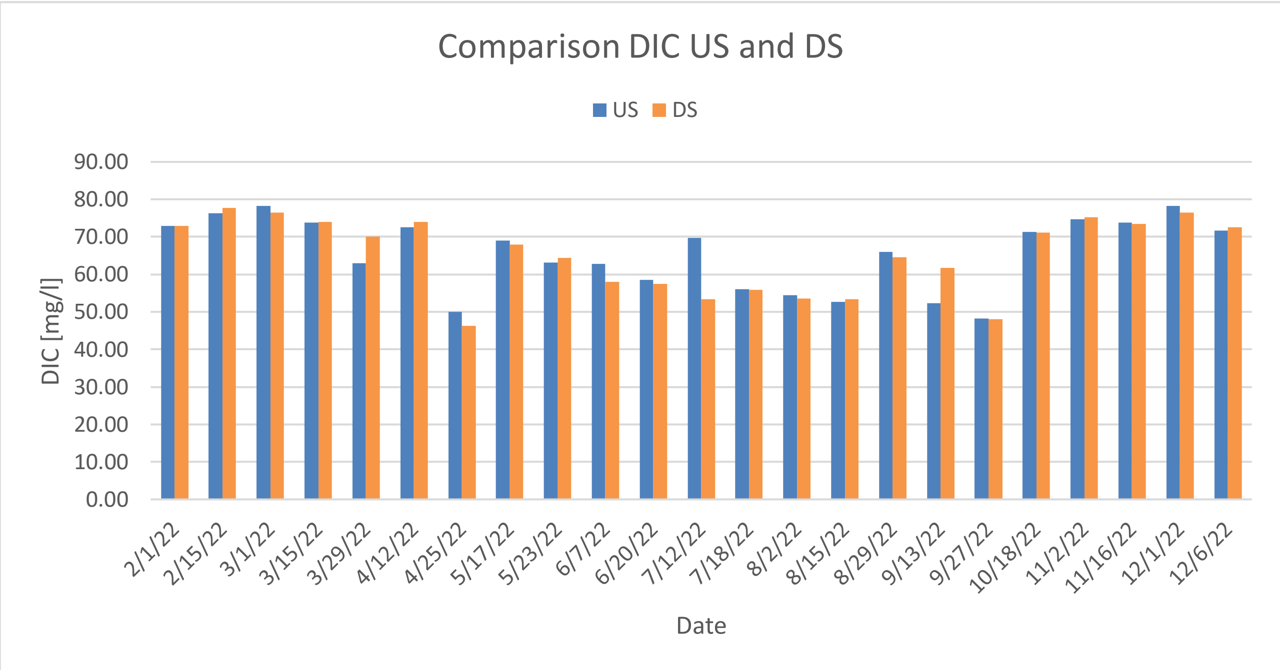

Figure 38: *DIC measurements in the Mederbach upstream and downstream of the beaver wetland, during the time period of 01.02.2022 and 06.12.2022.*

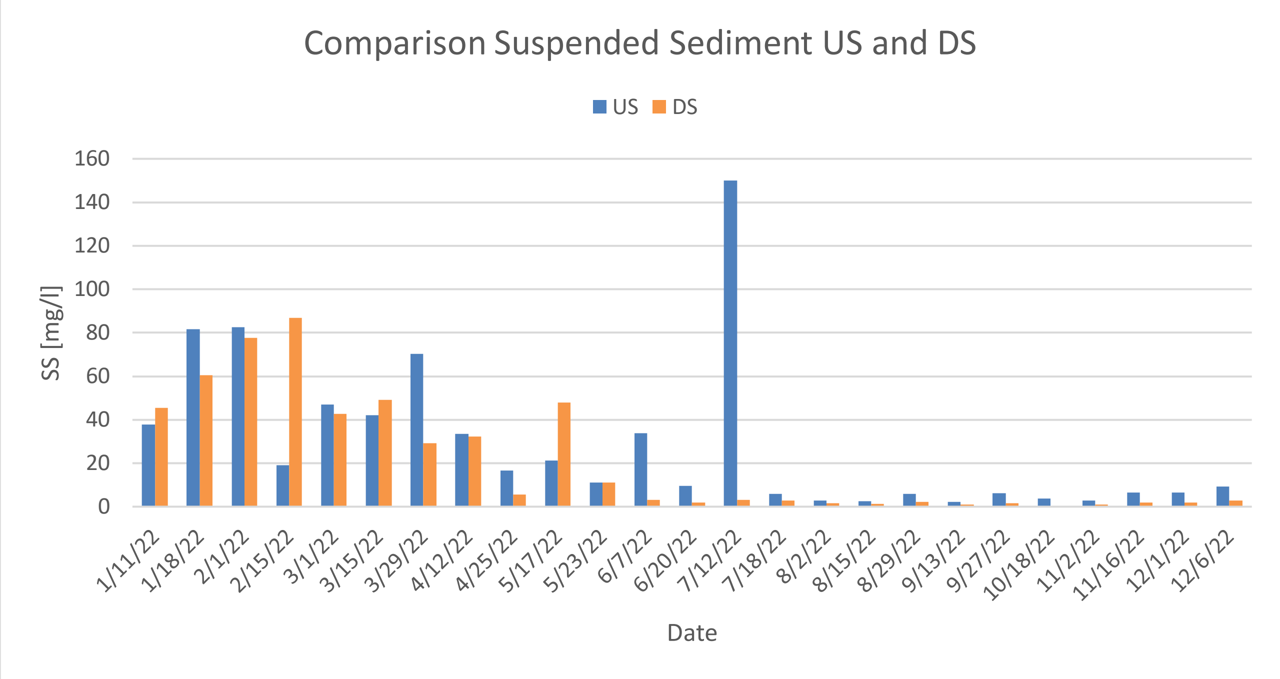

Figure 39: *Suspended sediment measurements in the Mederbach upstream and downstream of the beaver wetland, during the time period of 11.01.2022 and 06.12.2022.*

To analyze whether the beaver wetland acts as a source or sink for DOC, DIC, and suspended sediment, I compared the net retention. For this purpose, I have plotted the net retention of the absolute DOC, DIC, and suspended sediment measured values equated with the discharge net retention. Values above the 1:1 line indicate that the beaver wetland is acting as a sink and for values below the 1:1 line as a source. Most DOC values are below the 1:1 line, which also corresponds to the mean upstream and downstream DOC concentrations. In contrast, no clear trend is evident for DIC and for suspended sediment most values are above the 1:1 line (see Figure 40).

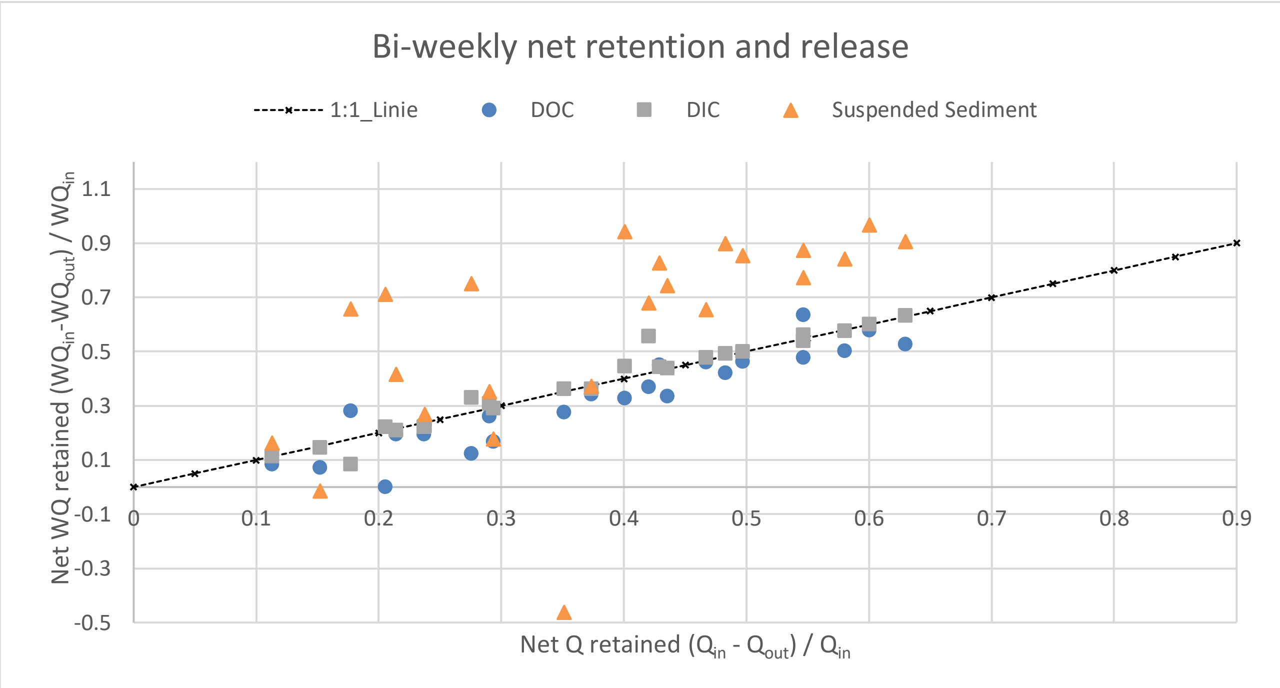

Figure 40: *Bi-weekly net retention and release of DOC, DIC & suspended sediment in mg/s and discharge in l/s.*

Based on the measured DOC and DIC values during the whole measuring period, I could calculate a concentration - discharge relation. To do this, I formed the logarithm of the respective measured concentration value and the discharge at the time of measurement from the water level-discharge relation and calculated the corresponding concentration from the linear relation between concentration and discharge (see Appendix B).

In comparison to DIC and DOC, I divided the study year for suspended sediment into two periods and then calculated the linear relation between concentration and discharge separately for both periods. For suspended sediment, I divided the calculations into the two halves of the year from 01.04.2022 to 20.06.2022 (1st half) and from 20.06.2022 to 01.04.2023 (2nd half). For the 1st half I calculated a linear function of "y = 0.7055x - 50.292" for upstream and "y = 0.6478x - 20.123" for downstream and for the 2nd half "y = 0.0197x + 2.4017" for upstream and "y = 0.0097x + 1.1634" for downstream (see Appendix B).

Along with the discharge calculation (see chapter 5.3), I determined the absolute values for DOC, DIC, and suspended sediment that flowed into and out of the study area during the study period in a temporal resolution of 15 minutes. Since the DOC, DIC, and suspended sediment were measured in mg/l and the discharge was in l/s I multiplied the values and got the reading in mg/s at a temporal resolution of 15min. Afterwards I multiplied these values with 900, since 15 minutes correspond to 900 seconds, and got the sum of the corresponding measured value in mg for each time period of 15 min. By summing up each 15min sequence, I obtained the absolute value for the corresponding parameter that flowed into and out of the study area over the measurement period.

According to these calculations, I could calculate the total of DOC, DIC and suspended sediment that flowed in and out of the study area in Marthalen while the measurement period from the 04.01.2022 – 04.01.2023 (see Table 2).

Table 2: *DOC, DIC and suspended sediment flux in and out of the study area.*

	US [t]	**DS [t]**	**Measurement period**
DOC	26	15.1	04.01.2022-04.01.2023
DIC	418.2	229.36	04.01.2022-04.01.2023
Suspended Sediment	212.1	129.1	04.01.2022-04.01.2023

5.5 Infiltration

Additionally, to the export downstream, I calculated the amount of DOC and DIC leaving the beaver wetland area by infiltration. According to Woo and Waddington (1990) the evaporation was 40% of the water balance for a wetland area in north Ontario with an open water area of 8840 m^2. In the study area in Marthalen, the cumulative discharge difference between upstream and downstream was 42.3 %. Based on Puttock et al. (2017) the discharge difference between upstream and downstream was 22 % for a study area in Southwest England. In their study area, evaporation accounts for 22% of the water balance. Based on these two studies, we have assumed for our study area that of 42.3% difference between upstream and downstream discharge, 32.3% is due to evaporation and 10% to infiltration. To calculate the amount of DOC and DIC exported by infiltration, I calculated the infiltration in l/s by 10% of the water balance in a temporal resolution of 15-minutes. By multiply the infiltration with the DOC and DIC concentration and 900 seconds I got the amount of DOC and DIC for each timespan of 15-minutes while the whole measurement period. We assumed the same concentration of DOC and DIC in the infiltrated water as for the measured concentration downstream. By summing each 15-minute timespan I calculated the total of DOC and DIC infiltrated in tones. According to this calculation, 2.8 t of DOC and 39 t of DIC have been exported from the study area from 04.01.2022 to 04.01.2023 by infiltration.

5.6 CO_2 & CH_4

While the measurement period we measured a total of 23 water flux from 18.01.2022 – 06.12.2022 and 19 soil flux measurements from 09.03.2022 – 30.11.2022. For the water flux measurements, we did three reference and three effective measurements. S1 (upstream), S5 (downstream) & S6 (further upstream) were reference and S2 (upper pond), S3 (middle pond) & S4 (lower pond) were effective measurements (see Figure 41 & Figure 42). The mean CH_4 flux for the effective measurements was 0.1 µg/m^2/s and for the reference 0.14 µg/m^2/s. The mean value for the effective CO_2 flux was 44 µg/m^2/s and for the reference 134 µg/ m^2/s. For CO_2 and CH_4 we measured the highest mean fluxes at S5 (downstream) and the lowest at S4 (lower pond).

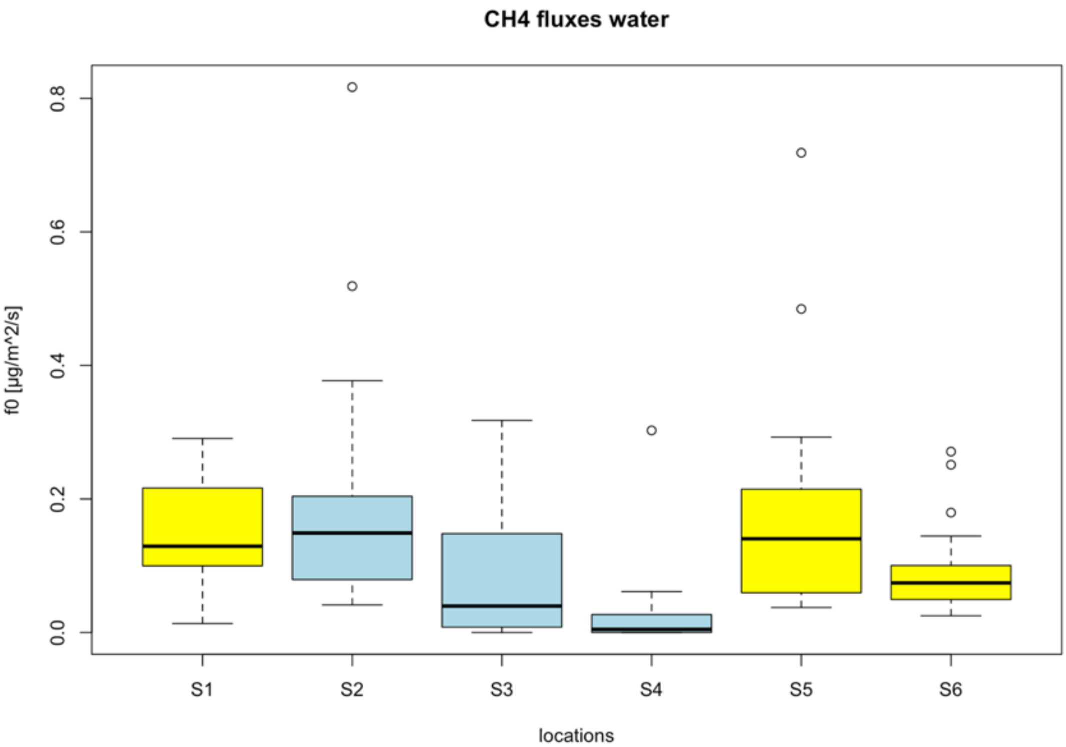

Figure 41: *Boxplots of CH_4 water flux measurements. The yellow boxplots show the reference and the blue ones the effective measurements.*

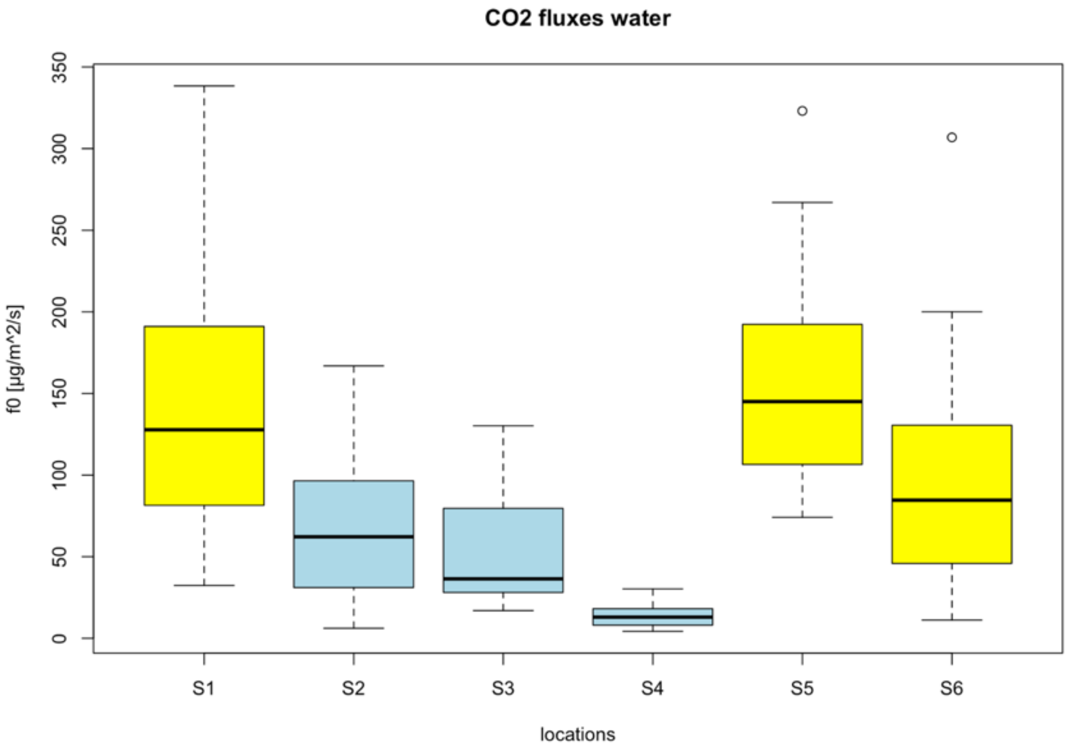

Figure 42: *Boxplots of CO_2 water flux measurements. The yellow boxplots show the reference and the blue ones the effective measurements.*

As for the water flux, we also performed three reference and three effective measurements for the soil flux. DS1 (dry soil near lower pond), DS2 (dry soil near middle pond) and DS3 (dry soil near upper pond) were reference and WS1 (wet soil lower pond), WS2 (wet soil middle pond) and WS3 (wet soil upper pond) were effective measurements (see Figure 43 & Figure 44). The mean CH_4 flux for the effective measurements was 0.0067 µg/m^2/s and for the reference -0.015 µg/m^2/s. For the CO_2 flux the mean value for the effective measurements was 324 µg/m^2/s and for the reference 130 µg/m^2/s.

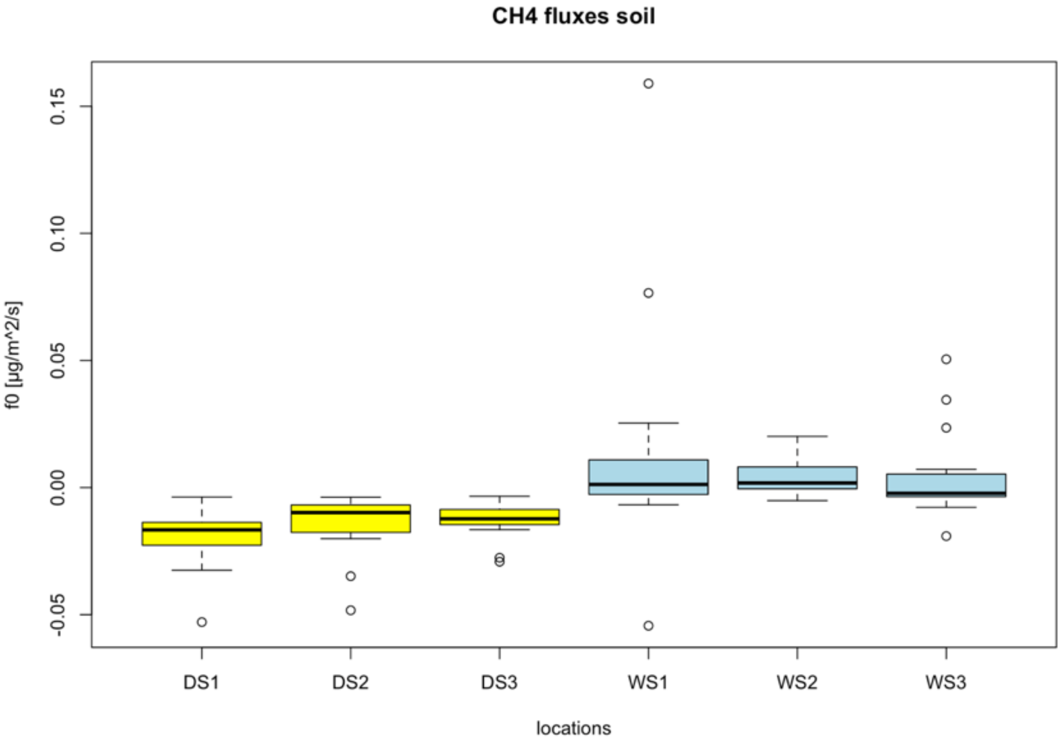

Figure 43: *Boxplots of CH_4 soil flux measurements. The yellow boxplots show the reference and the blue ones the effective measurements.*

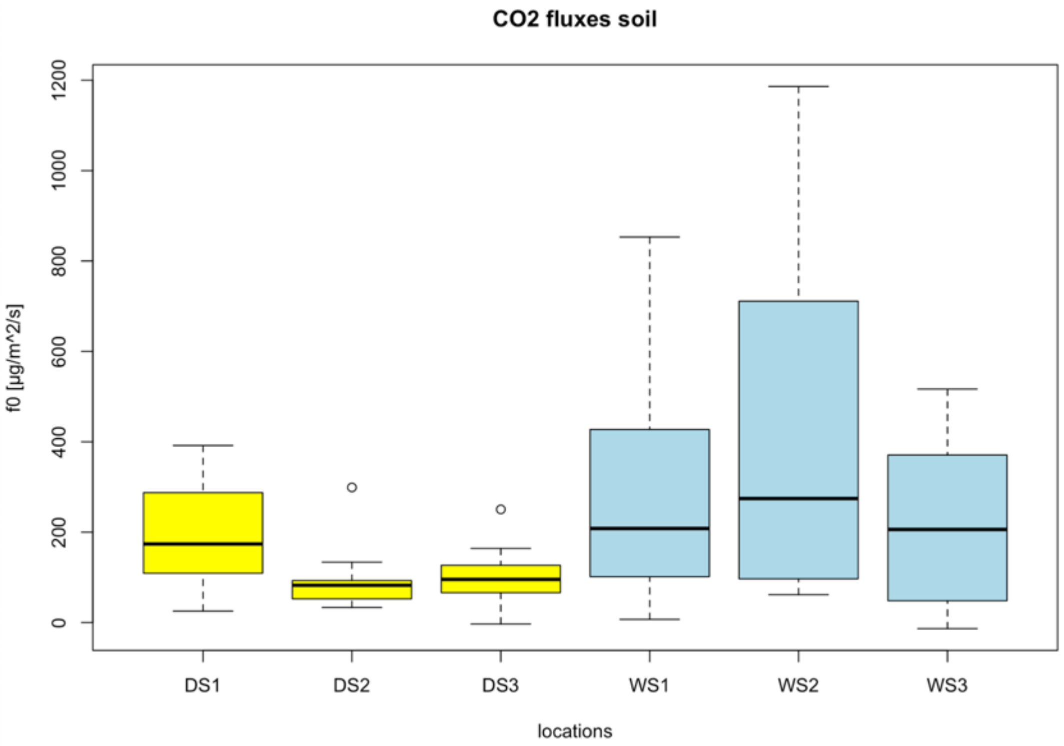

Figure 44: *Boxplots of CO_2 soil flux measurements. The yellow boxplots show the reference and the blue ones the effective measurements.*

To compare seasonal effects on water flux and soil flux measurements, I divided all measurements into calendar seasons and calculated the mean for the effective measurements (see Table 3). For the water flux measurements, the highest CO_2 fluxes were in winter and the lowest in summer. For the

CH_4 we measured the highest measurements in spring and the lowest in winter. Compared to the water flux measurements, the highest and lowest values for the soil flux measurements differed. We recorded the highest CO_2 and CH_4 values in summer and the lowest values in winter.

Table 3: *Mean CO_2 & CH_4 flux measurements for water and soil, divided into seasons.*

	Mean CO_2 [μg/m^2/s]	**Mean CH_4 [μg/m^2/s]**
Winter water	58.49	0.0439
Spring water	46.76	0.1525
Summer water	27.57	0.1321
Autumn water	44.94	0.0517
Winter soil	79.85	-0.0031
Spring soil	323.76	0.0069
Summer soil	585.49	0.0147
Autumn soil	160.44	0.0016

To calculate absolute mass of CO_2 and CH_4 for the study area throughout the measurement period, I combined the LiCor measurements with the drone photos. As mentioned in chapter 4.7 I set a threshold with the raster calculator to extract the water and soil areas. All objects with value 1 could assessed as water areas and all objects with the value 0 as non-water areas. I could interpret all non-water areas as soil areas, since there were either water areas or soil areas in the study area. Afterwards, I clipped the water and soil areas to the beaver wetland to exclude the upstream, downstream, and soil sections not impacted by beaver (dry soil) for the calculations. To represent the heterogeneity of the study area, I divided the water areas into channel, middle pond, and lower pond, and the soil areas into upper pond, middle pond, and lower pond (see Figure 45 & Figure 46).

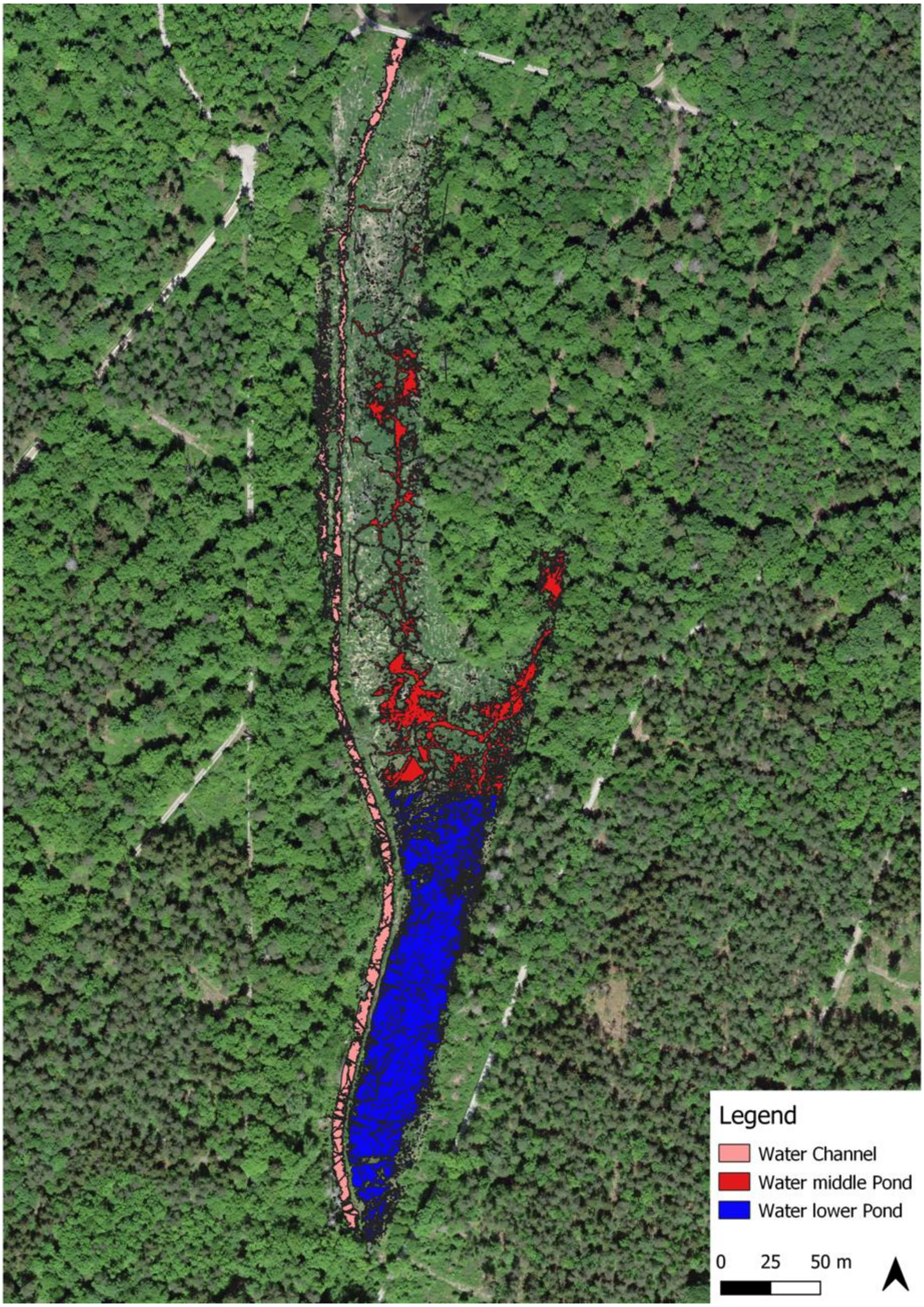

Figure 45: *Water areas in the study area divided into channel, middle pond, and lower pond (Background: Swisstopo, 2022b).*

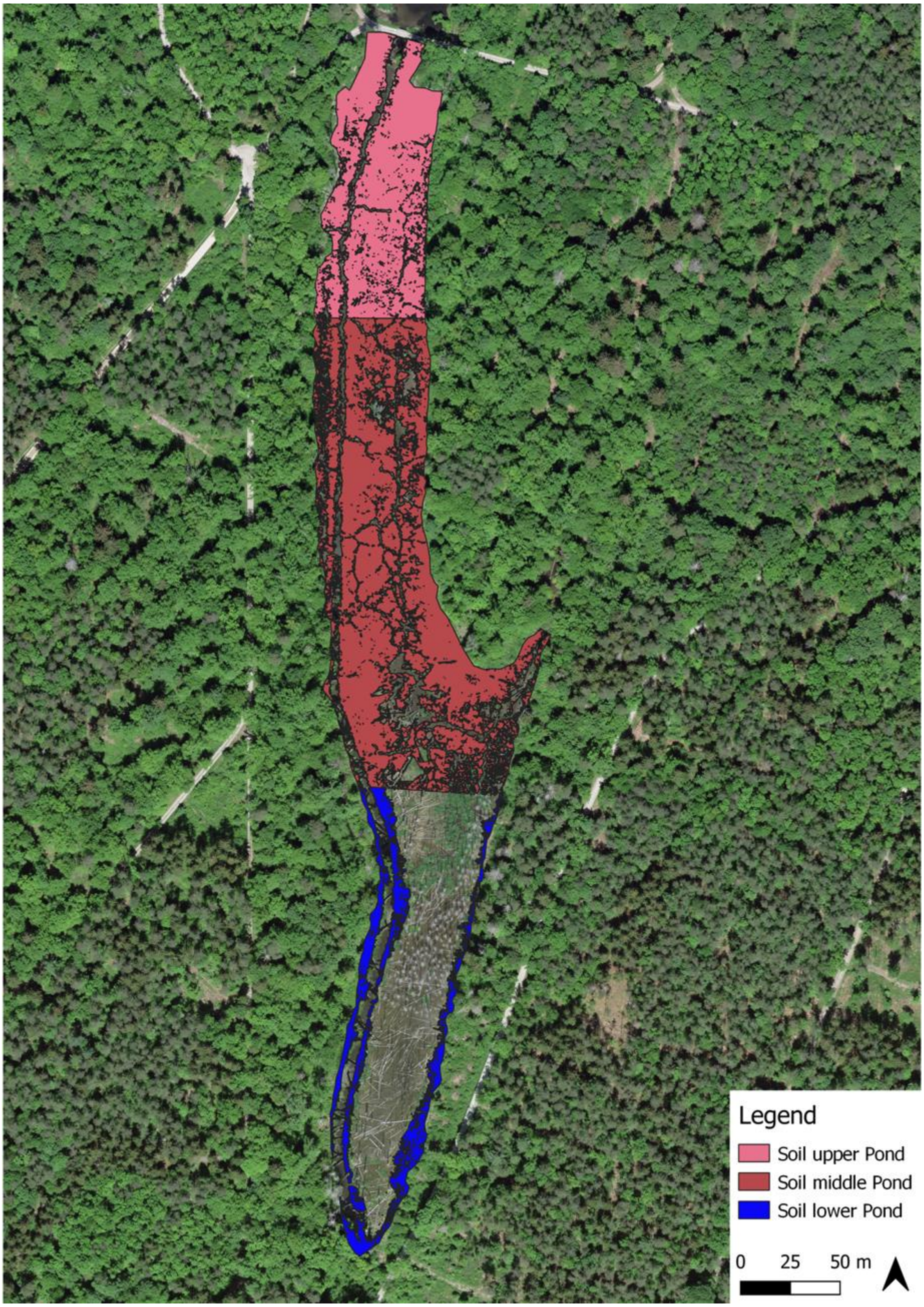

Figure 46: *Soil areas in the study area divided in upper pond, middle pond and lower pond (Background: Swisstopo, 2022b).*

Total 9 nine drone pictures were made while the measurement period. I did the calculations of CO_2 and CH_4 fluxes based on the drone image from 15.03.2022. The largest water area and soil area were in the lower pond and middle pond, respectively, and each accounted for more than half of the total area (see Table 4).

Table 4: *Water and soil areas based on the drone picture from 15.03.2022.*

	Area [m²]	Area total [m²]
Channel$_{water}$	2639	
Middle pond$_{water}$	3482	
Lower pond$_{water}$	6346	
Water total		12467
Upper pond$_{soil}$	5927	
Middle pond$_{soil}$	11740	
Lower pond$_{soil}$	2456	
Soil total		20123

The correlation coefficient for the effective CO_2 soil flux measurements and average daily temperature was between 0.85 and 0.93. To calculate the CO_2 concentration of the three wet soil locations, I calculated polynomial function second degree as a function of the air temperature (see Appendix C). Because air temperature was measured every 15 minutes with a HOBO logger throughout the measurement period, I was able to calculate the CO_2 soil flux for 2022 for each day. Then I multiplied the calculated reading from the polynomial function between CO_2 flux and air temperature by 900 and the total area per section (see Table 4) to determine the total flux for each 15 minute time interval. By summing the individual 15-minute time intervals for WS1, WS2, and WS3, I determined the total CO_2 flux from the soil flux measurements.

The correlation coefficient between the CH_4 soil and CH_4 and CO_2 water flux and air temperature and water temperature, respectively, was low, so I calculated the total atmospheric flux differently. Since the CO_2 and CH_4 fluxes were measured in µg/m^2/s, I could multiply the measured values by the corresponding area (e.g. channel area in m^2) and the time between the measurement interval (in seconds) and get the CO_2 and CH_4 mass for the corresponding subsection between two measurements. I did these calculations for all subsections (water: Channel, middle pond & lower pond; soil: Upper pond, middle pond, lower pond) separately. Then I summed up the calculations for the individual subsections between the measurement intervals and obtained the CO_2 and CH_4 mass of the entire beaver wetland during the measurement period from 04.01.2022 to 04.01.2023. We carried out the first water flux measurements on 18.01.2022. For the measurement period from 04.01.2022 - 02.02.2022 (second measurement) I used the measured value from 18.01.2022. Since we took the first soil flux measurements on 09.03.2022, I calculated the CH_4 flux values for the period from 01.04.2022 – 09.03.2022 from the mean flux values from 09.03.2022 and 30.11.2022.

According to these calculations, I could calculate the total mass of CO_2 and CH_4 for the soil and water flux in the study area in Marthalen while the measurement period from the 04.01.2022 – 04.01.2023 (see Table 5) Wet soil emits the most CO_2 in the study area. Calculated over the year, wet soil releases 8.67 kg/m^2/a. Converted for carbon, this corresponds to 2.37 kg/m^2/a. The water surfaces in the study area emit 1.16 kg CO_2 /m^2/a and 0.32 kg C/m^2/a, respectively. In comparison, more CH_4 is emitted from water surfaces than from wet soil. According to our calculations, the water surfaces emit 2.51 g CH_4/m^2/a and 1.88 g C/m^2/a, respectively. The soil areas emit 0.077g CH_4/m^2/a, and 0.057g C/m^2/a.

Table 5: *Total mass of CO_2 and CH_4 based on soil and water flux while the measurement period from the 04.01.2022 – 04.01.2023.*

	Water	**Soil**
CO_2 [t]	14.5	174.4
CH_4 [kg]	31.3	1.5
C (CO_2) [t]	4	47.6
C (CH_4) [kg]	23.4	1.2

To compare how much CO_2 and CH_4 would be released in the same area without the influence of the beavers, I made the same calculations as before with the CO_2 and CH_4 water- and CH_4 soil flux, using the reference measurements (water: S1 & S6; soil: DS1, DS2 & DS3). For the soil flux calculations, I measured the area of the beaver wetland without the channel and divided this area into three equal sections and used the reference flux measurements to calculate the annual mass of CO_2 and CH_4. For the water flux calculations, I divided the channel in the beaver wetland into two equal sections and used the two upstream locations (S1 & S6) to calculate the annual mass of CO_2 and CH_4 (see Table 6). I did not include the downstream reference location for this calculation because it was affected by the beaver wetland. Without the impact of the beaver in the same area as the actual beaver wetland area, 3.77 kg $CO_2/m^2/a$ and 1.03 kg $C/m^2/a$, respectively, would be emitted from the soil. For the water surface 3.79 kg $CO_2/m^2/a$ and 1.03 kg $C/m^2/a$, respectively, would be emitted from the water surface. In contrast, -0.46 g $CH_4/m^2/a$, respectively -0.34 g $C/m^2/a$ would be absorbed by the soil and 3.69 g $CH_4/m^2/a$ and 2.77 g $C/m^2/a$, respectively, would be emitted by the water.

Table 6: *Annual mass of CO_2 and CH_4 without the impact of the beaver.*

	Water	**Soil**
CO_2 [t]	10	112.9
CH_4 [kg]	9.7	-13.6
C (CO_2) [t]	2.7	30.8
C (CH_4) [kg]	7.3	-10.2

5.7 Carbon balance

I have presented the individual results on the specific carbon fluxes in a table and calculated the carbon imports and exports to determine the carbon balance (see Table 7). Based on these calculations, 175.9 tons more was transported into the study area than was exported for the year under investigation. This balance also includes calculations of the vegetation input per year and annual carbon storage in the soil. I did not perform these calculations myself, which is why they were not included in specific chapters in the results. However, they will be discussed in more detail in the discussion.

In total there is more carbon imported into the study area than exported again by hydrologic or atmospheric fluxes. However, the total amount of POC flowing into and out of the study area during the study period is not included in these calculations.

Table 7: *Calculation of the first carbon balance in the study area in Marthalen, during the measurement period from 04.01.2022 - 04.01.2023.*

	Mass fluxes	Mass fluxes in C (carbon)
DIC_{input} [t]	418.2	418.2
DOC_{input} [t]	26	26
$C_{vegetation}$		39
C_{soil}		Δ33.3
Total carbon input [t]		**516.5**
DIC_{output} [t]	229.4	229.4
DOC_{output} [t]	15.1	15.1
CH_4 water [kg]	31.3	23.4
CO_2 water [t]	14.5	4
CH_4 soil [kg]	1.5	1.2
CO_2 soil [t]	174.4	47.6
$C_{infiltration}$	41.2	41.2
Total carbon output [t]		**340.6**

6 Discussion

6.1 Meteorological conditions

Compared to the annual precipitation amounts from 2013 - 2021, the annual precipitation amount of 2022 was the lowest. Especially in July 2022 the precipitation values were low. In addition to the low precipitation amounts in July, the measured air temperature in the study area was highest compared to the other months.

Meteorological conditions such as precipitation and air temperature are important factors affecting discharge in the study area. The effects of precipitation on water level are shown in Figure 47 for February. The effects of precipitation on water level in the other months can be seen in the Appendix D. A precipitation event leads to an increase in water level in the study area, whereby the peak of the precipitation event, the upstream and downstream water level vary in time. First, the precipitation event occurred and then resulted in increased water levels upstream and finally the peak was visible downstream. This delay with respect to upstream occurs due to retention in the beaver wetland. The mean discharge for upstream in July calculated based on the PQ relation was 112 l/s, while in September, when there was more precipitation, the mean discharge was 182 l/s. In addition to its effect on discharge, precipitation also affects the amount of DOC, DIC, and Suspended sediment transported in the river network. The greater the discharge, the greater the total amount of DOC, DIC and suspended sediment flowing into and out of the study area.

In addition to precipitation, temperature can also affect discharge formation. The higher the temperatures, the higher the potential evaporation. As an example of this, in July there was not only little precipitation but also high temperatures, which in combination with the low precipitation resulted in low discharge.

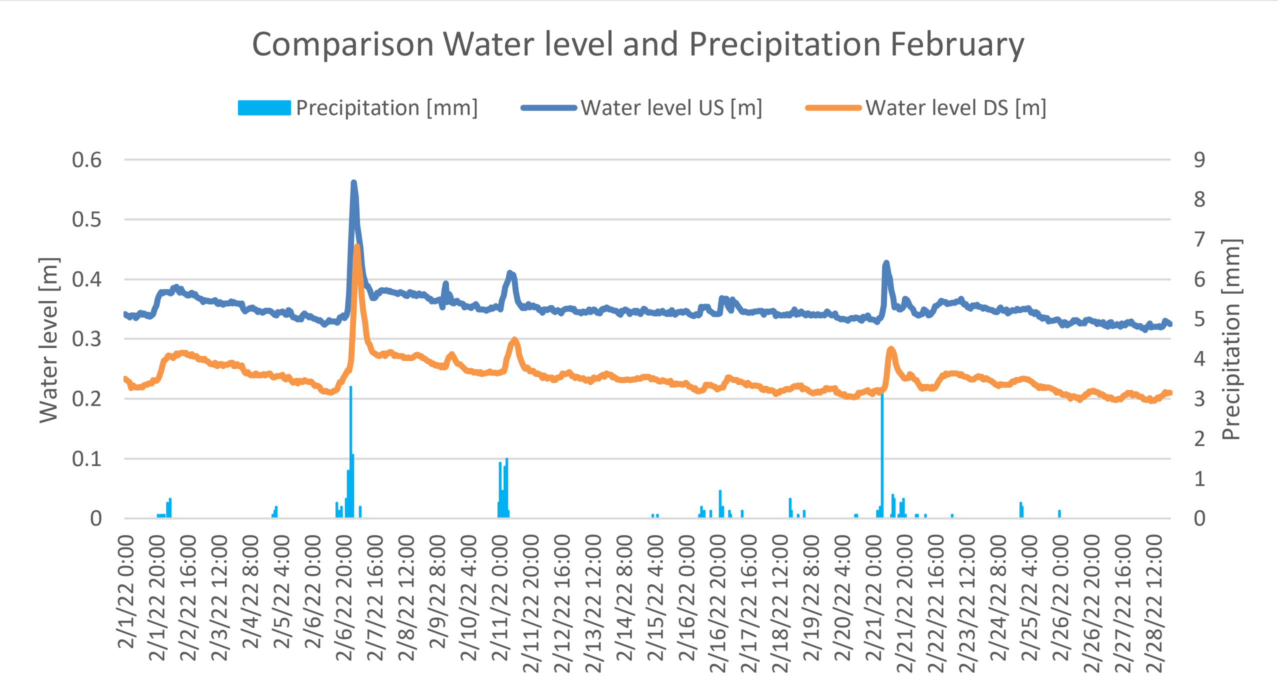

Figure 47: *Impact of precipitation on upstream and downstream water level in February in the study area.*

6.2 Bathymetry

No volume calculation has ever been performed in the study area, so I could not compare our measured values with other calculations. All GPS measurements to determine the water volume were made on one day, because the water level could have changed, which would have complicated the analyses. Nevertheless, most of the water areas could be recorded (see Appendix E). For those water surfaces we were unable to capture, I derived water depths for volume calculations from surrounding GPS measurements.

Basically, it can be analyzed that according to our calculations, the stored water volume in the study area is rather underestimated than overestimated. To calculate the volume, we measured the depth of the water surface to the pond waterbed. However, in many places in the study area, the top 30cm of the pond's waterbed was heavily saturated with water. In addition, the wet soils in the beaver wetland were also water saturated and provide another water storage. However, these additional water reservoirs were not included in the calculations of the stored water volume, as a corresponding analysis would have been too time-consuming and would not have justified the added value for investigating the research question. In addition, it can be assumed that the largest portion of the water volume is stored in the open water surfaces.

As mentioned in the results, I used four drone images and the volume determination from 26.03.2022 to calculate the relation between water level and volume. Nevertheless, with the calculation of the water level - volume relation the volume change over the year can be represented. Based on the water level logger installed in the middle pond, we were able to document the change in water level throughout the year in the beaver wetland area. It was shown that the water level in the middle pond was more constant compared to the upstream and downstream measurements and showed less change compared to fluctuating flows throughout the year (see Appendix F). The mean water level over the year was 0.41 m (max. 0.85 and min. 0.33) with a standard deviation of 0.036 m. This indicates that the scatter around the mean value is small. In addition, we were regularly in the study area throughout the year and did not observe large fluctuations in the water level.

Compared to older orthophotos from the study area, there were fewer open water areas during the study period. Especially in the upper pond changes can be observed. An example of this is shown in Figure 48. The orthophoto on the left shows a section of the upper and middle pond from the year 2013 and on the right the same section from the year 2022. In 2013 there were still several open water surfaces in the upper and middle pond, where there was mainly wet soil during the study period. During the second field campaign in winter, soil borings were made and a layer thickness of organic sediment of one meter was found in the upper pond before the original soil appeared before the arrival of the beaver. According to a study by He et al. (2023), the declining water level of a beaver pond can have an impact on the net CO_2 uptake of a study area and cause a beaver wetland to no longer be a CO_2 sink. This is also a development that can take place in the study area in Marthalen and shows the importance of the water level in the Beaver Pond respectively the water volume.

Figure 48: *Two Orthophotos of the upper and middle pond. On the left side from 2013 and on the right side from 2022 (Swisstopo, 2023).*

6.3 Discharge & water level

The calculation of the PQ-relation was crucial for this master thesis. From the calculation of the PQ-relation the discharge for the whole measuring period could be calculated in a 15-minute resolution and so it was possible to determine how much DOC & DIC flowed into and out of the study area over the whole measurement period. Therefore, it was important to measure a wide range of discharges both upstream and downstream. This was achieved because 97.2% upstream and 96.1% downstream of the calculated discharge values were within the discharge measurement range throughout the measurement period.

According to the results from the literature research (see Figure 6), we also measured a decrease in the downstream discharge in Marthalen compared to the upstream discharge. During the entire measurement period, the measured discharge upstream was 42.3 % higher than downstream. However, there were also seasonal differences. In winter the average discharge difference between upstream and downstream was 27.8% and in summer 50.2%. The differences in discharge between upstream and downstream were caused by infiltration of water in the flooded areas and by evaporation. The evaporation had an influence especially in the warm months. This can also be seen in the different seasonal discharge differences between upstream and downstream. However, it must be mentioned that in July another beaver dam was built about 30 m upstream of the downstream water level measuring point, which further increased the retention time between upstream and downstream and thus possibly also increased infiltration (see Figure 49). According to an exploratory borehole drilled in 1953, 50m southwest of the lower pond, the first 23 m of the subsurface consists mainly of gravelly material (see Appendix G). Therefore, it can be assumed that, in addition to evaporation, infiltration also contributed to the discharge difference between upstream and downstream. However, infiltration in the study area occurs mainly over wetland sites or only in certain areas where no organic material has been deposited and prevents infiltration.

Figure 49: *The last beaver dam in the study area, which was built during the measurement period.*

6.4 DOC, DIC & suspended sediment

As noted in the literature (Larsen et al., 2021), we measured higher DOC concentrations downstream compared to upstream and lower suspended sediment concentrations downstream compared to upstream in Marthalen. In contrast, we did not find any clear effects between the upstream and downstream concentrations for DIC.

Results on DOC concentrations indicate that due to primary production in the beaver wetland, higher concentrations were measured downstream. Figure 50 compares the concentration differences between downstream and upstream. From the end of April to mid-November the differences between downstream and upstream DOC concentrations are larger than at the beginning and end of the year. This is also consistent with the beginning and end of the growing season in the study area (see Figure 51). We measured the largest DOC concentration differences at the end of summer and in autumn. This corresponds to the finding of Mann and Wetzel (1995) which measured the highest impact of a wetland system to the DOC concentrations in summer and autumn. Contrary to the findings in the literature, we did not measure higher DOC concentrations in summer compared to the rest of the year. However, this may be related to the fact that the discharge in summer was lower than in the beginning and end of the year (see Appendix H). According to Raymond and Saires (2010) there is a positive correlation between the discharge and DOC concentration. However, DOC concentrations are influenced by many other factors. One example is the entry of wastewater input into the channel. A reason for the higher DOC concentration in autumn may be that leaves from the trees fall into the channel and are degraded (BAFU, 2010).

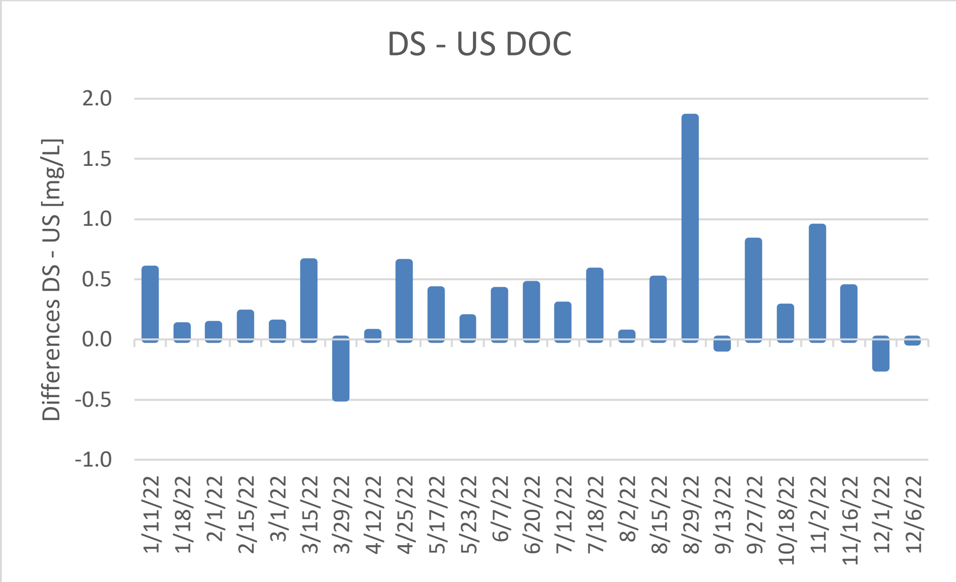

Figure 50: *Measured DOC concentration differences between downstream and upstream.*

Figure 51: *Change in vegetation during the year in the study area in Marthalen.*

The study area appears to have a filtering effect on suspended sediment transport and result in suspended sediment being deposited in the beaver wetland. According to the findings of Naiman et al. (1986), there are higher amounts of POC stored in an area influenced by beavers compared to an area without the impact of beavers. But the deposited POC fraction in a beaver-influenced area is smaller than the DOC fraction (Naiman et al., 1986). In this master thesis, we did not measure POC, but suspended sediment can be an indicator of POC (Larsen et al., 2021). However, to further investigate whether the study area in Marthalen acts as a POC sink or source, the POC fraction from the suspended sediment measurements would still need to be determined. The analyses of suspended sediment showed higher concentration values in the first half of the year than in the second half. One possible reason for this could be, the Mederbach stream above the study area was renaturalized in 2019, as described in Chapter 2.2. Therefore, the bank was not yet heavily vegetated in winter and early spring and sediment input from the bank into the channel may have been increased. As vegetation increased on the bank through the growing season, this could have had a reducing effect on sediment input, resulting in lower concentrations during the second half of the year. Another reason could have been that the suspended sediment water samples were stored from sampling until analysis in March 2023. During this time, individual components of the water may have precipitated and influenced the analysis when the filters were weighed. Since more time passed from the first sampling to the analysis than from the last sampling, this could be an explanation why the measured values differ in the first and second half of the year. However, for the influence on the carbon fluxes, the POC content is essential, which is why further analyses are necessary.

No influence of the study area on changes in DIC concentrations was detected. This could also be expected, since mainly biological feedback took place in the study area in Marthalen and thus mainly had an effect on DOC concentrations.

When analyzing the results, it was found that the total amount of carbon flowing into and out of the study area by transport in water is only slightly influenced by concentration, but mainly by discharge. Since over the whole year the discharge upstream was 42.3% higher than downstream, in absolute values more DOC, DIC and suspended sediment was transported into than out of the area. DIC had the biggest influence on the total carbon transport in the water. Therefore, when analyzing the total amount of transported carbon in and out of a study area, it is important to make enough discharge measurements to establish a meaningful relationship between the water level and discharge. In addition, the analyses of DIC must also be investigated, although no influence on concentration changes between upstream and downstream is to be expected.

6.5 Infiltration

The calculations to the amount of DOC and DIC exported by infiltration should more been considered as estimates than accurate calculations. We did not perform infiltration measurements by ourselves, but our calculations were based on results from other beaver wetlands. In addition, we have made assumptions regarding DOC and DIC concentrations in the infiltrated water. Therefore, our calculations to the infiltration should be considered with reservation. However, it is still possible to roughly represent the order of magnitude of how much DOC and DIC are exported from the study area by infiltration. The beaver wetland in Marthalen is a typical perched wetland, where percolation can only occur in specific locations or on the sides of open water areas where no layer of organic material interrupts the percolation. Possible locations where water infiltrates from the beaver wetland are northeast of the beaver lodge in the arm that enters the forested area and south of the lower pond where water from the floodplain flows back downstream into the channel.

6.6 CO_2 & CH_4

The measured CO_2 water flux in Marthalen were similar to the findings in the literature. In comparison, CH_4 measurements were lower than most measurements from water surfaces reported in the literature (see chapter 1.2). The CO_2 and CH_4 values from the wet soils were difficult to compare because there were hardly any studies from the wet soils compared to the CO_2 and CH_4 measurements from the beaver ponds. However, to represent total CO_2 and CH_4 measurements from an area impacted by beaver it is important to take measurements from the soils in addition to the open water surfaces. This will be discussed in more detail later.

In total we measured 14.5 t of CO_2 that corresponds to 1.16 kg/m^2/a or 3.19 g/m^2/d. According to the findings in the literature CO_2 flux were between 0.1 to 11.2 g/m^2/d (Nummi et al., 2018). In Marthalen, we measured rather lower CO_2 fluxes from the beaver ponds compared to the existing literature (see Nummi et al., 2018), but there were hardly any comparable studies from Europe to better classify our results.

For CH_4 we measured a total of 31.4 kg, which corresponds to 2.51 g/m^2/a or 6.88 mg/m^2/d. Compared to the literature (see Nummi et al., 2018), we measured much lower CH_4 fluxes in the study area in Marthalen. According to the literature, the results on CH_4 fluxes from the beaver ponds were between 27 and 919 mg/m^2/d. However, we measured CH_4 with the LiCor measuring device, which resulted from molecular diffusion. According to Weyhenmeyer (1999) CH_4 fluxes out of beaver ponds can be released as molecular diffusion and via gas bubbles. In their study area in Ontario, gas bubbles accounted for 65% (Weyhenmeyer, 1999). We also measured CH_4 fluxes caused by gas bubbles in our study area during the measurement period, but the results had not yet been evaluated by the end of this master's thesis. Therefore, it can be assumed that the total CH_4 flux, including CH_4 released via gas bubbles, is even larger for our study area.

We measured the largest CO_2 fluxes from the wet soil. In total 174.4 t is released from the wet soil to the atmosphere while the whole measurement period which corresponds to 8.67 kg/m^2/a or 23.75 g/m^2/d. According to Batson et al. (2015) 4 kg CO_2/m^2/a is released from a dry floodplain in Italy and 1.2 to 1.8 kg CO_2/m^2/a is released from a south European peatland (Danevčič et al., 2010). Our measurements were higher than these results, however, more research from beaver wetland areas is needed to better classify our results.

The measurements of CH_4 fluxes from the wetland were lower compared to the CH_4 flux measurements from the beaver pond. In total 1.5 kg CH_4 is released in our study area while the whole measurement period. We even measured CH_4 absorption especially while cooler air temperatures. This is also consistent with the results of Batson et al. (2015) and Danevčič et al. (2010) who measured -0.3 g CH_4/m2/a and -0.35 to 0.4 g CH_4/m2/a, respectively.

For the CO_2 measurements on the wet soil areas, I found a strong correlation between mean daily air temperature and the amount of CO_2 flux, and thus seasonal differences. Therefore, I could reconstruct the daily wet soil CO_2 concentrations for the entire measurement period. For all other atmospheric flux measurements from the water surfaces and wet soil, I could not find a sufficient correlation between the mean air temperature respectively water temperature, to reconstruct the concentrations between the individual measurements. Contrary to expectations, CH_4 flux from the water surface measurements were lower in summer than compared to the other seasons. Possible reasons for this could be that due to the growth and decomposition of the plants, an additional organic layer was deposited on the pond bottom and made it difficult for CH_4 to reach the water surface.

CO_2 emissions from soils had the largest impact on total carbon export from atmospheric flux measurements at Marthalen. On the other hand, the carbon fraction from CH_4 emissions had hardly any influence on the total carbon export. Therefore, in the study area in Marthalen it was important that besides the atmospheric flux measurements from the water areas also measurements from the wet soil areas were carried out to calculate the total carbon export.

According to the effective CO_2 and CH_4 measurements in the beaver wetland area, we also carried out reference measurements. Based on calculations of how much CO_2 and CH_4 would be released in the same area without the influence of the beavers, I found that more carbon was exported while the study period than would have been the case without the influence of the beavers. For water areas, less CO_2 and CH_4 is released per m^2 if there were no beaver wetland. However, due to the influence of the beavers, there are more open water areas and therefore more CO_2 and CH_4 are released overall than without the influence of the beavers if the water only flowed through the channel. Additionally, we have established that downstream after the beaver wetland, the CO_2 and CH_4 were higher than upstream. Wohl et al. (2013) have the same findings, which supports the thesis that the influence of beavers not only leads to higher CO_2 and CH_4 fluxes in the wetland, but also to more CO_2 and CH_4 being exported downstream.

To calculate the total amount of carbon exported by CO_2 and CH_4 emissions I calculated the soil and water areas by analyzing the drone pictures. Although different drone pictures with spectral resolution were accomplished, I referred the computations of the water and wet soil surfaces only to a drone picture of 15.03.2022. Reasons for this were that on the image from 15.03.2022 the water areas were clearly visible in contrast to the other images, since the vegetation period hat not yet started and therefore not covered the open water areas. In addition, there was sufficient solar radiation to ensure optimal multispectral resolution. A HOBO logger was installed in the study area during the entire measurement period and therefore we were able to monitor the change in water depth and thus also the inundated water area. By analyzing the water level data, I found that the water level showed only small fluctuations. On average, the water level was 0.41 m high with a standard deviation of 3.6 cm (see Figure 52) and at 0.39 m at the time of the drone survey on March 15, 2022. Additionally, we were in the study area regularly throughout the measurement period and did not detect any major changes in open water areas. Therefore, although I used only one drone image, we can assume that the water and wet soil areas were sufficiently mapped for the measurement period.

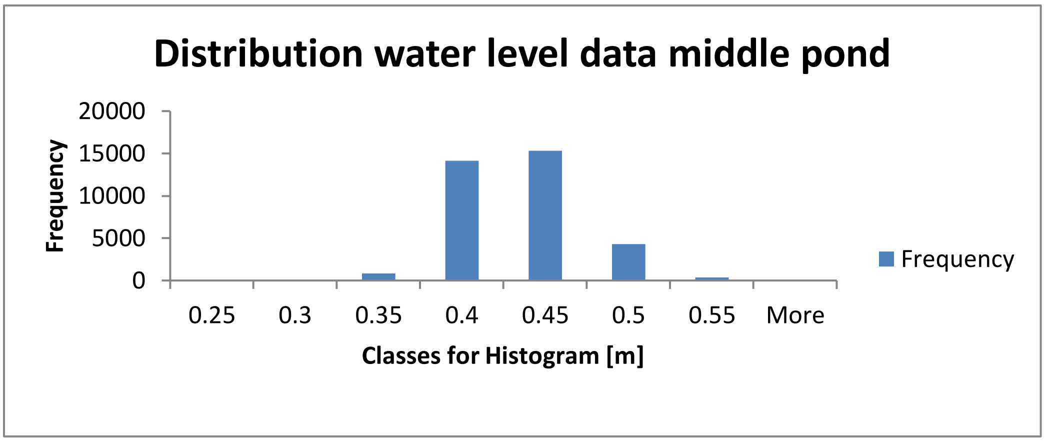

Figure 52: *Distribution water level in the middle pond. Most readings were between 0.35 - 0.4 m and between 0.4 - 0.45 m.*

6.7 Carbon balance

From the calculations of all specific carbon fluxes, I could make a first carbon balance. As mentioned in the results carbon stored in the soil and the biomass input are also included in the carbon balance.

During the winter field campaign, we took soil samples at several locations in the beaver wetland, which were later analyzed in the laboratory at Wageningen University. From the analyses in the laboratory, projections could be made of how much carbon is stored annually in the soil. Based on this calculation, about 33.3 t of carbon is annually stored in the soil. According to Brouwers (2021) the main input of carbon stored in the soil is due to annually emergent vegetation. In chapter 5.7, the carbon input in the soil is described as Δ 33.3 t, since the total value is determined from the other carbon input and output fluxes.

In a Bachelor thesis made in the beaver wetland area in Marthalen in 2021 the amount carbon in the biomass was calculated. The annual carbon input by the biomass is 39 t. In addition to carbon stored in biomass, carbon in deadwood was calculated and estimated at 895 t (Brouwers, 2021). The fraction of carbon stored in deadwood was not included in this carbon balance because the decomposition processes are very slow due to anaerobic conditions (Larsen et al., 2021) in the water and therefore have only a minor influence on the carbon balance.

The DOC and DIC is imported by the Mederbach into the study area. Some DOC and DIC is then deposited in the soil, and some is exported with the infiltrated water or downstream from the beaver wetland. Part of the additional carbon stored in the soil is then available for aerobic and anaerobic microbial metabolic pathways and can result in carbon being exported as CO_2 and CH_4 (Larsen et al., 2021). In our study area, CO_2 export was considerably higher than CH_4 export. In addition to the export of CO_2 and CH_4 by open water areas and wet soil, CO_2 is reabsorbed by vegetation through photosynthesis and stored as carbon (He et al., 2023). In summer, we measured lower CO_2 fluxes from the water surfaces compared to the other seasons. One reason for this could be that the CO_2 was absorbed by the aquatic plants before it could be released into the atmosphere. As vegetation is degraded, additional carbon is deposited in the soil (Rosell et al., 2005) or exported as DOC and therefore results in higher DOC concentrations downstream compared to upstream due to primary production in the study area (Kalinin et al., 2016). For an illustration of the different carbon fluxes, see Figure 53.

In total based on the calculations there is 516.5 t of carbon imported and 337.3 t exported out of the study area. This represents a difference of 179.2 t of carbon imported more than exported from the study area. It can be concluded that the investigation area in Marthalen represents a carbon sink for the measurement period from 04.01.2022 to 04.01.2023. DIC in and output and CO_2 measurements from the wet soil areas had the largest influences (see Figure 53).

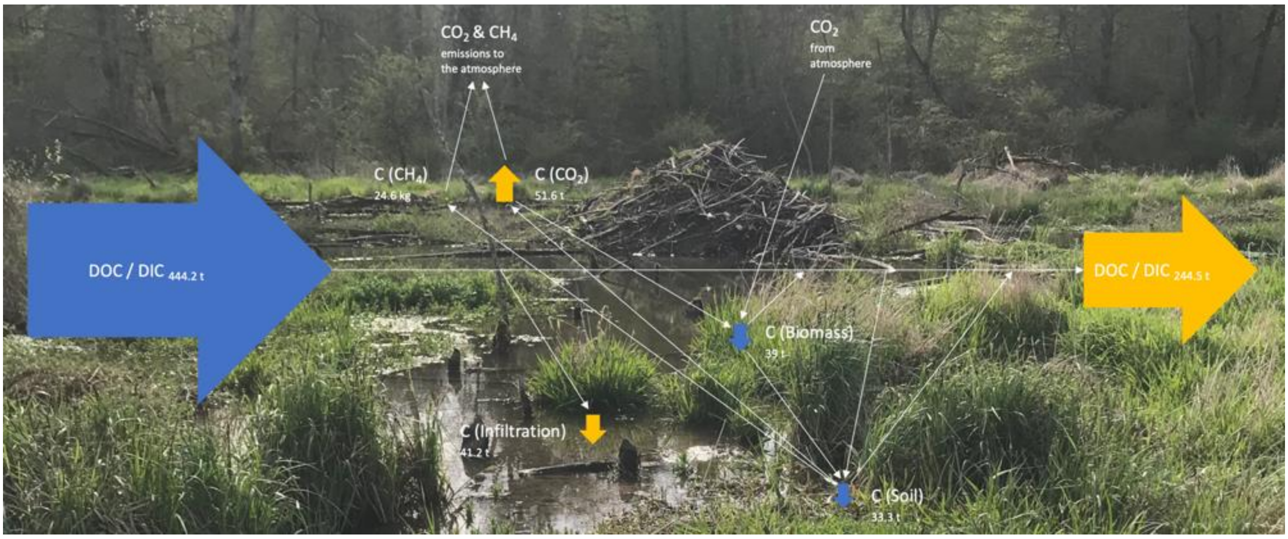

Figure 53: *Carbon fluxes in and out of the study area while the measurement period from 04.01.2022 - 04.01.2023. Blue arrows show carbon input and yellow arrows carbon output (own photo).*

6.8 Limitations

One limitation of this master's thesis was the amount of sampling per measurement day. We performed CO_2 and CH_4 measurements at three sites each for the open water and wet soil areas. More measurements could have been made to represent the heterogeneity of the study area even better. In particular, for the CO_2 measurements from the wet soil areas, we found differences between the individual measurement points. However, this could not be realized in this master thesis, because already the different single measurements of the different carbon fluxes took a lot of time and additionally mobility in the study area was complicated, so it would have been difficult to take measurements at more sites.

Another limiting factor was the calculation of the amount of DOC and DIC export by infiltration. To better represent this carbon export quantity, groundwater quality samples could have been taken at various locations in the study area to determine the DOC and DIC concentrations in the groundwater and the quantity by monitoring the groundwater level. However, on the one hand it would have been expensive to install the piezometers for this maser thesis and, we had no information where the groundwater is located in the study area.

To complete the carbon balance, POC inputs and outputs would also need to be included. According to Naiman et al. (1986) the POC concentration were smaller than DOC concentrations. Since the study area in Marthalen had a filtering effect on the suspended sediment measurements in addition to the lower concentrations compared to DOC, it can be assumed that the carbon balance would not have been fundamentally different.

6.9 Outlook

According to our research, CO_2 emissions from wet soils account for the largest amount of total carbon export from atmospheric fluxes. Therefore, it is important for further studies to consider these fluxes as well to calculate the total CO_2 export of a study area. In addition, we have not yet evaluated the CO_2 and CH4 measurements from the tree flux and vegetation flux. Although the initial analysis indicates that they have only a small effect on total CO_2 and CH_4 emissions, a full evaluation would still be interesting to see if this thesis is confirmed.

Although DIC concentrations are little affected by the beaver wetland, much carbon may still be deposited due to the difference in discharge between upstream and downstream. Since DIC was detected in higher concentrations than DOC, the inclusion of DIC in the total carbon balance is essential and therefore recommended for further studies.

As mentioned earlier, we have not yet been able to analyze the total amount of POC transported into and out of the study area as part of this master's thesis. Therefore, it would be interesting to evaluate this additional carbon flux to be able to classify to what extent the carbon balance is influenced by the POC fluxes.

The total annual mass of carbon stored in biomass was calculated using a bachelor's thesis from 2021. Since drone images with a multispectral resolution were also taken during the study period, these evaluations could be carried out again to determine the amount of carbon stored in the biomass for the study period. On the one hand, the calculations of the bachelor thesis could be verified, and on the other hand, annual changes could be analyzed.

Besides the analyzes to the carbon fluxes, other water quality parameters were measured flowing into and out of study area by the Mederbach. The following water quality parameters were measured:

Sodium, Magnesium, Calcium, Fluoride, Chloride, Bromide, Nitrate and Ammonium. These data would be available for future studies, and it would be interesting to see what influence the study area in Marthalen has on the individual water quality parameters.

7 Conclusion

The goal of this master thesis was to measure the different carbon fluxes that were imported and exported while the measurement period from the 04.01.2022 till 04.01.2023 in the beaver wetland area in Marthalen, to calculate the carbon balance. The main carbon fluxes that have an impact on the overall balance are DIC and DOC imports and exports, and CO_2 emissions from Beaver Pond and wet soil areas. In comparison, CH_4 emissions had little impact on the overall carbon balance.

While the measurement period we measured higher DOC concentration downstream compared to upstream. This was consistent with findings from the literature. However, to measure the total mass of DOC as well as DIC and suspended sediment, discharge must be included. Because significantly more discharge flowed into the study area than flowed out, it was discharge, not concentration, that determined how much carbon was imported and exported from Mederbach.

Compared to the reference measurements, more CO_2 and CH_4 is released due to the influence of the beaver than in the same situation if the study area had not been influenced by the beavers. For CO_2 and CH_4 fluxes from water surfaces, we measured lower fluxes in the effective measurements than in the reference measurements, but with the inclusion of the water surface, the total CO_2 and CH_4 fluxes were larger than in the reference measurements.

Because measurements and sampling were conducted at regular intervals throughout the year, seasonal influences on carbon fluxes could also be recorded. Thereby, different findings resulted, related to the different carbon fluxes. As an example, CO_2 and CH_4 emissions from the wet soil areas were highest in summer. This could not be observed for the CO_2 and CH_4 fluxes from the beaver pond. DIC concentrations were similar throughout the year regardless of season and DOC concentrations were smaller in summer compared to winter and autumn.

Over the year more carbon was imported than exported from the study area. It can be assumed that the beaver wetland in Marthalen is a carbon sink and thus has a positive impact against climate change and shows the importance of similar beaver wetland in relation to carbon storage. However, these results should not be considered constants that are the same for each successive year. Beaver wetlands are subject to a natural process of flooding and drainage. (Johnston et al., 2014). Compared to older orthophotos, it was evident that the water surfaces had decreased in size in recent years. Therefore, it can be assumed that the investigated beaver wetland will drain and sediment up. Therefore, it would be interesting to further investigate the study area in the future to better understand the changes of the different carbon fluxes in relation to the evolution from flooding to beaver meadows.

References

BAFU (Bundesamt für Umwelt) (2010). Methoden zur Untersuchung und Beurteilung der Fliessgewässer. Chemisch-physikalische Erhebungen, Nährstoffe. Umwelt-Vollzug Nr. 1005. Bundesamt für Umwelt, Bern. 44 S.

BAFU (Bundesamt für Umwelt) (2013). NAWA – Nationale Beobachtung Oberflächengewässerqualität. *Konzept Fliessgewässer*.

BAFU (Bundesamt für Umwelt) (2021). Nährstoffe in Fliessgewässern. https://www.bafu.admin.ch/bafu/de/home/themen/wasser/fachinformationen/zustand-der-gewaesser/zustand-der-fliessgewaesser/wasserqualitaet-der-fliessgewaesser/naehrstoffe-in-fliessgewaessern.html. Last access: 22.03.2022.

Baker-Blocker, A., Donahue, T. M., & Mancy, K. H. (1977). Methane flux from wetlands areas. *Tellus*, *29*(3), 245-250. https://doi.org/10.3402/tellusa.v29i3.11353

Barber, T. R., Burke Jr, R. A., & Sackett, W. M. (1988). Diffusive flux of methane from warm wetlands. *Global Biogeochemical Cycles*, *2*(4), 411-425. https://doi.org/10.1029/GB002i004p00411

Batson, J., Noe, G. B., Hupp, C. R., Krauss, K. W., Rybicki, N. B., & Schenk, E. R. (2015). Soil greenhouse gas emissions and carbon budgeting in a short-hydroperiod floodplain wetland. *Journal of Geophysical Research: Biogeosciences*, *120*(1), 77-95. https://doi.org/10.1002/2014JG002817

Binkert, L. (2022). Analyse des Regen-Abflussverhaltens in einem stark vergletscherten Einzugsgebiet (master thesis). University of Berne.

Błędzki, L. A., Bubier, J. L., Moulton, L. A., & Kyker-Snowman, T. D. (2011). Downstream effects of beaver ponds on the water quality of New England first-and second-order streams. *Ecohydrology*, *4*(5), 698-707. https://doi.org/10.1002/eco.163

Brouwers, T. (2021). Busy Beaver Capture Carbon (bachelor thesis). University of Wageningen.

Bubier, J. L., Moore, T. R., & Roulet, N. T. (1993). Methane emissions from wetlands in the midboreal region of northern Ontario, Canada. *Ecology*, *74*(8), 2240-2254. https://doi.org/10.2307/1939577

Burke, R. A., Martens, C. S., & Sackett, W. M. (1988). Seasonal variations of D/H and 13C/12C ratios of microbial methane in surface sediments. *Nature*, *332*(6167), 829-831. https://doi.org/10.1038/332829a0

Burns, D. A., & McDonnell, J. J. (1998). Effects of a beaver pond on runoff processes: comparison of two headwater catchments. *Journal of Hydrology*, *205*(3-4), 248-264. https://doi.org/10.1016/S0022-1694(98)00081-X

BWG (Bundesamt für Wasser und Geologie) (2002). Einsatz künstlicher Tracer in der Hydrologie. *Praxishilfe*.

Catalán, N., Herrero Ortega, S., Gröntoft, H., Hilmarsson, T. G., Bertilsson, S., Wu, P., Levanoni, O., Bishop, K. & Bravo, A. G. (2017). Effects of beaver impoundments on dissolved organic matter quality and biodegradability in boreal riverine systems. *Hydrobiologia*, *793*(1), 135-148. https://doi.org/10.1007/s10750-016-2766-y

Chaubey, I., Ward, G.M. (2006). Hydrologic budget analysis of a small natural wetland in Southeast USA. J. *Environ. Inform. 8* (1), 10–21.

Chemie.de (n.d.) Bibergeil. https://www.chemie.de/lexikon/Bibergeil.html. Last access: 28.12.2021.

Chen, B., Yang, R., Liu, Z., Sun, H., Yan, H., Zeng, Q., Zeng, S., Zeng, C. & Zhao, M. (2017). Coupled control of land uses and aquatic biological processes on the diurnal hydrochemical variations in the five ponds at the Shawan Karst Test Site, China: Implications for the carbonate weathering-related carbon sink. *Chemical Geology*, *456*, 58-71. https://doi.org/10.1016/j.chemgeo.2017.03.006

Cheremisinoff, N. P., & Davletshin, A. (2015). *Hydraulic fracturing operations: handbook of environmental management practices*. John Wiley & Sons.

Cirmo, C. P., & Driscoll, C. T. (1993). Beaver pond biogeochemistry: acid neutralizing capacity generation in a headwater wetland. *Wetlands*, *13*(4), 277-292.

Correll, D. L., Jordan, T. E., & Weller, D. E. (2000). Beaver pond biogeochemical effects in the Maryland Coastal Plain. *Biogeochemistry*, *49*(3), 217-239. https://doi.org/10.1023/A:1006330501887

CSCF (Centre Suisse de Cartographie de la Faune) (n.d.a). Ausrottung. http://www.cscf.ch/cscf/de/home/biberfachstelle/informationen-zum-biber/biber-in-der-schweiz/ausrottung.html. Last access: 20.04.2022.

CSCF (Centre Suisse de Cartographie de la Faune) (n.d.b). Wiederansiedelung und erste Bestandeserhebungen. http://www.cscf.ch/cscf/de/home/biberfachstelle/informationen-zum-biber/biber-in-der-schweiz/wiederansiedlung.html. Last access: 20.04.2022.

CSCF (Centre Suisse de Cartographie de la Faune) (n.d.c). Aktuelle Verbreitung. http://www.cscf.ch/cscf/de/home/biberfachstelle/informationen-zum-biber/biber-in-der-schweiz/aktuelle-verbreitung.html. Last access: 20.04.2022

CSCF (Centre Suisse de Cartographie de la Faune) (n.d.d). Kohlenstoffkreislauf. https://www.unine.ch/cscf/de/home/biberfachstelle/projets-nationaux-sur-le-castor/fonction-des-barrages-de-castor/cycle-du-carbone.html. Last access: 20.04.2022.

CSCF (Centre Suisse de Cartographie de la Faune) (n.d.e). Nationale Biberprojekte 2021-2023. https://www.unine.ch/cscf/de/home/biberfachstelle/projets-nationaux-sur-le-castor.html. Last access: 10.01.2023.

Dahm, C. N., Trotter, E. H., & Sedell, J. R. (1987). Role of anaerobic zones and processes in stream ecosystem productivity. *Chemical Quality of Water and the Hydrological Cycle*, 157-178.

Danevčič, T., Mandic-Mulec, I., Stres, B., Stopar, D., & Hacin, J. (2010). Emissions of CO2, CH4 and N2O from Southern European peatlands. *Soil Biology and Biochemistry*, *42*(9), 1437-1446. https://doi.org/10.1016/j.soilbio.2010.05.004

Devito, K. J., & Dillon, P. J. (1993). Importance of runoff and winter anoxia to the P and N dynamics of a beaver pond. *Canadian Journal of Fisheries and Aquatic Sciences*, *50*(10), 2222-2234. https://doi.org/10.1139/f93-248

Dillon, P. J., Molot, L. A., & Scheider, W. A. (1991). *Phosphorus and nitrogen export from forested stream catchments in central Ontario* (Vol. 20, No. 4, pp. 857-864). American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. https://doi.org/10.2134/jeq1991.00472425002000040025x

DIN EN 1484 (1997). Water analysis—Guidelines for the determination of total organic carbon (TOC) and dissolved organic carbon (DOC).

DIN, ENISO 9963-1 (1995). 9963-1: 1996-02: Wasserbeschaffenheit–Bestimmung der Alkalinität–Teil 1: Bestimmung der gesamten und der zusammengesetzten Alkalinität (ISO 9963-1: 1994). *German version EN ISO*, 9963-1.

Driscoll, C. T., Holsapple, J., Schofield, C. L., & Munson, R. (1998). The chemistry and transport of mercury in a small wetland in the Adirondack region of New York, USA. *Biogeochemistry*, *40*(2), 137-146. https://doi.org/10.1023/A:1005989229089

Ecke, F., Levanoni, O., Audet, J., Carlson, P., Eklöf, K., Hartman, G., McKie, B., Ledesma, J., Segersten, J., Truchy, A. & Futter, M. (2017). Meta-analysis of environmental effects of beaver in relation to artificial dams. *Environmental Research Letters*, *12*(11). https://doi.org/10.1088/1748-9326/aa8979

Ford, T.E., Naiman, R.J. (1988). Alteration of carbon cycling by beaver: methane evasion rates from boreal forest streams and rivers. *Can. J. Zool. 66* (2), 529–533. https://doi.org/10.1139/z88-076.

Fuller, M. R., & Peckarsky, B. L. (2011). Does the morphology of beaver ponds alter downstream ecosystems?. *Hydrobiologia*, *668*(1), 35-48. https://doi.org/10.1007/s10750-011-0611-x

Fuss, R. (2020). Gasfluxes. Greenhouse Gas Flux Calculation from Chamber Measurements. R package version 0.4-4. https://CRAN.R-project.org/package=gasfluxes

Green, K. C., & Westbrook, C. J. (2009). Changes in riparian area structure, channel hydraulics, and sediment yield following loss of beaver dams. *Journal of Ecosystems and Management*, *10*(1). https://doi.org/10.22230/jem.2009v10n1a412

Harriss, R. C., & Sebacher, D. I. (1981). Methane flux in forested freshwater swamps of the southeastern United States. *Geophysical Research Letters*, *8*(9), 1002-1004. https://doi.org/10.1029/GL008i009p01002

He, H., Moore, T., Humphreys, E. R., Lafleur, P. M., & Roulet, N. T. (2023). Water level variation at a beaver pond significantly impacts net CO 2 uptake of a continental bog. *Hydrology and Earth System Sciences*, *27*(1), 213-227. https://doi.org/10.5194/hess-27-213-2023

Hillman, G. R., Feng, J. C., Feng, C. C., & Wang, Y. (2004). Effects of catchment characteristics and disturbances on storage and export of dissolved organic carbon in a boreal headwater stream. *Canadian Journal of Fisheries and Aquatic Sciences*, *61*(8), 1447-1460. https://doi.org/10.1139/f04-082

HOBO U20L Manual (n.d.). HOBO U20L Water Level Logger (U20L-0x) Manual. https://www.onsetcomp.com/files/manual_pdfs/17153-G%20U20L%20Manual.pdf. Last access: 01.06.2022.

HOBOware Pro (n.d.). *Powerful tools to enhance your analysis for stand-alsone data loggers* [Computer Software]. https://www.onsetcomp.com/products/software/hoboware. Last access: 11.04.2023.

Hodkinson, I.D. (1975). Energy flow and organic matter decomposition in an abandoned beaver pond ecosystem. *Oecologia 21*(2), 131–139. https://doi.org/10.1007/BF00345556

Johnston, C.A. (2014). Beaver pond effects on carbon storage in soils. *Geoderma 213*(0), 371–378. https://doi.org/10.1016/j.geoderma.2013.08.025

Johnston, C. A. (2017). *Beavers: boreal ecosystem engineers* (pp. p-272). Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-319-61533-2

Jones, B.M., Tape, K.D., Clark, J.A., Nitze, I., Grosse, G., Disbrouw, J. (2020). Increase in beaver dams controls surface water and thermokarst dynamics in an Arctic tundra region, Baldwin Peninsula, northwestern Alaska. *Environmental Research Letters*, *15*(7), 075005 https://doi.org/10.1088/1748-9326/ab80f1.

Kalinin, A., Covino, T., & McGlynn, B. (2016). The influence of an in-network lake on the timing, form, and magnitude of downstream dissolved organic carbon and nutrient flux. *Water Resources Research*, *52*(11), 8668-8684. https://doi.org/10.1002/2016WR019378

Kantonaler Gestaltungsplan (2004). Marthalen. *Kantonaler Gestaltungsplan Kiesabbaugebiet Niedermartalen, Revision 2009*.

Karran, D.J., Westbrook, C.J., Bedard-Haughn, A. (2018). Beaver-mediated water table dynamics in a Rocky Mountain fen. *Ecohydrology 11*(2), e1923.

Klotz, R. L. (1998). Influence of beaver ponds on the phosphorus concentration of stream water. *Canadian Journal of Fisheries and Aquatic Sciences*, *55*(5), 1228-1235. https://doi.org/10.1139/f97-318

Koschorreck, M., Herzsprung, P., Brands, E., Kirch, P.M., Dalbeck, L. (2016). Minor effect of beaver dams on stream dissolved organic carbon in the catchment of a German drinking water reservoir. *Limnologica 61*, 36–43. https://doi.org/10.1016/j. limno.2016.09.005.

Kothawala, D. N., Evans, R. D., & Dillon, P. J. (2006). Changes in the molecular weight distribution of dissolved organic carbon within a Precambrian shield stream. *Water resources research*, *42*(5). https://doi.org/10.1029/2005WR004441

Larsen, A., Larsen, J. R., & Lane, S. N. (2021). Dam builders and their works: Beaver influences on the structure and function of river corridor hydrology, geomorphology, biogeochemistry and ecosystems. *Earth-Science Reviews*, *218*, 103623. https://doi.org/10.1016/j.earscirev.2021.103623

Law, A., McLean, F., Willby, N.J. (2016). Habitat engineering by beaver benefits aquatic biodiversity and ecosystem processes in agricultural streams. *Freshwater Biology*, *61*(4), 486–499. https://doi.org/10.1111/fwb.12721.

Lazar, J. G., Addy, K., Gold, A. J., Groffman, P. M., McKinney, R. A., & Kellogg, D. Q. (2015). Beaver ponds: resurgent nitrogen sinks for rural watersheds in the northeastern United States. *Journal of environmental quality*, *44*(5), 1684-1693. https://doi.org/10.2134/jeq2014.12.0540

Lee, M. (n.d.). Bäche und Überschwemmungen. https://www.marthalen.ch/de/portrait/geschichte/?action=showinfo&info_id=3635. Last access: 10.01.2022.

Leithold, E. L., Blair, N. E., & Perkey, D. W. (2006). Geomorphologic controls on the age of particulate organic carbon from small mountainous and upland rivers. *Global Biogeochemical Cycles*, *20*(3). https://doi.org/10.1029/2005GB002677

Levanoni, O., Bishop, K., McKie, B.G., Hartman, G., Ekl¨of, K., Ecke, F. (2015). Impact of beaver pond colonization history on methylmercury concentrations in surface water. Environ. Sci. Technol. 49 (21), 12679–12687. https://doi.org/10.1021/acs. est.5b03146.

LI-7810 CH4/CO2/H2O Trace Gas Analyzer (2021). *Instruction Manual*. 98.

Mackenzie, F. T., & Lerman, A. (2006). *Carbon in the Geobiosphere:-Earth's Outer Shell* (Vol. 25). Springer Science & Business Media.

Mann, C. J., & Wetzel, R. G. (1995). Dissolved organic carbon and its utilization in a riverine wetland ecosystem. *Biogeochemistry, 31*(2), 99-120. https://doi.org/10.1007/BF00000941

Maret, T. J., Parker, M., & Fannin, T. E. (1987). The effect of beaver ponds on the nonpoint source water quality of a stream in southwestern Wyoming. *Water Research*, *21*(3), 263-268. https://doi.org/10.1016/0043-1354(87)90204-1

Margolis, B. E., Castro, M. S., & Raesly, R. L. (2001). The impact of beaver impoundments on the water chemistry of two Appalachian streams. *Canadian Journal of Fisheries and Aquatic Sciences*, *58*(11), 2271-2283. https://doi.org/10.1139/f01-166

MeteoSchweiz (2023). Datenportal für Lehre und Forschung (IDAweb). https://www.meteoschweiz.admin.ch/service-und-publikationen/service/wetter-und-klimaprodukte/datenportal-fuer-lehre-und-forschung.html. Last access: 10.04.2023.

Moore, R. D. (2005). Slug injection using salt in solution. *Streamline Watershed Management Bulletin*, *8*(2), 1-6.

Moore, T., Roulet, N., & Knowles, R. (1990). Spatial and temporal variations of methane flux from subarctic/northern boreal fens. *Global Biogeochemical Cycles*, *4*(1), 29-46. https://doi.org/10.1029/GB004i001p00029

Müller-Schwarze, D. (2011). The beaver–its life and impact, 2nd edn.

Muskopf, S. A. (2007). The effect of beaver (Castor canadensis) dam removal on total phosphorus concentration in Taylor Creek and Wetland, South Lake Tahoe, California.

Nägeli, R. (2020). *Fleudebüel Pfaffeholz und Strick. Marthaler und Elliker Flur-, Wald-, Orts- und Familiennamen*. Gemeinde Marthalen

Naiman, R. J. (1982). Characteristics of sediment and organic carbon export from pristine boreal forest watersheds. *Canadian Journal of Fisheries and Aquatic Sciences*, *39*(12), 1699-1718. https://doi.org/10.1139/f82-226

Naiman, R.J., Johnston, C.A., Kelley, J.C. (1988). Alteration of north American Streams by beaver. *BioScience 38*(11), 753–762. https://doi.org/10.2307/1310784.

Naiman, R.J., Melillo, J.M. (1984). Nitrogen budget of a subarctic stream altered by beaver (Castor canadensis). *Oecologia 62*(2), 150–155. https://doi.org/10.1007/ bf00379007.

Naiman, R.J., Melillo, J.M., Hobbie, J.E. (1986). Ecosystem alteration of boreal forest streams by beaver (Castor canadensis). *Ecology 67*(5), 1254–1269. https://doi.org/ 10.2307/1938681.

Naiman, R.J., Pinay, G., Johnston, C.A., Pastor, J. (1994). Beaver influences on the long-term biogeochemical characteristics of boreal forest drainage networks. *Ecology 75*(4), 905–921. https://doi.org/10.2307/1939415.

Neumayer, M., Teschemacher, S., Schloemer, S., Zahner, V., & Rieger, W. (2020). Hydraulic modeling of beaver dams and evaluation of their impacts on flood events. *Water*, *12*(1), 300. https://doi.org/10.3390/w12010300

Nummi, P., Vehkaoja, M., Pumpanen, J., Ojala, A. (2018). Beavers affect carbon biogeochemistry: both short-term and long-term processes are involved. *Mammal Review, 48*(4), 298–311.

Nyssen, J., Pontzeele, J., Billi, P. (2011). Effect of beaver dams on the hydrology of small mountain streams: example from the Chevral in the Ourthe Orientale basin, Ardennes, Belgium. J. Hydrol. 402 (1–2), 92–102. https://doi.org/10.1016/j.jhydrol.2011.03.008

Pro natura (n.d.). Bibersee Marthalen ZH: Toter Wald oder lebendiges Feuchtgebiet?. https://www.pronatura.ch/de/bibersee-marthalen-zh-toter-wald-oder-lebendiges-feuchtgebiet. Last access: 08.02.2022.

Puttock, A., Graham, H. A., Cunliffe, A. M., Elliott, M., & Brazier, R. E. (2017). Eurasian beaver activity increases water storage, attenuates flow and mitigates diffuse pollution from intensively-managed grasslands. *Science of the total environment*, *576*, 430-443. https://doi.org/10.1016/j.scitotenv.2016.10.122

QGIS Development Team (2022). *QGIS Geographic Information System. Open Source Geospatial Foundation* (Version 3.26.3) [Computer Software]. https://qgis.org/en/site/. Last access: 10.04.2023.

Raymond, P. A., & Saiers, J. E. (2010). Event controlled DOC export from forested watersheds. *Biogeochemistry*, *100*, 197-209. https://doi.org/10.1007/s10533-010-9416-7

Regnier, P., Friedlingstein, P., Ciais, P., Mackenzie, F. T., Gruber, N., Janssens, I. A., ... & Thullner, M. (2013). Anthropogenic perturbation of the carbon fluxes from land to ocean. *Nature geoscience*, *6*(8), 597-607. https://doi.org/10.1038/ngeo1830

Rosell, F., Bozser, O., Collen, P., & Parker, H. (2005). Ecological impact of beavers Castor fiber and Castor canadensis and their ability to modify ecosystems. *Mammal review*, *35*(3-4), 248-276. https://doi.org/10.1111/j.1365-2907.2005.00067.x

Roulet, N.T., Crill, P.M., Comer, N.T., Dove, A., Boubonniere, R.A. (1997). CO2 and CH4 flux between a boreal beaver pond and the atmosphere. *Journal of Geophysical Research: Atmospheres*, *102*(D24), 29313–29319. https://doi.org/10.1029/97JD01237.

Roy, V., Amyot, M., & Carignan, R. (2009). Beaver ponds increase methylmercury concentrations in Canadian shield streams along vegetation and pond-age gradients. *Environmental science & technology*, *43*(15), 5605-5611. https://doi.org/10.1021/es901193x

RStudio Team. (2022). *RStudio: Integrated Development Environment for R* (Version 4.2.1) [Computer software]. http://www.rstudio.com/. Last access: 10.04.2023.

Rudd, J. W., & Hamilton, R. D. (1978). Methane cycling in a eutrophic shield lake and its effects on whole lake metabolism 1. *Limnology and oceanography*, *23*(2), 337-348. https://doi.org/10.4319/lo.1978.23.2.0337

Smith, M. E., Driscoll, C. T., Wyskowski, B. J., Brooks, C. M., & Cosentini, C. C. (1991). Modification of stream ecosystem structure and function by beaver (Castor canadensis) in the Adirondack Mountains, New York. *Canadian Journal of Zoology*, *69*(1), 55-61. https://doi.org/10.1139/z91-009

Spalinger, R. (2019). Ein Bach wird umgeleitet. https://www.andelfinger.ch/themen/weinland/ein-bach-wird-umgeleitet/. Last access: 08.01.2023.

Svensson, B. H., & Rosswall, T. (1984). In situ methane production from acid peat in plant communities with different moisture regimes in a subarctic mire. *Oikos*, 341-350. https://doi.org/10.2307/3544151

Swisstopo (2019). SWISSIMAGE 10cm. https://www.swisstopo.admin.ch/de/geodata/images/ortho/swissimage10.html. Last access: 10.04.2023.

Swisstopo (2022a). Landeskarten (farbig). https://www.geo.admin.ch/de/geo-dienstleistungen/geodienste/darstellungsdienste-webmapping-webgis-anwendungen/web-map-services-wms.html. Last access: 10.04.2023.

Swisstopo (2022b): SWISSIMAGE 10cm. https://www.swisstopo.admin.ch/de/geodata/images/ortho/swissimage10.html. Last access: 10.04.2023.

Swisstopo (2022c): Swiss Map Raster 10. https://www.swisstopo.admin.ch/de/geodata/maps/smr/smr10.html. Last access: 10.04.2023.

Swisstopo (2023). Swissimage Zeitreise. https://map.geo.admin.ch/?lang=de&topic=ech&bgLayer=ch.swisstopo.pixelkarte-farbe&layers=ch.swisstopo.swissimage-product&layers_timestamp=current&E=2689435.27&N=1274310.56&zoom=11.39419305577972. Last access: 11.03.2023

Thomas, H., & Nisbet, T. (2007). An assessment of the impact of floodplain woodland on flood flows, Water Environ. *J*, *21*, 114-126. https://doi.org/10.1111/j.1747-6593.2006.00056.x

Trumbore SE, Czimczik CI. (2008). An uncertain future for soil carbon. *science*, *321*(5895), 1455-1456.

Wegener, P., Covino, T., & Wohl, E. (2017). Beaver-mediated lateral hydrologic connectivity, fluvial carbon and nutrient flux, and aquatic ecosystem metabolism. *Water Resources Research*, *53*(6), 4606-4623. https://doi.org/10.1002/2016WR019790

Wernli, H. R. (2011): Einführung in die Tracerhydrologie. Skript zum Hydrologischen Praktikum. Bern: Universität Bern.

Westermann, P. (1993). Temperature regulation of methanogenesis in wetlands. *Chemosphere*, *26*(1-4), 321-328. https://doi.org/10.1016/0045-6535(93)90428-8

Westermann, P., & Ahring, B. K. R. (1987). Dynamics of methane production, sulfate reduction, and denitrification in a permanently waterlogged alder swamp. *Applied and Environmental Microbiology*, *53*(10), 2554-2559. https://doi.org/10.1128/aem.53.10.2554-2559.1987

Weyhenmeyer, C.E., 1999. Methane emissions from beaver ponds: rates, patterns, and transport mechanisms. *Global biogeochemical cycles*, *13*(4), 1079–1090

Whitfield, C. J., Baulch, H. M., Chun, K. P., & Westbrook, C. J. (2015). Beaver-mediated methane emission: The effects of population growth in Eurasia and the Americas. *Ambio*, *44*(1), 7-15. https://doi.org/10.1007/s13280-014-0575-y

Wohl, E. (2013). Landscape-scale carbon storage associated with beaver dams. *Geophysical research letters*, *40*(14), 3631–3636. https://doi.org/10.1002/grl.50710.

Wohl, E., Dwire, K., Sutfin, N., Polvi, L., & Bazan, R. (2012). Mechanisms of carbon storage in mountainous headwater rivers. *Nature communications*, *3*(1), 1263. https://doi.org/10.1038/ncomms2274

Woo, M. K., & Waddington, J. M. (1990). Effects of beaver dams on subarctic wetland hydrology. *Arctic*, 223-230.

Yavitt, J. B., Angell, L. L., Fahey, T. J., Cirmo, C. P., & Driscoll, C. T. (1992). Methane fluxes, concentrations, and production in two Adirondack beaver impoundments. *Limnology and Oceanography*, *37*(5), 1057-1066. https://doi.org/10.4319/lo.1992.37.5.1057

Yavitt, J.B., Fahey, T.J. (1994). Beaver impoundments in temperate forests as sources of atmospheric CO2. *Geophysical research letters*, *21*(11), 995–998.

Yavitt, J. B., Lang, G. E., & Sexstone, A. J. (1990). Methane fluxes in wetland and forest soils, beaver ponds, and low-order streams of a temperate forest ecosystem. *Journal of Geophysical Research: Atmospheres*, *95*(D13), 22463-22474. https://doi.org/10.1029/JD095iD13p22463

Zahner, V. (1997). Einfluß des Bibers auf gewässernahe Wälder. *Diss. Univ. München*.

8 Appendix

8.1 Appendix A

Table A1: Basis for calculating of the PQ-relation.

	Date	time	Discharge [m^3/s]	Level [m]	Temperature [°C]	Base conductivity [µS/cm]	Peak [µS/cm]	Mixing distance [m]	Amout of salt [g]	Calibration coefficient [(mg/l)/µS/cm)]
DS	19.01.2022		0.17	0.26	5.9	772	881	130	1500	0.5
US	19.01.2022		0.19	0.37	5.8	765	957	75	2000	0.5
DS	01.02.2022	10:30	0.11	0.222	5.3	891	1004	130	1126	0.5
US1	01.02.2022	11:30	0.16	0.34	5.1	832	950	75	1320	0.5
US2	01.02.2022	11:30	0.15	0.34	5.1	828	928	75	1148	0.5
DS1	16.02.2022	09:30	0.11	0.214	4.7	819	877	150	810	0.5
DS2	16.02.2022	09:50	0.11	0.215	4.7	815	886	150	1007	0.5
US	16.02.2022	11:00	0.19	0.352	6.4	817	911	75	1260	0.5
DS1	01.03.2022	14:00	0.09	0.205	4.8	806	854	150	653	0.5
DS2	01.03.2022	14:40	0.1	0.208	4.8	800	855	150	850	0.5
US	01.03.2022	15:40	0.12	0.328	6.9	815	926	75	1217	0.5
DS	08.03.2022	14:15	0.08	0.193	4.3	801	865	150	805	0.5
US	08.03.2022	15:30	0.11	0.328	6.5	811	908	75	1150	0.5
DS	15.03.2022	13:10	0.08	0.206	7.6	773	844	150	1000	0.5
US	15.03.2022	14:30	0.13	0.338	8.4	781	886	75	1157	0.5
DS	29.03.2022	13:10	0.07	0.187	9.5	769	829	150	770	0.5
US1	29.03.2022	14:40	0.11	0.317	11.8	790	909	75	996	0.5
US2	29.03.2022	15:10	0.11	0.317	11.9	767	884	75	992	0.5
DS	03.04.2022	14:00	0.09	0.192	5.8	709	778	150	810	0.5
US	03.04.2022	15:00	0.12	0.311	6.9	739	965	75	1200	0.5
DS1	09.04.2022	15:00	0.19	0.292	10.9	565	740	150	3200	0.5

DS2	09.04.2022	16:45	0.18	0.281	11.8	584	727	150	2280	0.5
DS3	09.04.2022	17:30	0.17	0.277	11.9	592	702	150	1800	0.5
US1	09.04.2022	18:15	0.25	0.394	11	722	918	75	2800	0.5
US2	09.04.2022	19:00	0.23	0.392	11	724	867	75	2000	0.5
DS	12.04.2022	13:50	0.13	0.22	11.2	753	838	150	1091	0.5
US1	12.04.2022	15:20	0.18	0.347	13.5	771	904	75	1506	0.5
US2	12.04.2022	15:40	0.15	0.344	13.9	765	898	75	1396	0.5
DS	25.04.2022	13:15	0.09	0.208	11.7	517	602	150	1080	0.5
US1	25.04.2022	15:10	0.31	0.410	12.2	552	652	75	1520	0.5
US2	25.04.2022	15:30	0.31	0.404	12.8	524	627	75	1507	0.5
DS1	27.04.2022	09:00	0.15	0.262	10.6	598	678	150	1185	0.5
DS2	27.04.2022	09:45	0.16	0.256	10.8	601	704	150	1450	0.5
US	27.04.2022	11:00	0.21	0.378	11.9	643	799	75	2000	0.5
DS	17.05.2022	13:05	0.08	0.181	19.1	754	816	150	703	0.5
US	17.05.2022	14:30	0.09	0.324	20.1	783	897	75	910	0.5
DS	23.05.2022	13:20	0.06	0.176	19.8	740	817	150	702	0.5
US	23.05.2022	14:45	0.09	0.317	20.4	775	880	75	860	0.5
DS	07.06.2022	13:10	0.08	0.192	20.2	613	692	150	805	0.5
US	07.06.2022	14:45	0.1	0.331	19.2	672	770	75	954	0.5
DS	16.06.2022	09:00	0.04	0.161	19.7	746	831	150	800	0.5
US	16.06.2022	10:15	0.06	0.302	20.2	774	871	75	1000	0.5
DS	12.07.2022	08:45	0.03	0.152	19.2	730	825	150	774	0.5
US1	12.07.2022	09:50	0.06	0.304	19.2	756	856	75	820	0.5
US2	12.07.2022	11:05	0.32	0.439	18	722	801	75	1380	0.5
DS	18.07.2022	12:50	0.03	0.128	22.2	714	793	150	697	0.5
US	18.07.2022	14:30	0.05	0.275	23.8	740	842	75	804	0.5
DS	02.08.2022	12:30	0.03	0.156	23	721	776	150	659	0.5
US	02.08.2022	14:20	0.05	0.295	24.5	746	836	75	780	0.5
DS	13.09.2022	12:45	0.03	0.137	16.7	719	796	150	700	0.5

US	13.09.2022	14:30	0.07	0.323	19.3	753	834	75	865	0.5
DS	27.09.2022	11:45	0.06	0.184	13.2	573	653	150	952	0.5
US	27.09.2022	13:15	0.17	0.405	13.9	550	642	75	1502	0.5
DS	18.10.2022	12:15	0.05	0.173	14.3	755	829	150	971	0.5
US	18.10.2022	13:30	0.1	0.356	15.5	770	851	75	1071	0.5
DS	22.10.2022	08:30	0.22	0.317	14.5	473	559	150	1800	0.5
US	22.10.2022	09:30	0.37	0.503	14.6	476	591	75	3010	0.5
DS	02.11.2022	12:15	0.05	0.178	12.2	798	872	150	952	0.5
US	02.11.2022	13:30	0.1	0.36	13.6	814	905	75	1085	0.5
DS	09.11.2022	16:30	0.09	0.224	9.9	769	854	150	1300	0.5
US	09.11.2022	17:30	0.24	0.414	11.9	648	785	75	3000	0.5
DS	10.11.2022	08:45	0.06	0.2	10.6	615	711	150	1300	0.5
US	10.11.2022	09:45	0.15	0.392	11.2	678	848	75	3000	0.5
US	10.11.2022	10:30	0.15	0.392	11.9	680	791	75	2200	0.5
DS	06.12.2022	12:15	0.11	0.247	5.4	721	782	150	1200	0.5
US	06.12.2022	13:30	0.21	0.423	6.7	721	818	75	1562	0.5
DS	23.12.2022	10:00	0.15	0.26	8.4	866	931	150	1300	0.5
DS	23.12.2022	10:30	0.15	0.26	8.4	883	963	150	1460	0.5
US	23.12.2022	11:30	0.43	0.502	9	846	944	75	2098	0.5

8.2 Appendix B

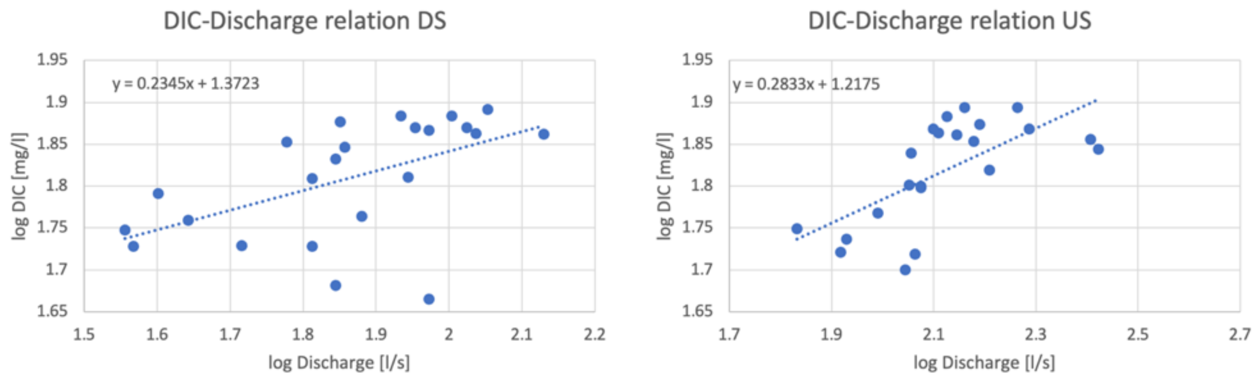

Figure 54: *DIC - discharge relation downstream (left) and upstream (right).*

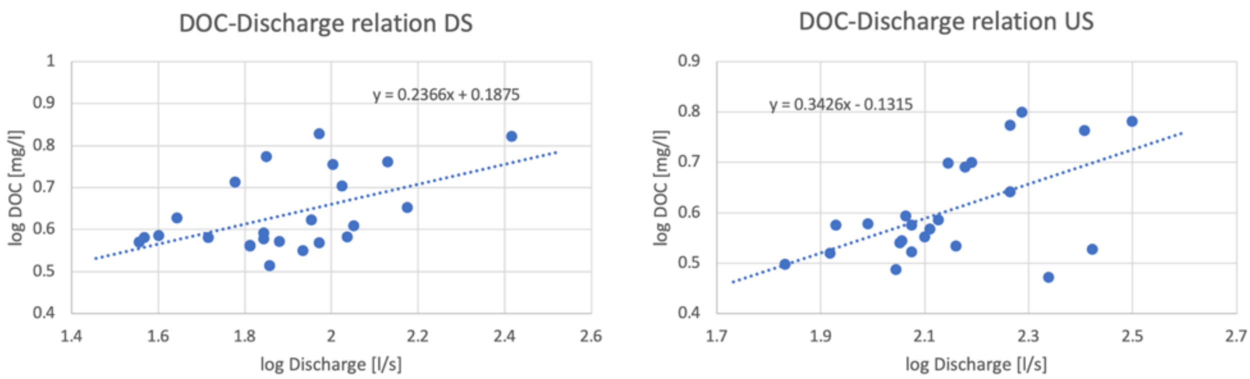

Figure 55: *DOC – discharge relation downstream (left) and upstream (right).*

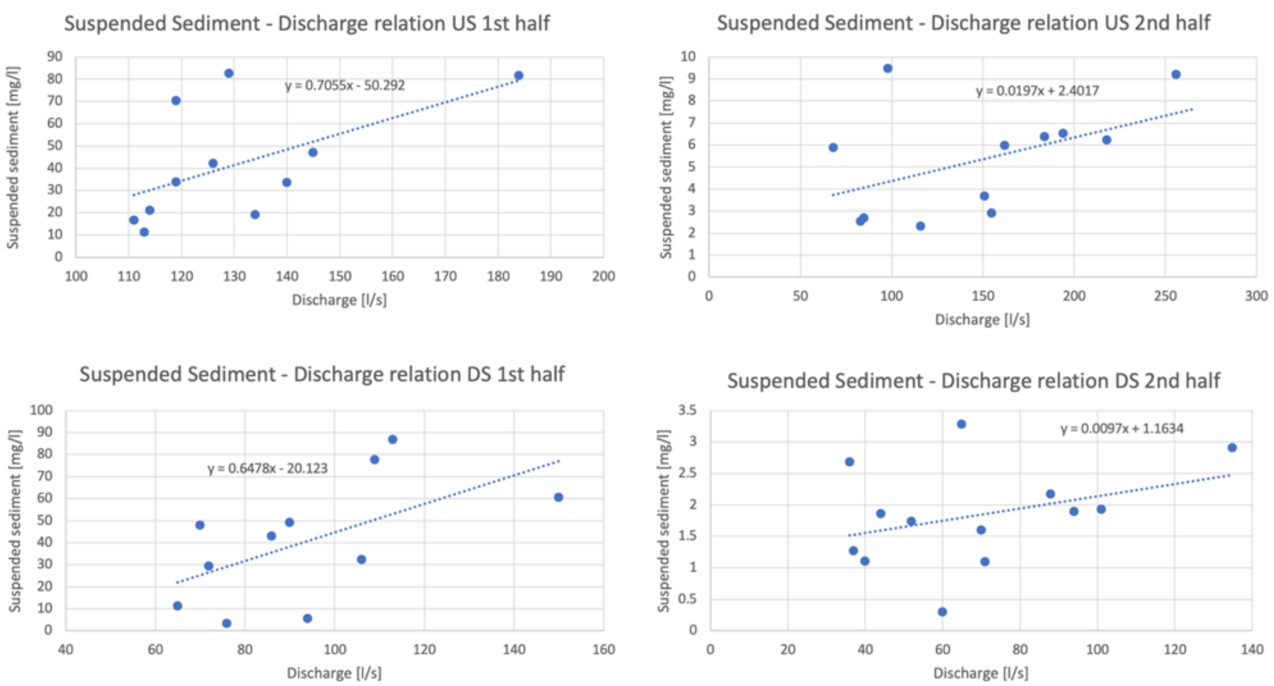

Figure 56: *Suspended sediment – discharge relation upstream for 1st half of the year (top left), 2nd half of the year (top right), and suspended sediment – discharge relation downstream for 1st half (bottom left) and 2nd half of the year (bottom right).*

8.3 Appendix C

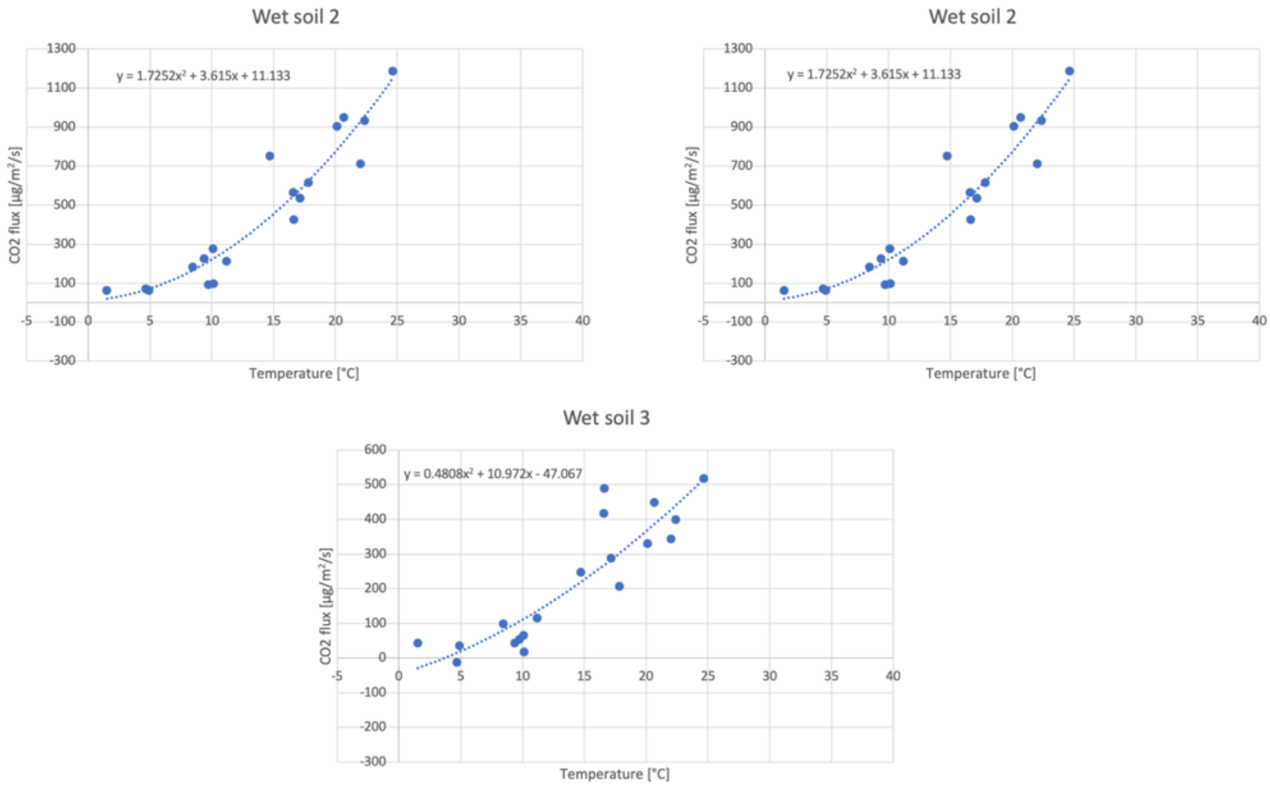

Figure 57: *Second degree polynomial function describing the CO_2 flux through daily mean temperature.*

8.4 Appendix D

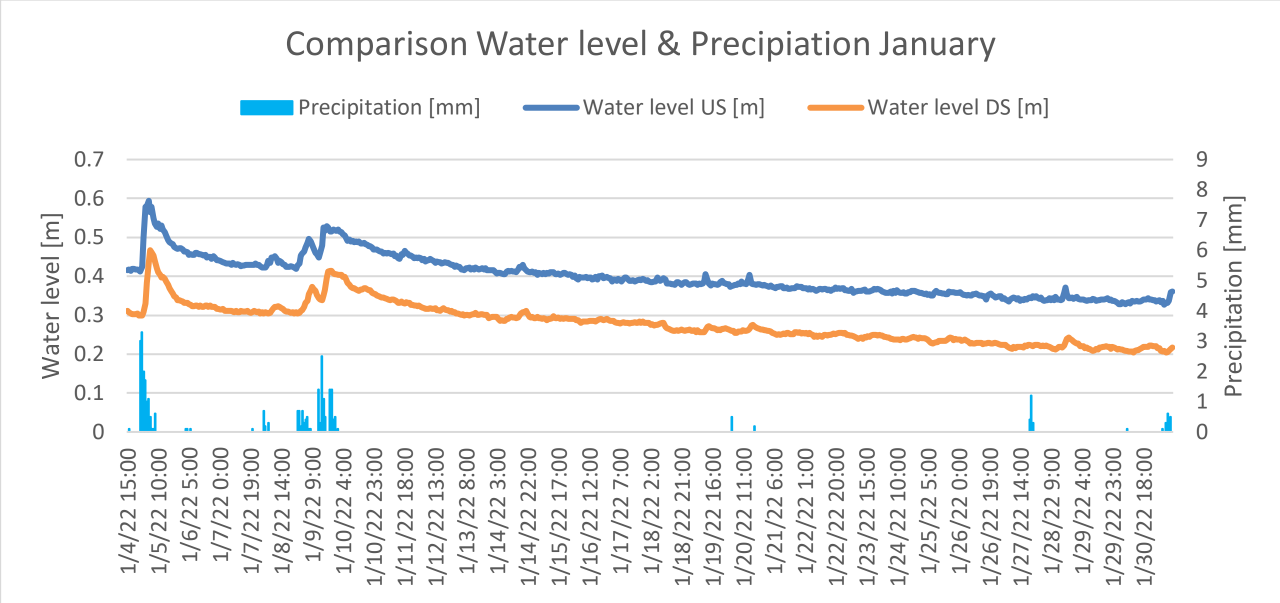

Figure 58: *Impact of precipitation to the upstream and downstream water level in January.*

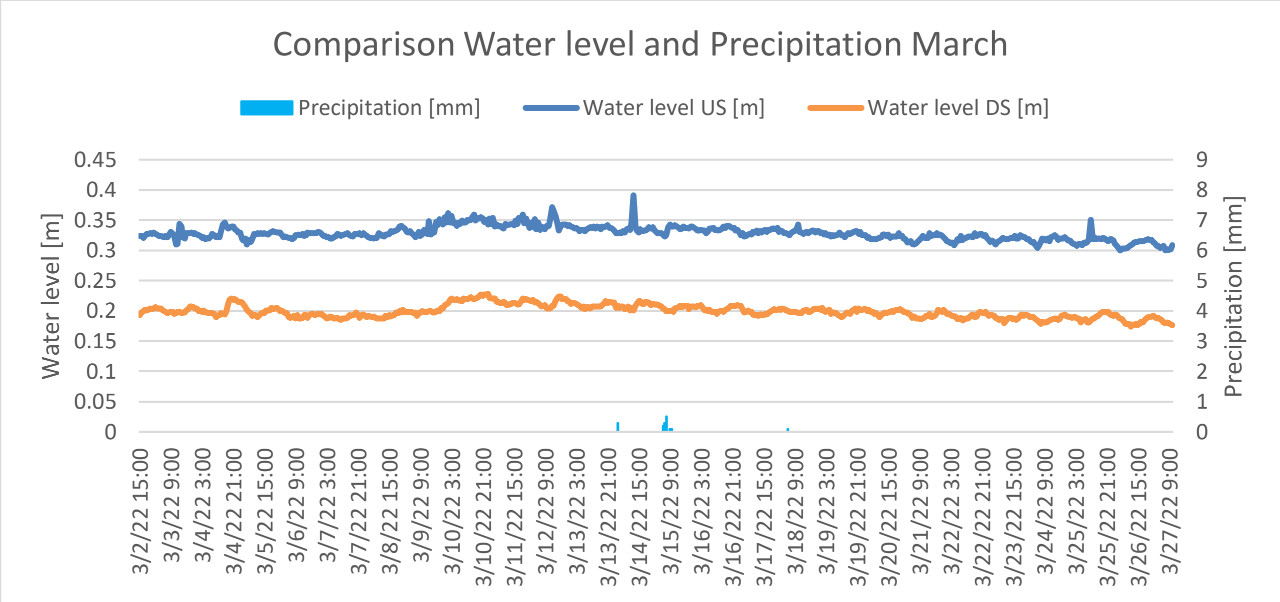

Figure 59: *Impact of precipitation to the upstream and downstream water level in March.*

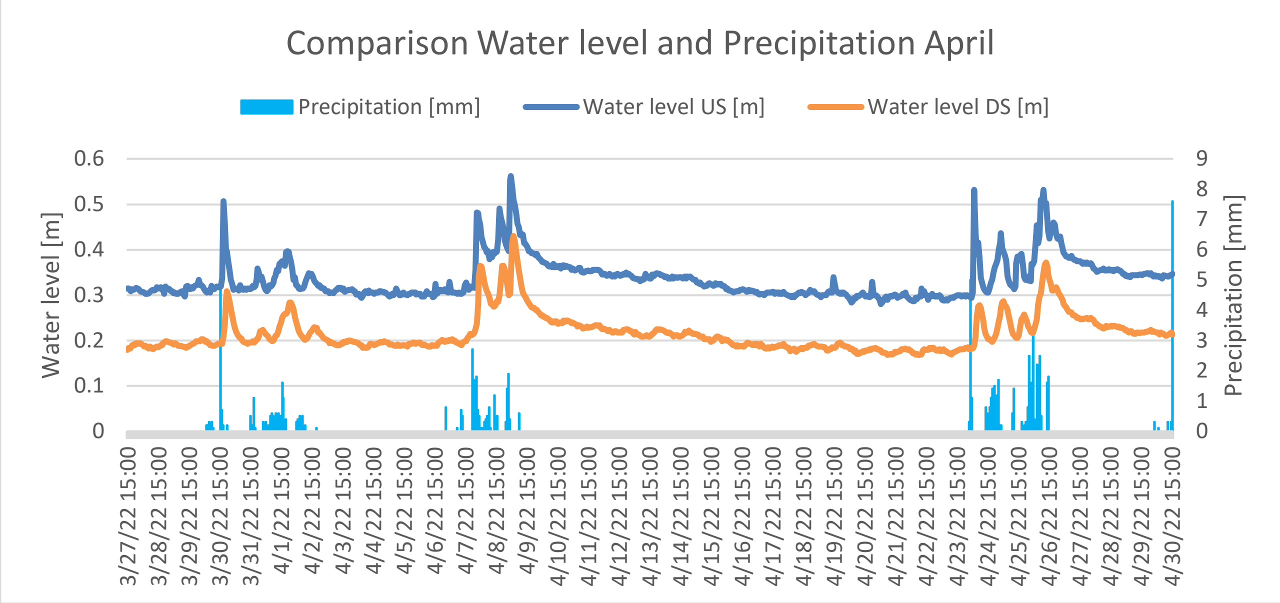

Figure 60: *Impact of precipitation to the upstream and downstream water level in April.*

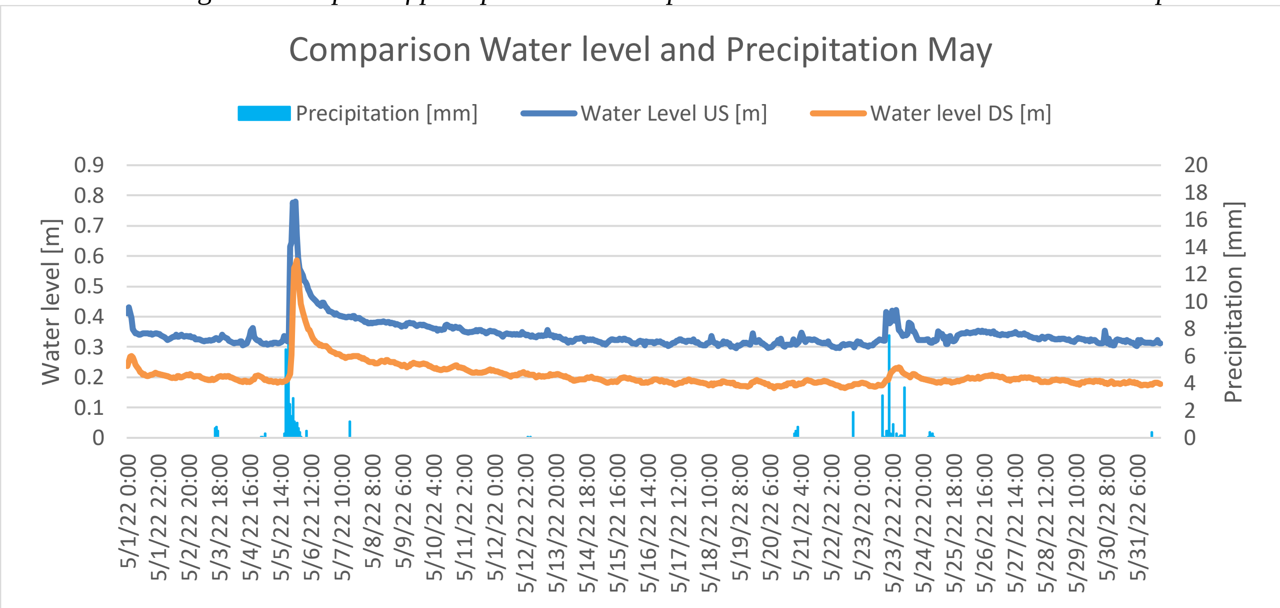

Figure 61: *Impact of precipitation to the upstream and downstream water level in May*.

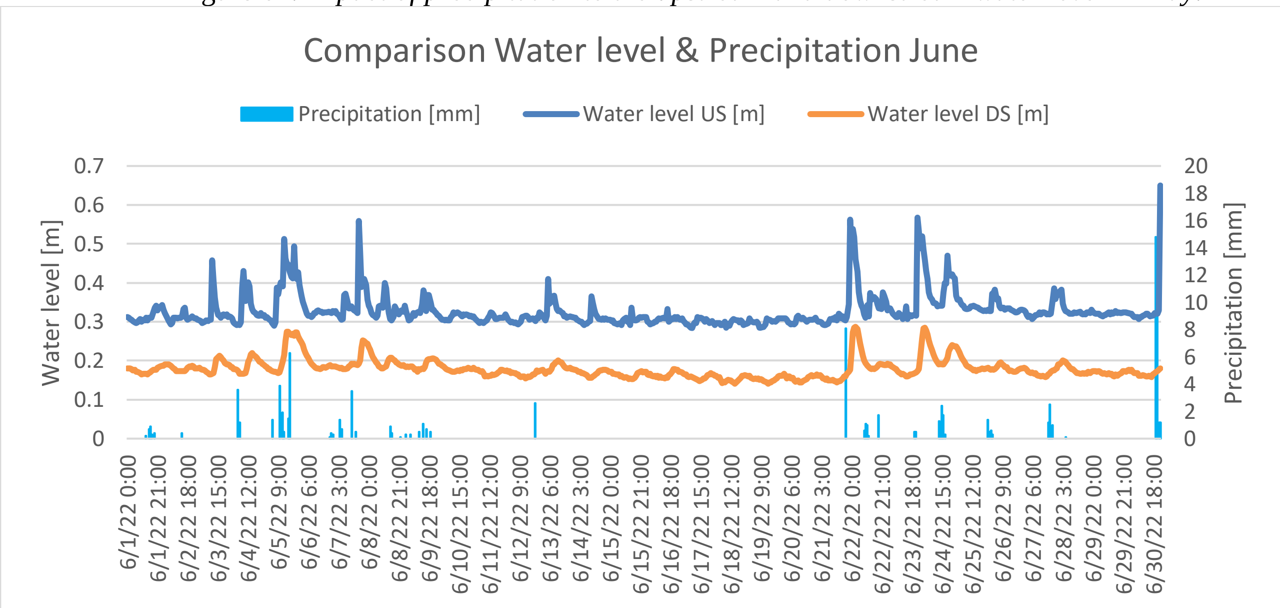

Figure 62: *Impact of precipitation to the upstream and downstream water level in June.*

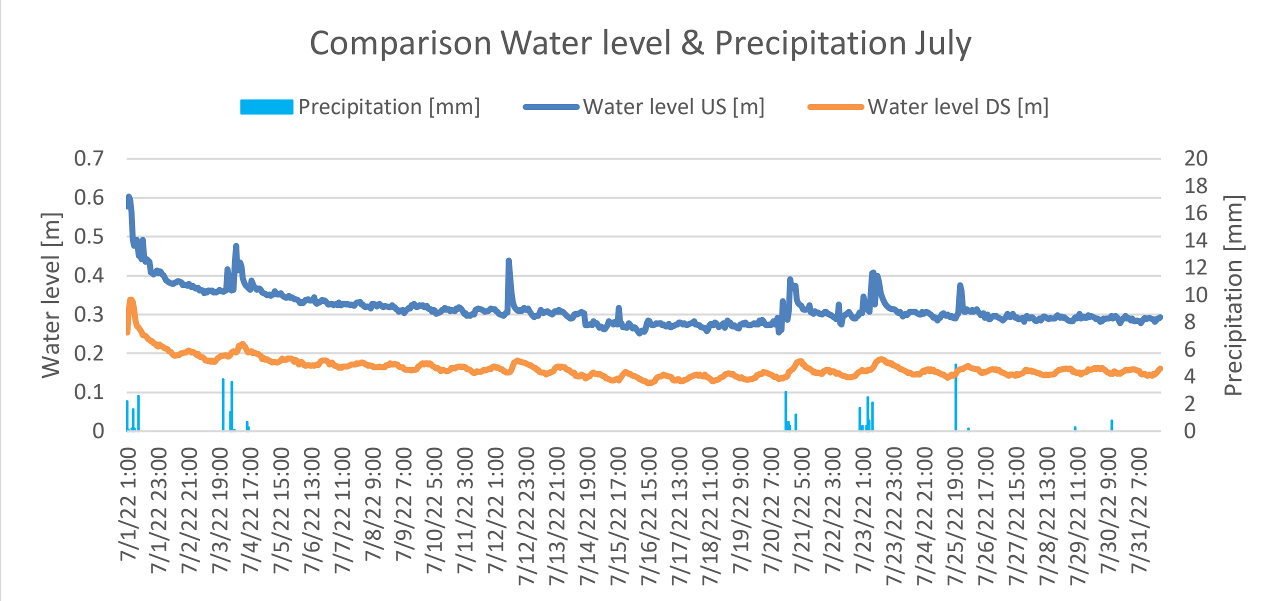

Figure 63: *Impact of precipitation to the upstream and downstream water level in July.*

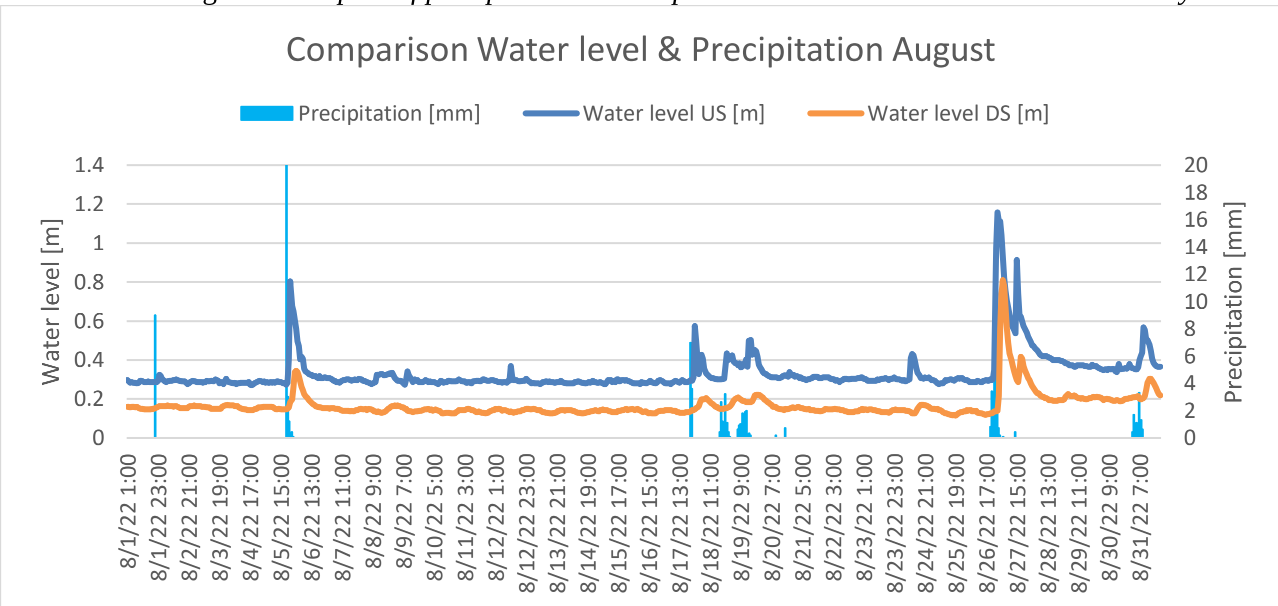

Figure 64: *Impact of precipitation to the upstream and downstream water level in August.*

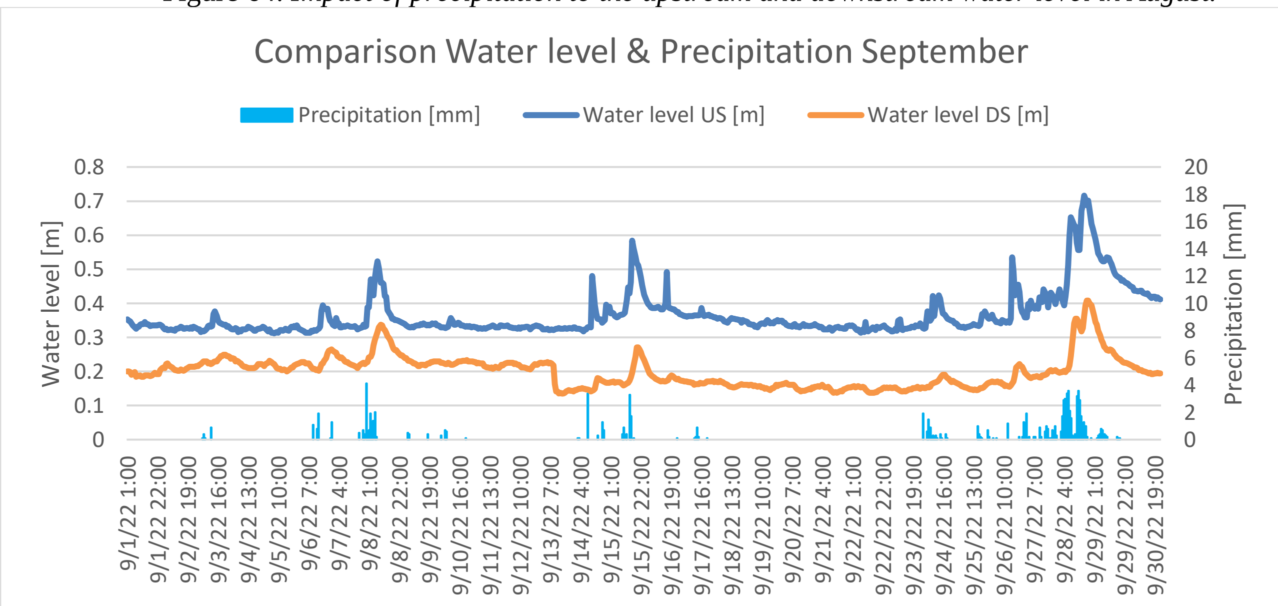

Figure 65: *Impact of precipitation to the upstream and downstream water level in September.*

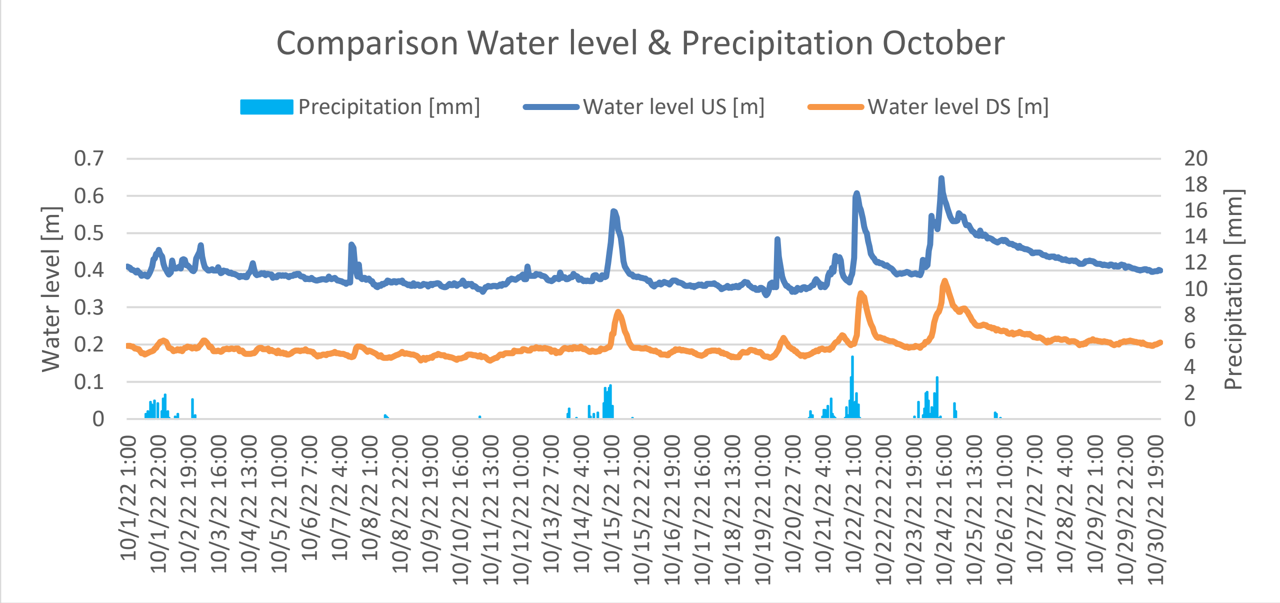

Figure 66: *Impact of precipitation to the upstream and downstream water level in October.*

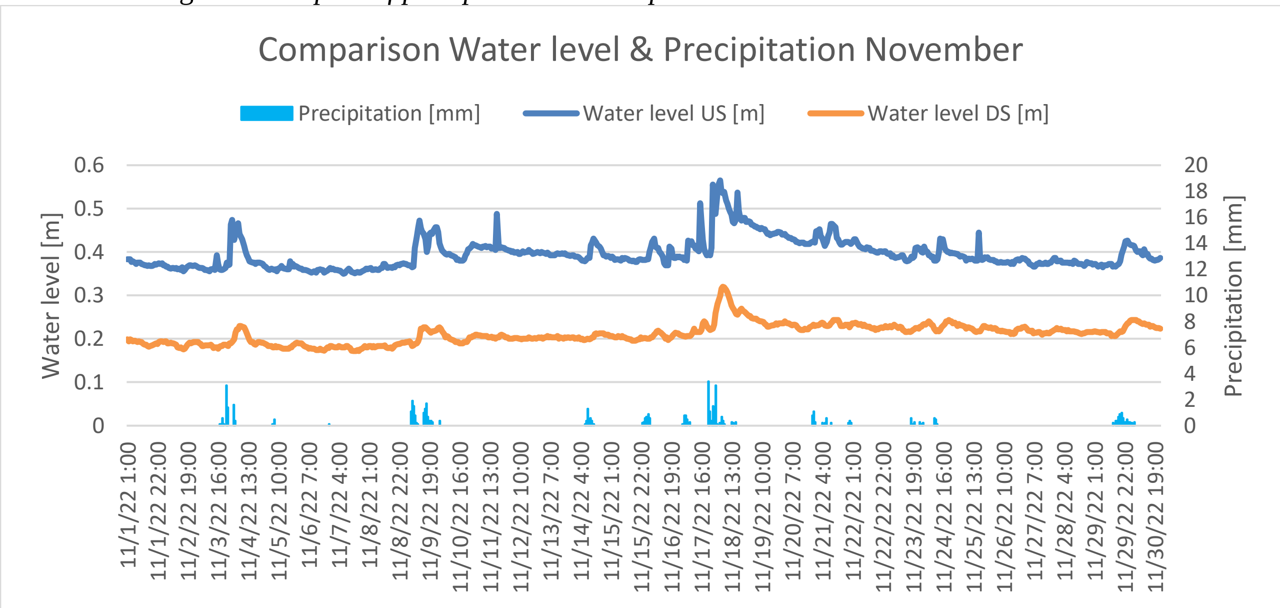

Figure 67: *Impact of precipitation to the upstream and downstream water level in November.*

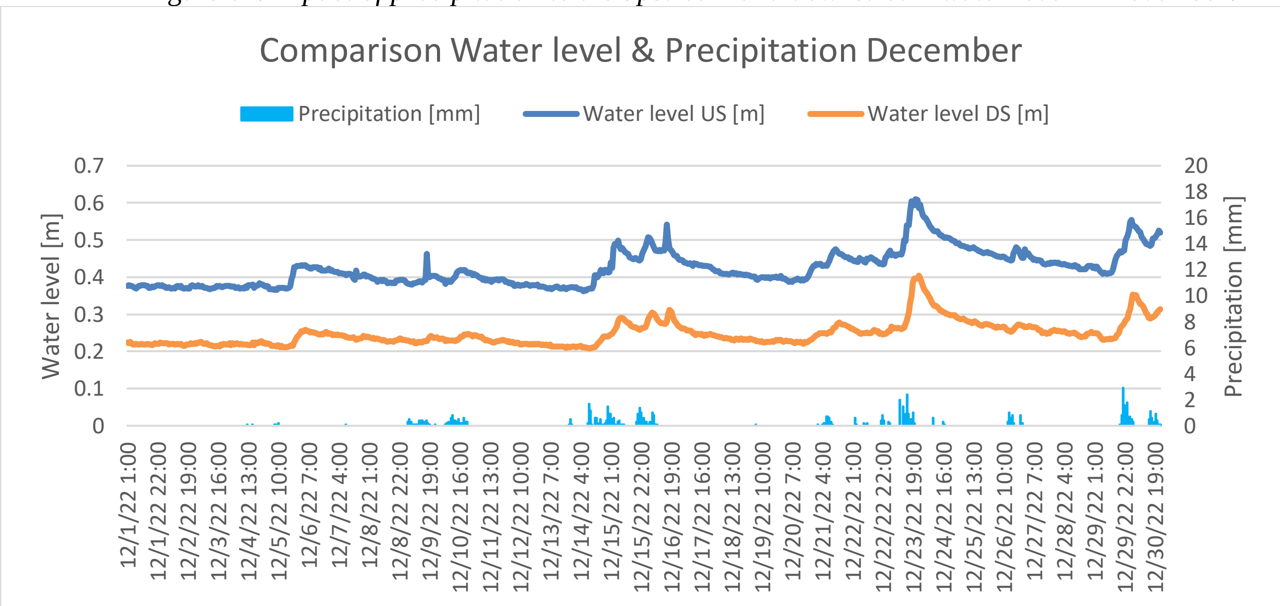

Figure 68: *Impact of precipitation to the upstream and downstream water level in December.*

8.5 Appendix E

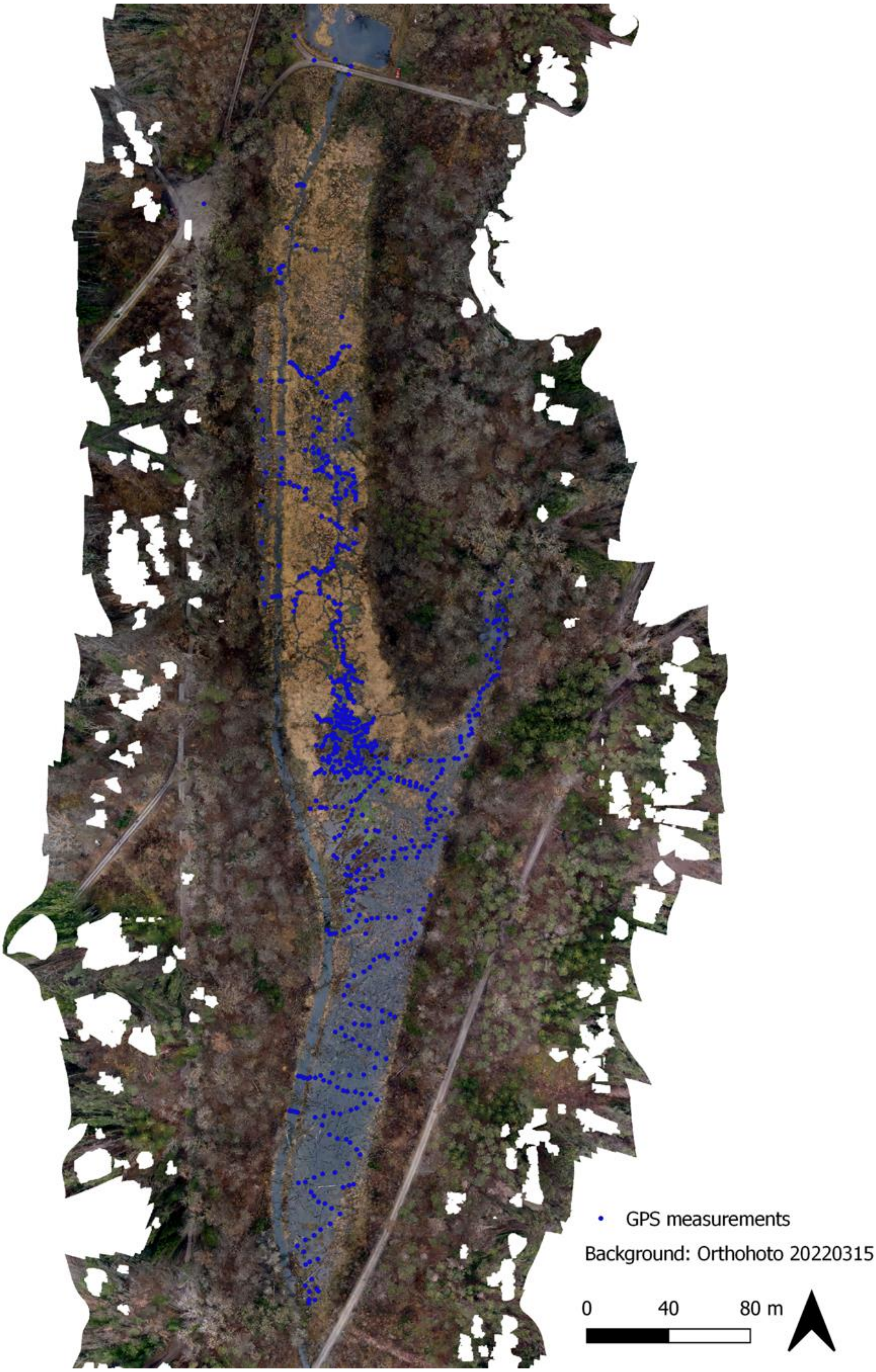

Figure 69: *GPS measurements from 26.03.2022 for calculation of water volume in the study area (own illustration, Background: Swisstopo, 2019).*

8.6 Appendix F

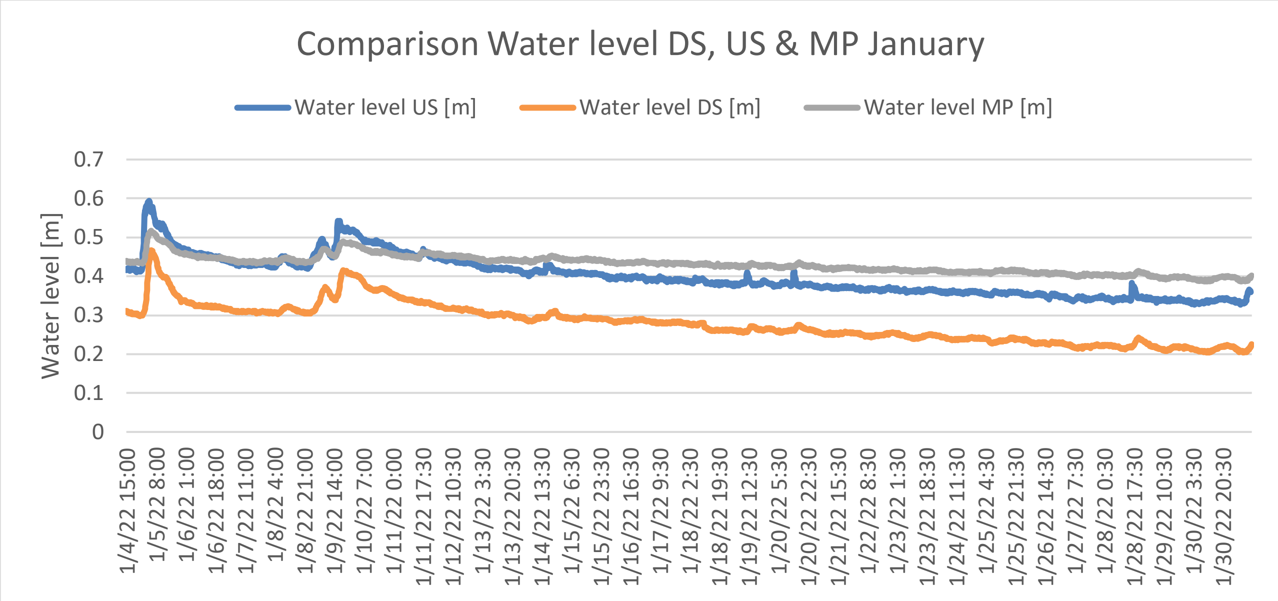

Figure 70: *Development of water level upstream, downstream and in the middle pond in January.*

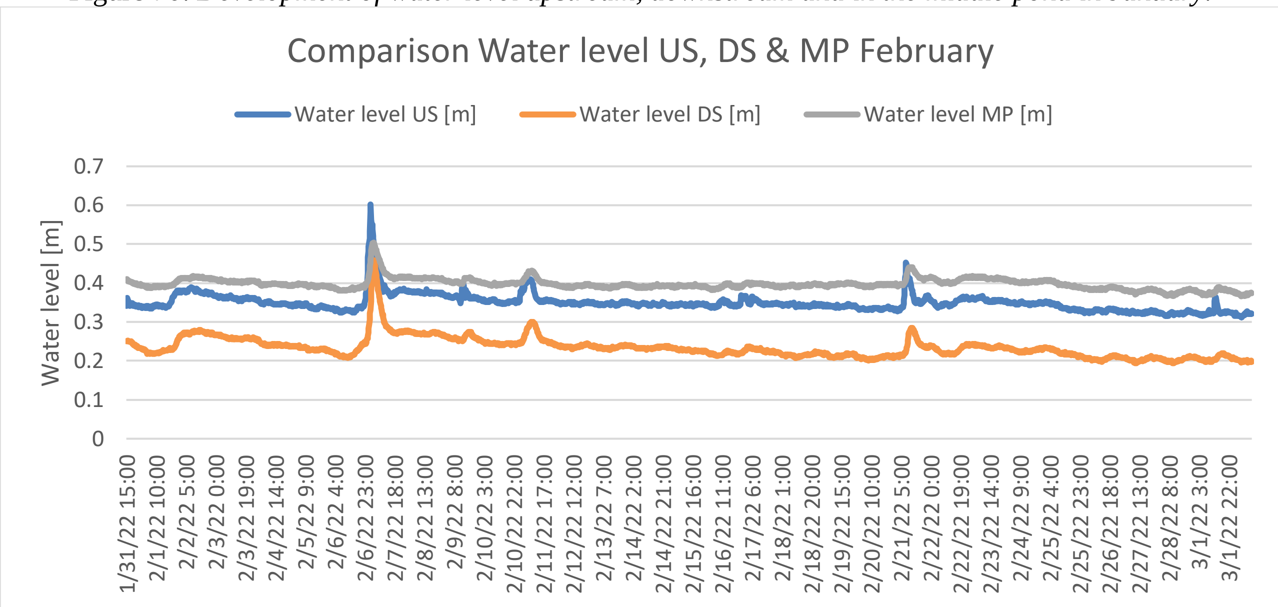

Figure 71: *Development of water level upstream, downstream and in the middle pond in February.*

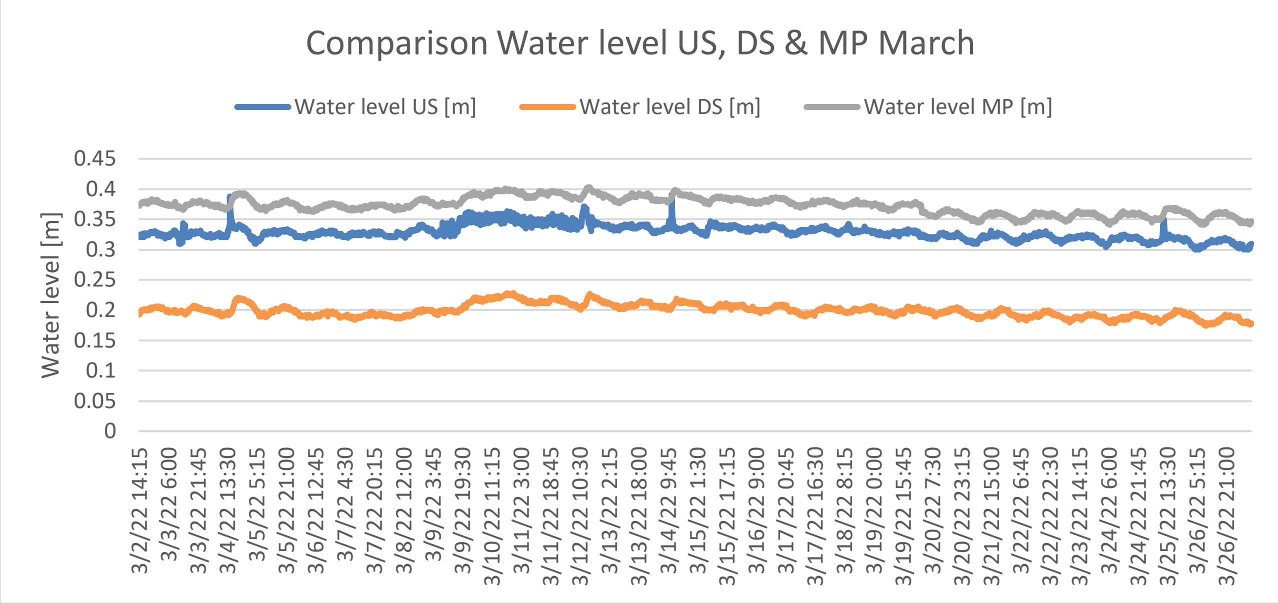

Figure 72: *Development of water level upstream, downstream and in the middle pond in March.*

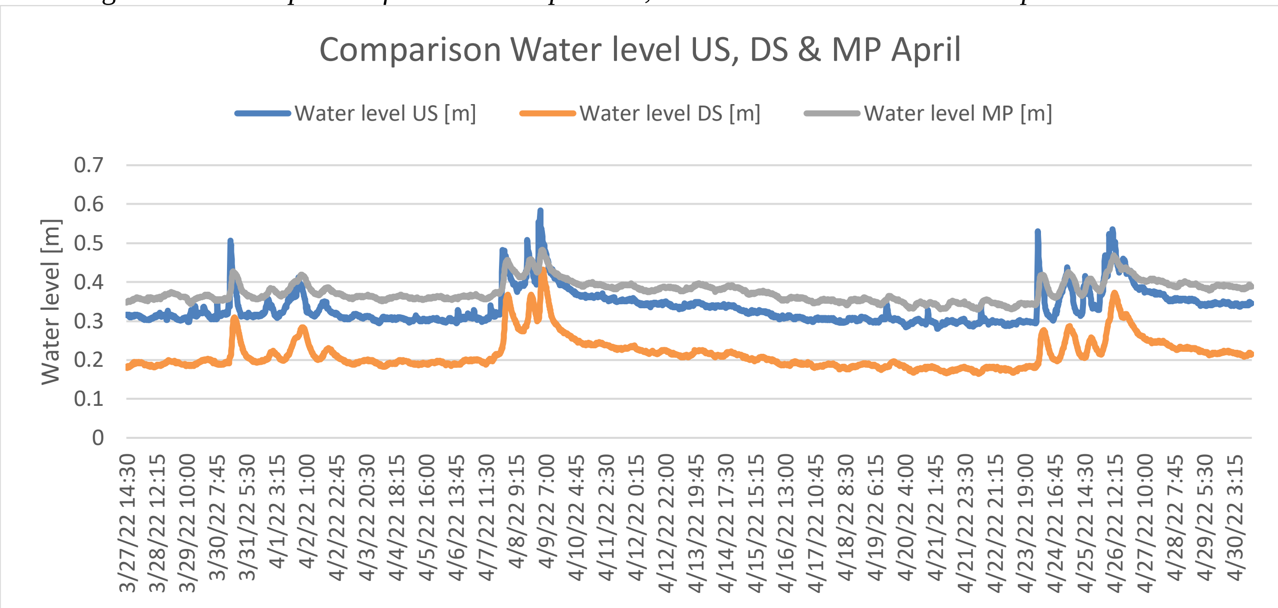

Figure 73: *Development of water level upstream, downstream and in the middle pond in April.*

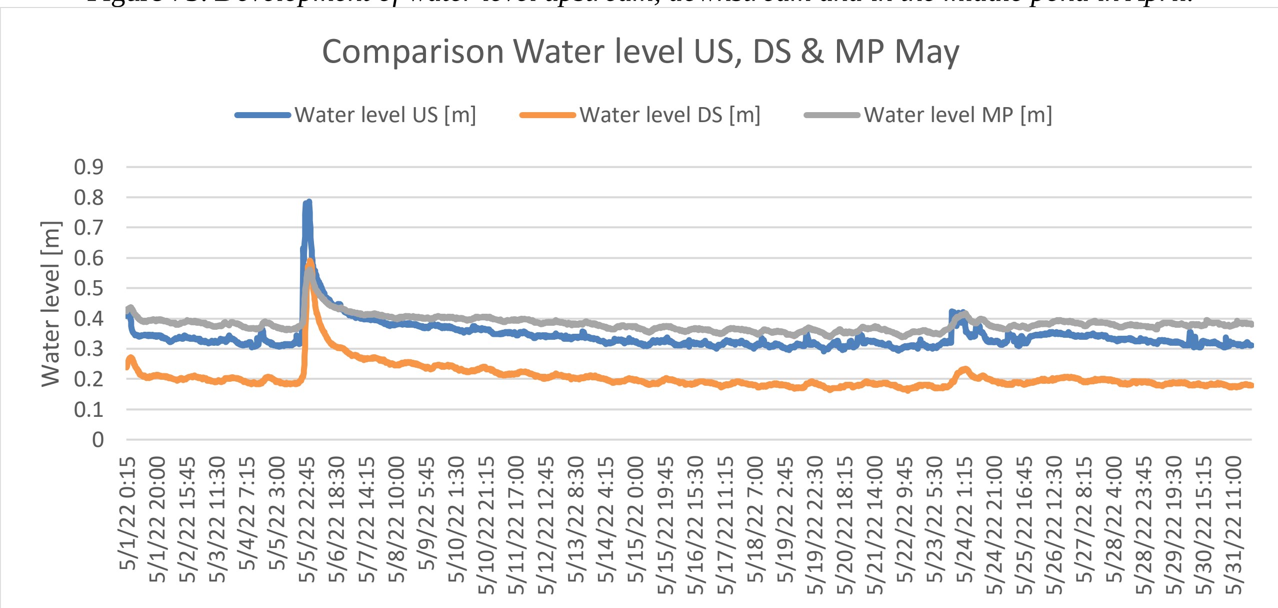

Figure 74: *Development of water level upstream, downstream and in the middle pond in May.*

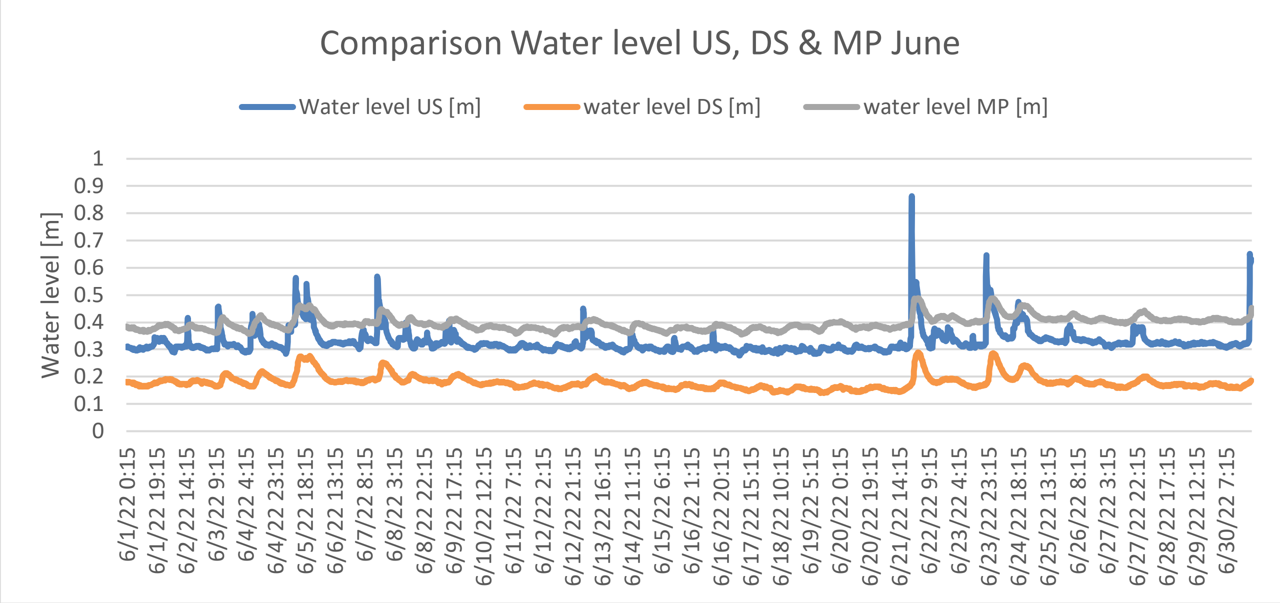

Figure 75: *Development of water level upstream, downstream and in the middle pond in June.*

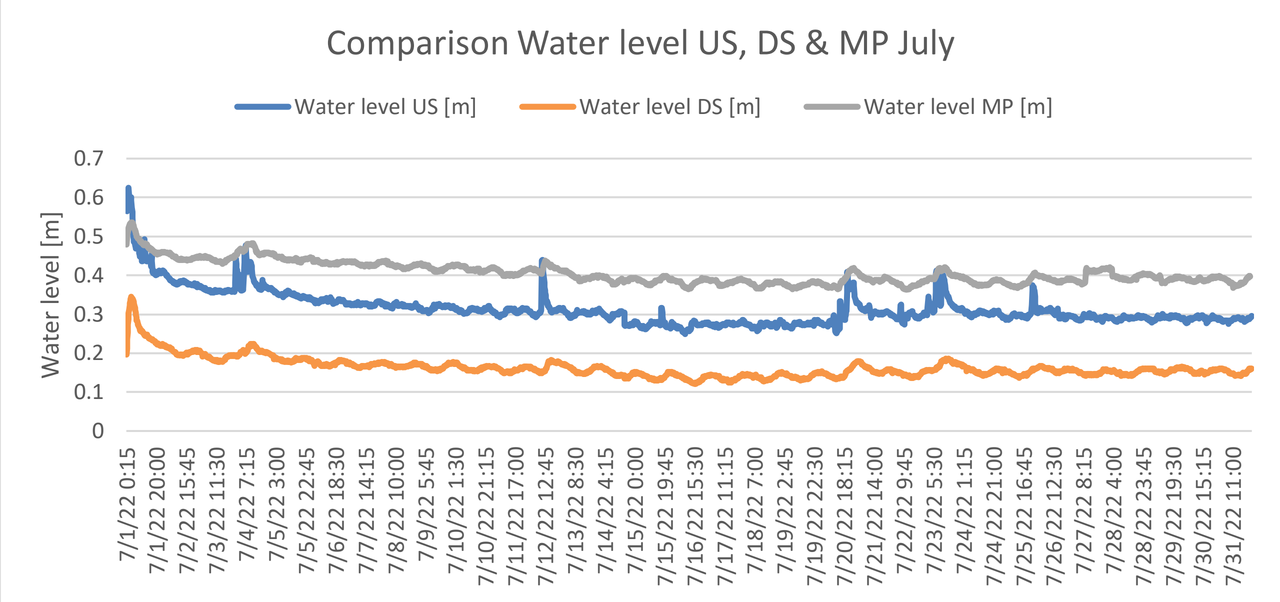

Figure 76: *Development of water level upstream, downstream and in the middle pond in July.*

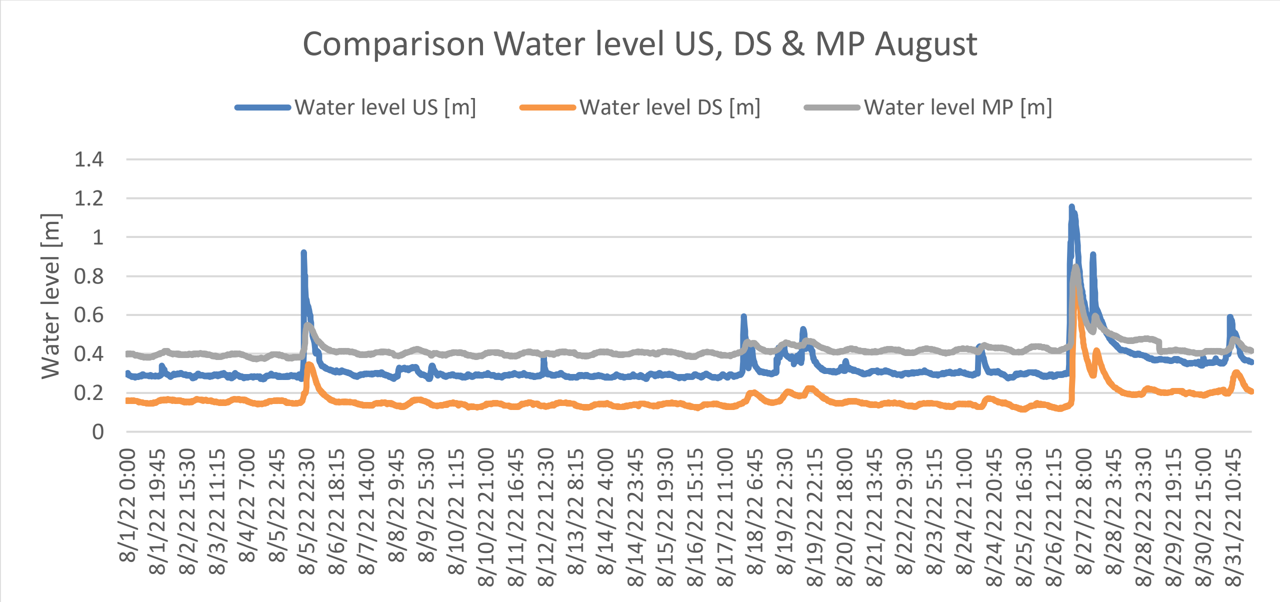

Figure 77: *Development of water level upstream, downstream and in the middle pond in August.*

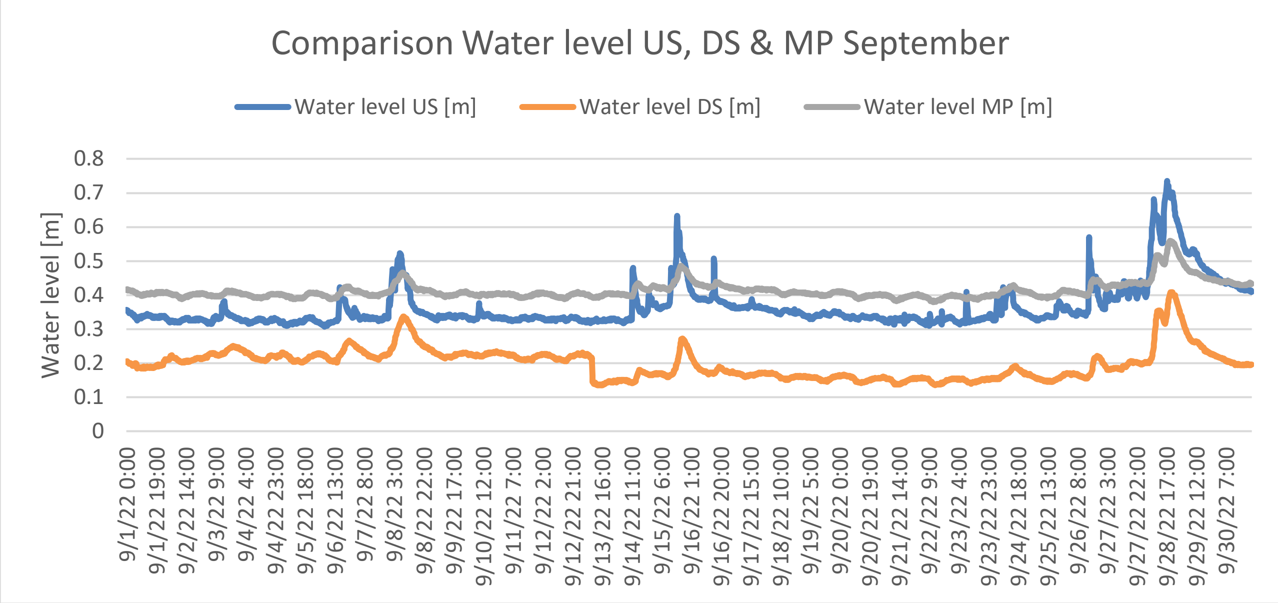

Figure 78: *Development of water level upstream, downstream and in the middle pond in September.*

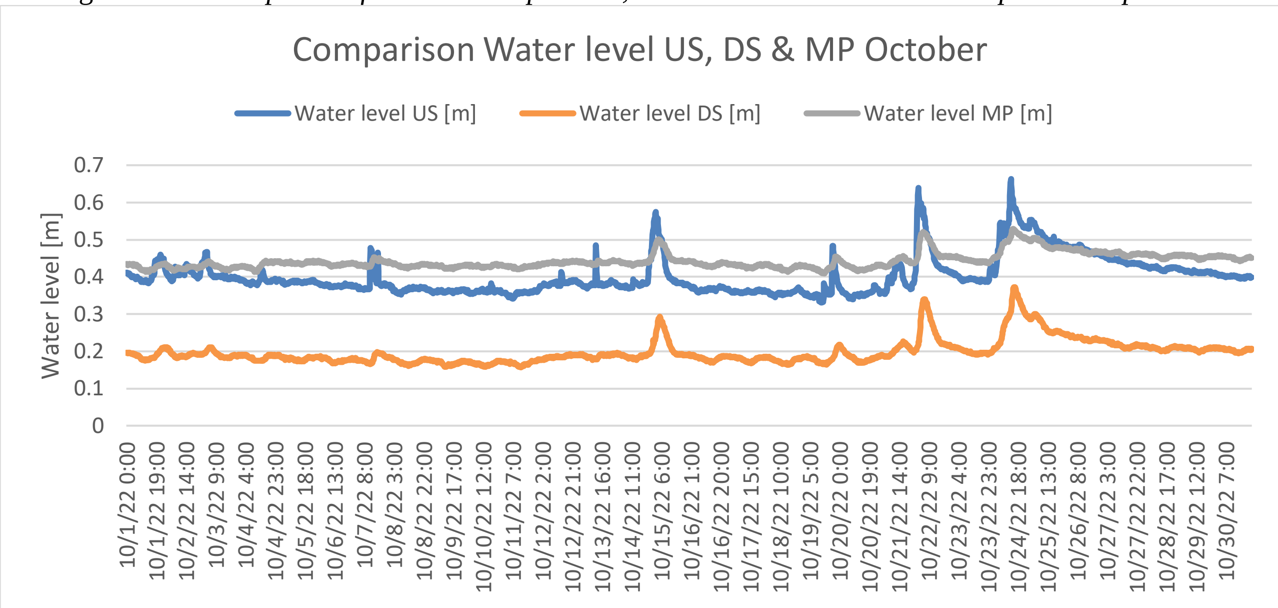

Figure 79: *Development of water level upstream, downstream and in the middle pond in October.*

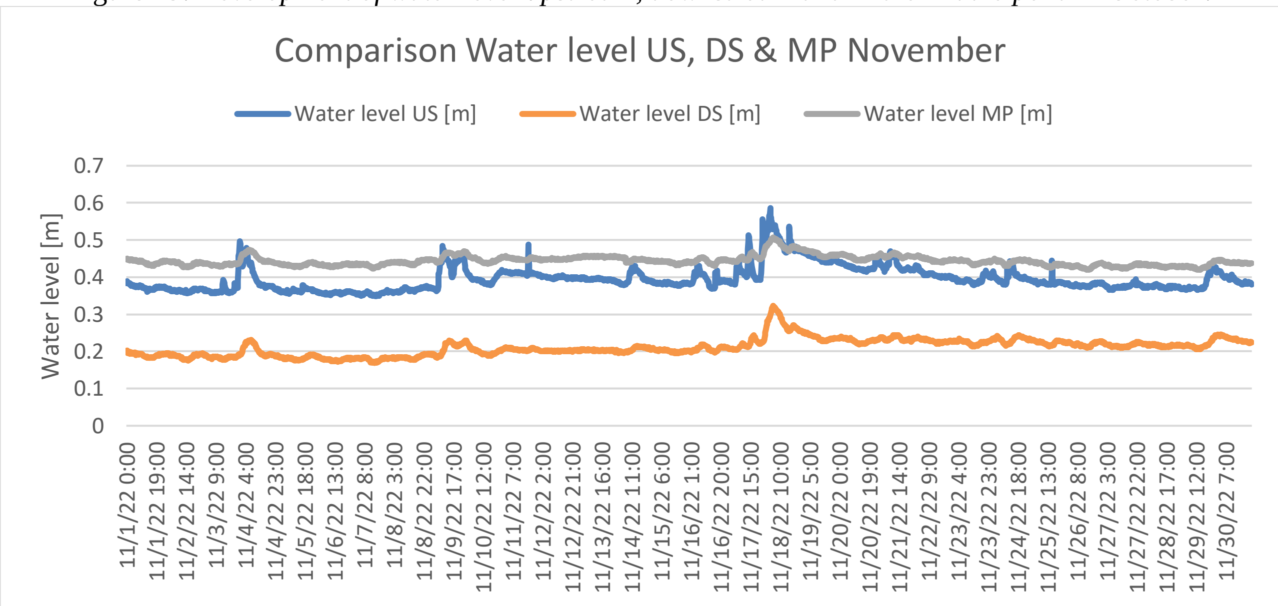

Figure 80: *Development of water level upstream, downstream and in the middle pond in November.*

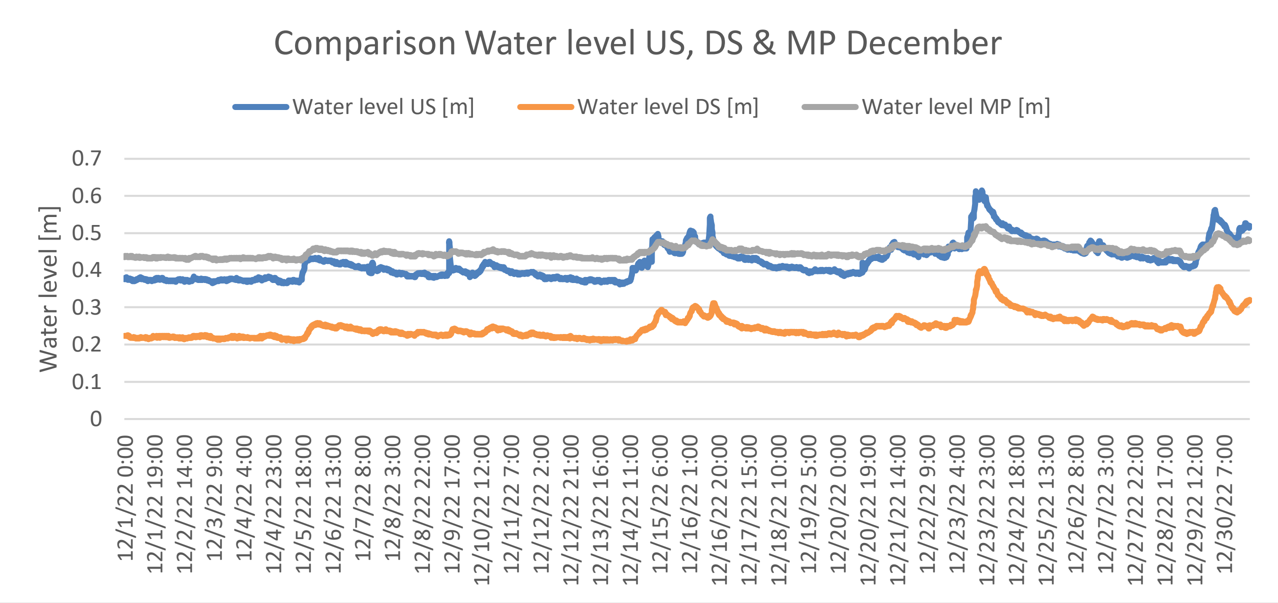

Figure 81: *Development of water level upstream, downstream and in the middle pond in December.*

8.7 Appendix G

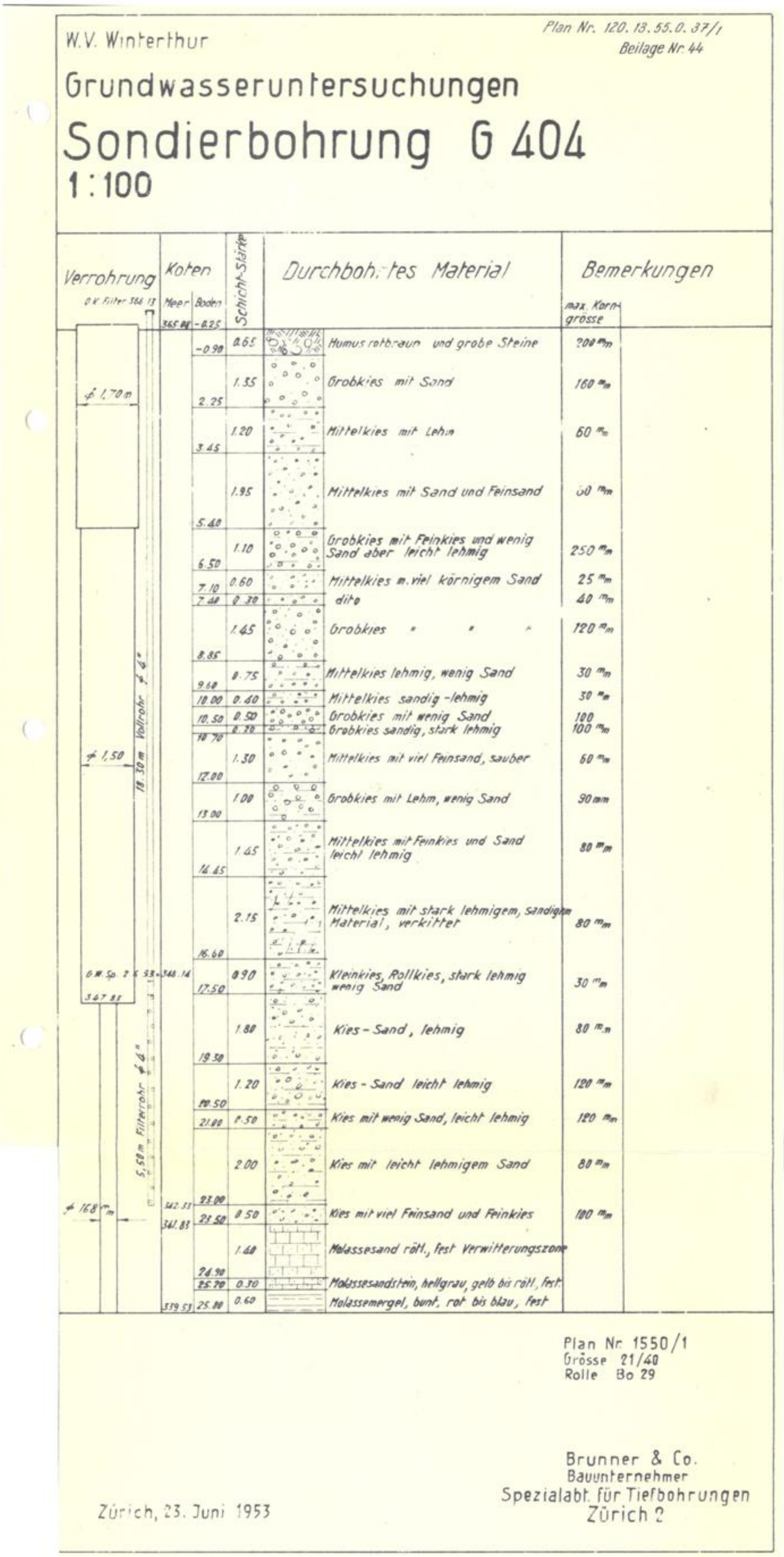

Figure 82: *Exploratory borehole 50 m southwest of the lower pond from 1953.*

8.8 Appendix H

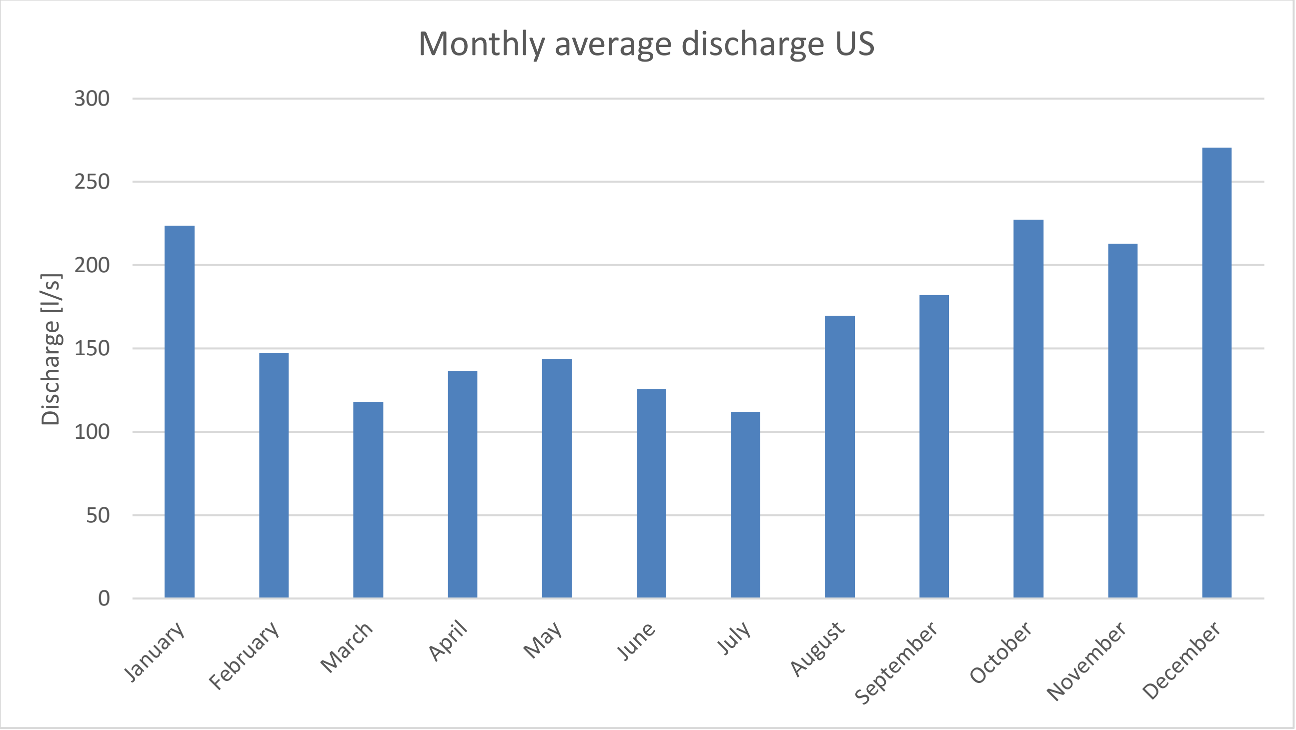

Figure 83: *Monthly average discharge measured upstream of the beaver wetland.*

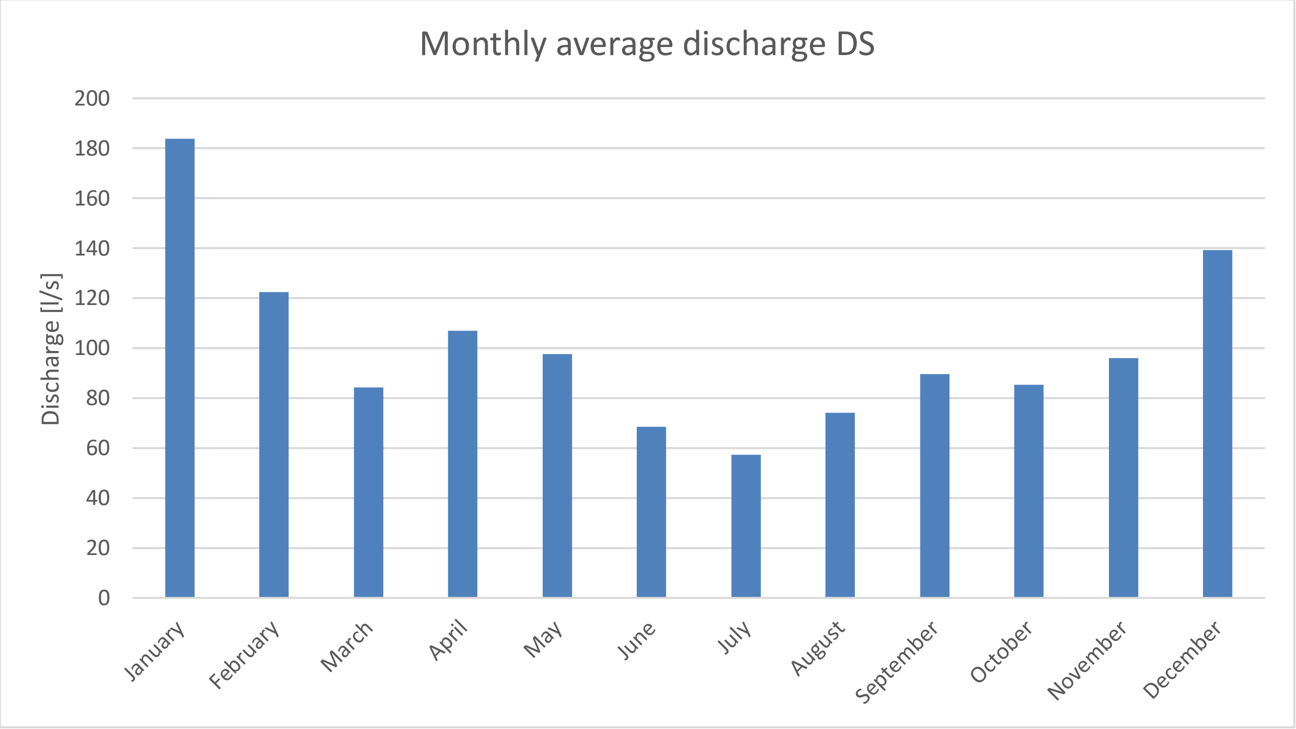

Figure 84: *Monthly average discharge measured upstream of the beaver wetland.*

Declaration of consent

on the basis of Article 30 of the RSL Phil.-nat. 18

Name/First Name: d'Epagnier/Raphael Fabrice

Registration Number: 17-104-977

Study program: Geography Master Mono

Bachelor ☐ Master ☑ Dissertation ☐

Title of the thesis: Beaver impacts on the riverine carbon budget in a study area in Marthalen (CH)

Supervisor: Dr. Annegret Larsen

I declare herewith that this thesis is my own work and that I have not used any sources other than those stated. I have indicated the adoption of quotations as well as thoughts taken from other authors as such in the thesis. I am aware that the Senate pursuant to Article 36 paragraph 1 litera r of the University Act of 5 September, 1996 is authorized to revoke the title awarded on the basis of this thesis.

For the purposes of evaluation and verification of compliance with the declaration of originality and the regulations governing plagiarism, I hereby grant the University of Bern the right to process my personal data and to perform the acts of use this requires, in particular, to reproduce the written thesis and to store it permanently in a database, and to use said database, or to make said database available, to enable comparison with future theses submitted by others.

Bern / 14.04.2023

Place/Date

Signature