

Towards a carbon budget for the Marthalen beaver wetland

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1. Overview

Beaver impacts on the water and ecosystems in a landscape are known to have a potentially large impact on the carbon cycling of the river and riparian system. However, these potential impacts remain largely unquantified, and poorly understood. The goal of this work was to make a first estimate of the carbon budget of a beaver-influenced area (Figure 1). It is part of the national beaver project "Functionality of beaver damming activity in the landscape - a project to strengthen the ecological infrastructure" of the Federal Office for the Environment FOEN (Angst and Auberson, in prep). The aim of the national beaver project is to evaluate the potential of the beaver in the context of expanding and strengthening the ecological infrastructure. The aim is to assess the ecosystem services provided and to investigate the influence of the beaver on biodiversity in various types of watercourses.

The beaver wetland in Marthalen is the biggest impacted territory of beavers in Switzerland. We conducted a year-long monitoring campaign to comprehensively measure the dominant fluxes and storages, including upstream and downstream dissolved organic carbon (DOC) dissolved inorganic carbon (DIC) concentrations and water discharge, CO₂ and CH₄ emissions from the beaver pond and wetland soils, and finally biomass and organic matter storages in the wetland. The analysis shows that more carbon is sequestered than exported and therefore the beaver wetland is on balance a relatively large carbon sink, estimated to be ~60 t of carbon per year (~17% of C inputs are retained every year). This estimate, based on the differences between C inputs and outputs from the system, closely matches our estimates of annual C storages in seasonal biomass and accumulation of organic sediment, suggesting our balance estimates are relatively robust despite the uncertainties. The conversion of the system from a forested floodplain to a wetland also provided a one-off input of ~500 t of C as woody material to the wetland following dieback and is now largely sequestered as an additional C storage component in the wetland. DIC imports and exports, and CO₂ exports were the largest fluxes within the beaver system and therefore were the largest drivers of the overall budget. Interestingly, CO₂ emissions from the wetland soils are significantly higher than those from the pond water surface, and CH₄ emissions were consistently orders of magnitude lower than CO₂ fluxes from both the pond and wetland soils, and therefore had little overall impact on the carbon balance of the system. The primary driver of the large carbon sink is most likely algal and aquatic plant photosynthetic uptake of DIC within the wetland system. Thus, the introduction of the beaver wetland has increased water losses due to evaporation, and also greatly increased aquatic net primary production to create a large C sink. This carbon sink is also likely larger than the floodplain forest present prior to the wetland, meaning the overall carbon sink has increased as a result of beaver impacts.



Figure 1: Different carbon fluxes which contribute to the calculation of the carbon balance of a specific area (CSCF, n.d.d)

2. Marthalen beaver wetland

The study was conducted in a beaver created wetland near Marthalen (Canton of Zurich), a subsection of the Mederbach as it flows through a heavily forested area (Niederholz), after which it flows into the Thur river. The Niederholz reach of the river is dominated by palaeo-Rhine gravel deposits, and thus prior to WW2 the Mederbach lost most of its discharge to seepage and infiltration in a series of wet meadows (Nägeli, 2020). Following WW2, increased conversion of meadows to farmland prevented this divergent flow and increased discharge in the Mederbach which caused persistent ponding in the Niederholz and thus increased tree stress and death. As a result, in 1955 a clay lined canal was constructed through the Niederholz to convey this water. In ~ 2007 a beaver family colonised a part of the Mederbach in the Niederholz and began damming the stream. Temporary and permanently flooded areas were created and over time the landscape changed from completely forested to an open wetland area. In 2013, the canton of Zurich, the municipality of Marthalen and Pro Natura jointly formed a 50 year forest protection contract. The area protected by this contract is about 10 hectares, and Figure 2 shows the area of this forest to wetland transformation.



Figure 2: Two orthophotos of the study area. On the left side from 2006 and on the right side from 2022 (Swisstopo, 2023).

The aim of this study was to establish a carbon budget for this beaver created wetland system (Figure 1). Beaver impacts are expanding and the implications for impacted terrestrial and aquatic carbon cycling remain largely unknown. In order to achieve this, we established a combination of automated and field data collection sites across the wetland, targeted to capture the main components of the system, namely the inflowing and outflowing water and carbon fluxes, fluxes from open water areas, and fluxes from the wet and dry wetland soils (Figure 3).

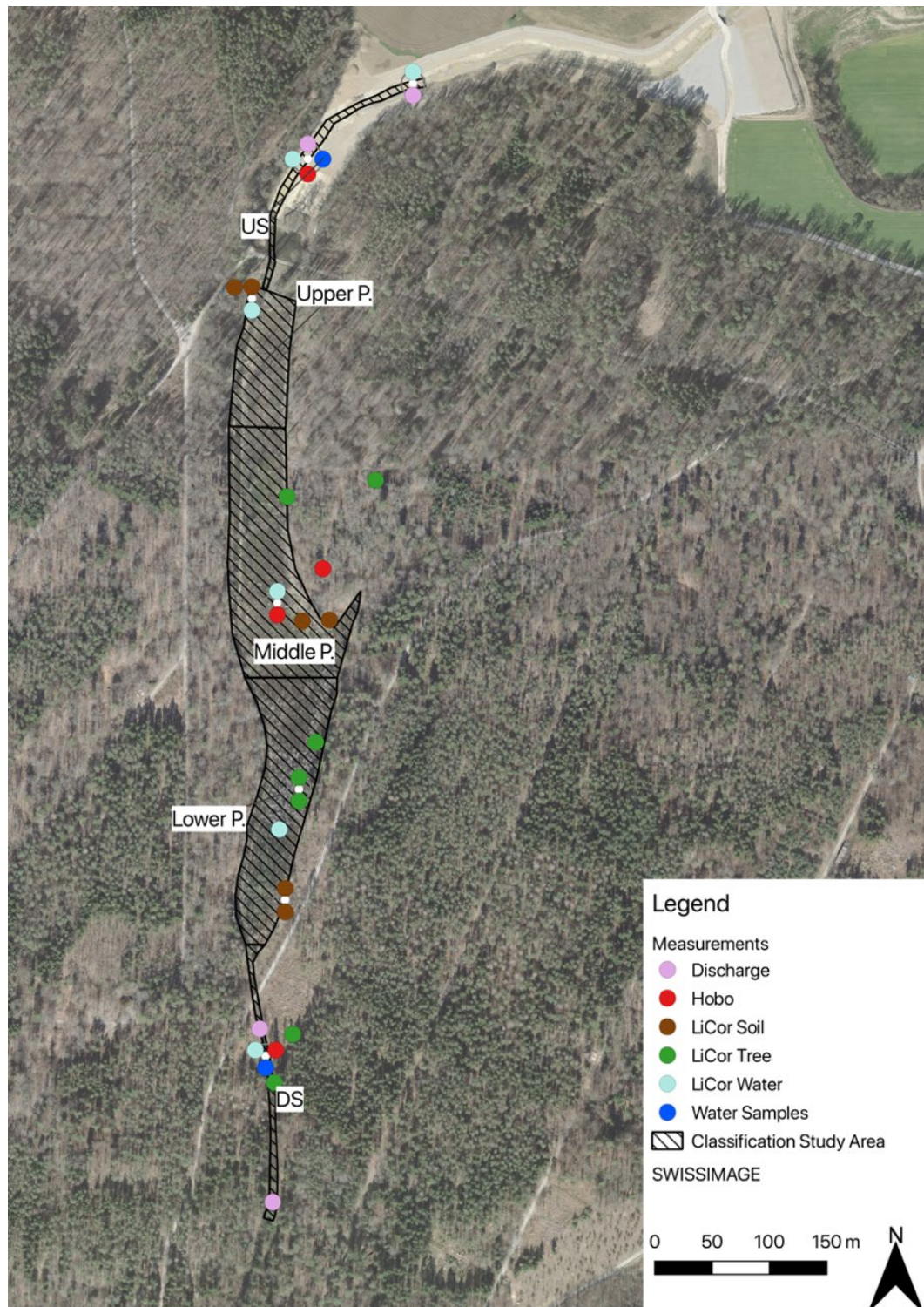


Figure 3. Monitoring locations and definition of the wetland subsections at Marthalen.

3. Water balance controls

We established automated water level monitoring locations upstream and downstream of the wetland (Figure 3) and conducted regular salt gauging across a range of flow conditions to establish a robust flow rating curve to convert these water level estimates to discharge. Overall, our discharge monitoring indicates a ~40% decrease in discharge from upstream to downstream in the beaver impacted system. This water loss over a short distance is relatively

large and can be due to some combination of evaporation and infiltration. Two previous water balance studies from beaver impacted systems indicate evaporation losses to be 20 - 40% (Puttock et al. 2017; Woo and Waddington, 1990), thus Marthalen is in this range if these losses were due to evaporation alone. However, there are two features that make the Marthalen wetland somewhat unique in terms of the scale of the water losses: 1) the infiltration losses are probably much higher than most other beaver impacted sites, as the wetland has been created atop highly permeable unsaturated gravel deposits. Support for this also comes from the pre-WW2 river condition in which the river usually lost all its water to infiltration and seepage before it could reach the Thur (Nägeli, 2020). 2) Evaporation losses are likely enhanced by the unusual shape of the wetland, partly due to the road construction, which limits water outflow and encourages water ponding in largely disconnected flow areas. Thus, although we expect evaporative losses to increase in principle across all beaver impacted sites where ponds and wetlands are created (Larsen et al. 2021), the geometry of ponding at Marthalen may cause these losses to be more extreme than could be typically expected. The exact partitioning of the water balance losses are unknown, thus we assume based on general water balance considerations that infiltration losses constitute 10%, and evaporation 30%, of these losses. This assumption provides an important constraint on the carbon budget outputs through their influence on the estimated losses of DIC and DOC via infiltrating water.

4. Estimating the carbon budget components

DIC and DOC: In order to estimate annual loads for a carbon budget, the bi-weekly sampling data must be extrapolated to daily load (i.e. concentration x discharge) values and then aggregated to an annual mass. The most robust method for achieving this is known as Weighted Regressions on Time, Discharge, and Season (WRTDS) (Hirsch et al. 2010). We apply these locally weighted based methods to estimate a daily load or flux value for each location, and then sum all daily values for the year to derive the total annual mass estimate for both DIC and DOC.

CO₂ and CH₄ fluxes: We installed soil flux chamber collars across wetland and reference soil locations for repeat bi-weekly flux measurements. We also conducted water surface flux monitoring using an aquatic flux chamber with the same sampling frequency. Wetland soil and water surface areas estimated using classification of drone imagery

Biomass:

Wetland biomass estimation was based on a supervised classification that was performed on 5 drone flights (Table 1), and the final vegetation area quantification was based on a drone flight from 25/08/2022. Canopy covered the edges of a part of the wetland, this was accounted for based on visual estimation of the wetland boundaries throughout the year, especially during winter when canopy was transparent. This approach resulted in the addition of 90% of the canopy area to the *P. arundinacea* area, and 10% was added to the *S. palustris* area. A detailed classification of wetland species was possible by comparing the drone imagery to photos that were taken in the field (Table 1), and the classified raster was compared to a drone video for reassurance. The classified species were converted into feature classes in order to perform carbon storage calculations. For this, the dry weight of each species was used, which was sampled from 40 x 40 cm plots in the field, dried under laboratory conditions at constant temperature of 30dC for 2 days, and values were converted to square meter. In case no field measurements were available, values were retrieved from literature with a standard deviation of 10%.

Table 1. Field observations and corresponding drone imagery per season.

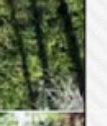
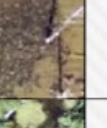
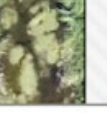
Latin name (English name)	Photo	Drone imagery January (19/01/22)	Drone imagery March (15/03/22)	Drone imagery May (17/05/22)	Drone imagery August (25/08/22)	Drone imagery December (12/01/22)
<i>Phalaris arundinacea</i> (Reed canary grass)						
<i>Stachys palustris</i> (Marsh woundwort)						
<i>Najas officinale</i> (Watercress)						
<i>Spartanium erectum</i> (Branched bur-reed)						
<i>Solanum dulcamara</i> (Bittersweet nightshade)						
<i>Ceratophyllum demersum</i> (Hornwort) ¹						
Algae bloom ²						

Table 2. Carbon storage calculations of wetland vegetation.

Species	Biomass (g m ⁻²)	% Carbon (average ± standard dev.)	Area (m ²)	Mean C storage (tonnes)	Std. Dev. C storage (tonnes)
<i>P. arundinacea</i>	1586.9	42.15 ± 1.09 (Britson et al., 2016)	Original: 14667.0 Canopy: 2151.2 Total: 16819.2	11.25	0.29
<i>S. palustris</i>	2200	44.36 ± 0.84%	Original: 4939.9 Canopy: 239.0 Total: 732.9	5.05	0.16
<i>N. officinale</i>	412.5 [1]	44.77 ± 4.48	383.0	0.07	0.007

		(Maqbool & Khan, 2013)			
<i>S. erectum</i>	140.0	44.79 ± 0.53 (Kulikova et al., 2023)	3038.4	0.19	0.002
<i>C. demersum</i>	958.1	39.37 ± 3.94 (Kusolsongtawee et al., 2018)	1958.6	0.22	0.02
Algae bloom	139.4	42.96 ± 1.70 (Cole et al., 2014)	897.9	0.05	0.002
Total aboveground carbon storage of wetland vegetation				16.83	0.46

[1] No biomass data for *N. officinale* available from field measurements. Source: Maqbool & Khan (2013).

Deadwood C storage

Based on NDVI of the winter imagery (19/01/2022), we classified all woody biomass lying and standing in the pond, which is mostly deadwood. Based on a digital surface model from photogrammetry, we calculated biomass above pond water level. Then, we added to all partially submerged deadwood 50% volume, assuming that approximately half of the tree is visible in the aerial imagery. Then, the carbon stored in the deadwood was calculated. For this, the pond subset was divided into two parts. Based on field observations it was assumed that the deadwood in the south was dominated by *Picea abies* and in the north by *Quercus robur*, *Fraxinus excelsior* and *Alnus glutinosa* with a ratio of 1:1:1. The deadwood volume was multiplied with the oven dry weight of the corresponding tree species using a species-specific content-shrinkage relationship. The total mass per species was multiplied with the specific carbon content, and the sum of these carbon contents led to the total carbon mass of deadwood. The total deadwood volume was found to be 2303.7 m³. The volume was divided over four tree species with a total carbon storage of 500.4 ± 14.3 tonnes (Table 3).

Table 3. Carbon storage in deadwood

<i>Latin name</i> (English name)	Oven dry weight (kg m ⁻³)	% C (Mean ± Std. Dev.)	Volume (m ³)	Mean C storage (tonnes)	Std. Dev. C storage (tonnes)
<i>P. abies</i> (Norway spruce)	356 ± 1.7 (Sopushynskyy et al., 2017)	50.30 ± 0.1% (Jagodziński et al., 2020)	1425.3	255.2	1.2
<i>Q. robur</i> (Common oak)	584.3 ± 1.53 (Vavřík & Gryc, 2012)	49.02 ± 0.50% (Matthews, 1993)	292.8	83.9	0.2
<i>F. excelsior</i> (European ash)	606 ± 38 (Le Goff et al., 2004)	49.29 ± 0.08% (Matthews, 1993)	292.8	87.5	5.5
<i>A. glutinosa</i> (Common alder)	499.75 ± 50 (Adapted from Meier, 2010)	50.47 ± 0.39% (Matthews, 1993)	292.8	73.8	7.4

Total aboveground carbon storage of deadwood	2303.7	500.4	14.3
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It remains unclear how much deadwood contributes to the carbon sequestered in the pond sediments (see below). Based on pre-beaver (2004) of gross yearly wood growth calculations of the beaver pond area from the forestry department of the Kanton Zuerich (Kanton Zürich, Baudirektion, Waldentwicklung und Ressourcen) (8.6 m³/ha/year) and a general 25% C-content in wood, we calculated a 9.3 t increase of C-storage per year for the beaver pond area. However, these estimations are not species-specific, so must be considered an estimation.

Sedimentary organic C storage: Soil carbon measurements were analysed to assess carbon sequestration in the pond. We investigated soil profiles using a hand auger, and sampled at each sampling location the soft, post-beaver soil, and the hard, pre-beaver soil. For reference, soil profiles in the surroundings were also investigated and sampled. To calculate mass, soil density samples were taken using a equal volume cylinder. Samples were dried at constant 30dC for 2 days under laboratory conditions, and weighed. Total organic carbon (TOC) content was measured using RockEval Pyrolysis. Then, we calculated soil carbon content for all soil types separately, and TOC% accumulation per year using the total number of years since the start of beaver damming.

Table 4.

	Beaver horizon		
	Mean	SE	SD
Volume (m³)	10100	1774	3414
Mass (mt)	7274	1612	2991
Carbon sequestration (mt yr⁻¹)	41.9	13.6	28.2

Abbreviations: SE – standard error, SD – standard deviation, mt – metric tonnes.

5. Carbon budget interpretation

Our full breakdown of the estimated annual carbon budget is provided in Table 5. Key results are that DIC is both the largest C input and output to the system, and that the beaver wetland is overall a net C sink. After DIC, the largest output is CO₂ emissions from the wetland soils, with CO₂ emissions from the water surfaces being relatively low. It is critical to note the mass unit differences between CO₂ and CH₄ fluxes, with all CH₄ losses being many orders of magnitude lower than CO₂, and thus a very minor contributor to the overall carbon budget of the system. Infiltration losses of water carrying DOC and DIC may also be an important C

loss pathway (but to the regional aquifer, not to the atmosphere), however because of the uncertainty surrounding the total infiltration losses within the water budget, these estimates should be considered preliminary.

We estimate the overall net C sink of the system to be ~63 metric tonnes per year, or ~17% of the C inputs, based on the differences between the total C inputs and outputs. This is largely, but not exclusively, driven by the differences in DIC output vs input concentrations.

Importantly, this sink estimate is remarkably close to the storage changes we estimate for biomass and organic sediment accumulation (~58.7 metric tonnes per year). This suggests our carbon budget estimates are relatively close to closure, and thus relatively robust despite the clear uncertainties.

The driver of this net C sink is clearly most related to the DIC loss pathway(s), which are likely dominated by the uptake of HCO_3^- through algal and aquatic vegetation for use as a CO_2 source in photosynthesis. Credibility for this increasing aquatic net primary productivity (NPP) interpretation comes from the ubiquitous abundance of aquatic plants and algae within the Marthalen beaver system, as well as the clear dominance of cumulative DIC uptake during the spring and summertime photosynthetically active periods (Figure 4).

The increased NPP provides seasonal biomass C storage that will later decay and be available as increased organic matter storage in wetland sediments, or potentially exported downstream. Our estimates of the annual change in biomass and sedimentary organic matter storage are remarkably close to the difference in measured C inputs and outputs, suggesting that the majority of these NPP increases are retained as additional C storage within the wetland.

Table 5. Components and carbon mass [t or kg] estimates. Note, CH_4 values in [kg] are highlighted in italics, the rest of the values are reported in metric tonnes [t]. The two values highlighted in grey indicate they should be compared, as the difference in inputs and outputs should be accounted for in the measured storage changes.

Component	C mass [t or kg] / yr
<i>Inputs</i>	
DIC _{input} [t]	347.5
DOC _{input} [t]	26.4
Total carbon inputs [t]	373.9
<i>Outputs</i>	
DIC _{output} [t]	202.7
DOC _{output} [t]	15.5
CH ₄ water [kg]	23.4
CO ₂ water [t]	4
CH ₄ soil [kg]	1.2
CO ₂ soil [t]	47.6
C _{infiltration}	41.2
Total carbon outputs [t]	311
Inputs - outputs [t]	62.9
<i>Storages</i>	
C biomass [t]	16.8
Organic C sediment [t]	41.9
Total storage	58.7

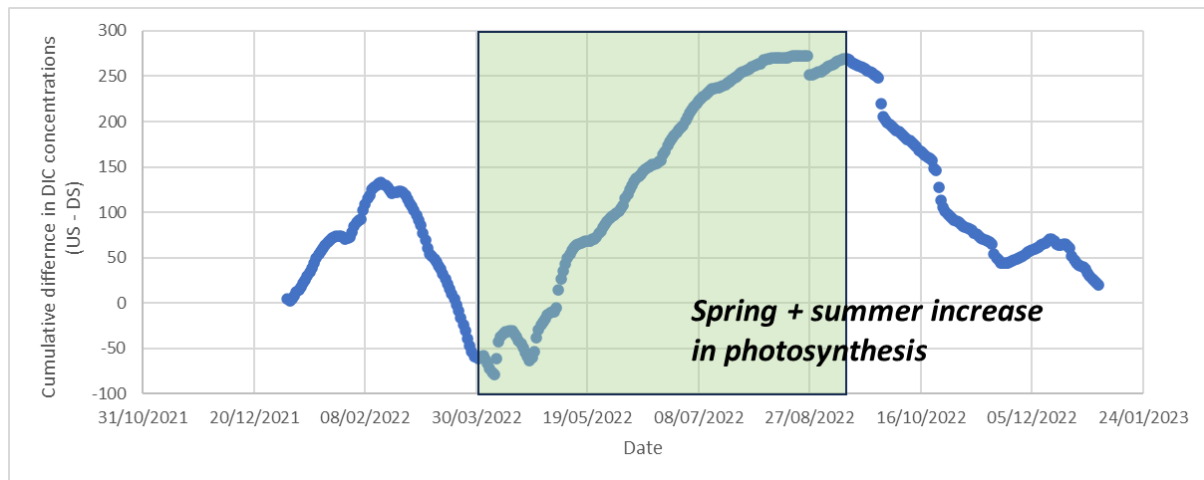


Figure 4. Cumulative difference (US - DS DIC concentrations). Note, this uses daily concentration values estimated using the WRTDS model. The consistent trend in DIC losses from upstream to downstream coincides with the onset of spring and summer conditions, supporting increasing aquatic net primary production as the main driver.

6. Implications

In the absence of the beaver wetland system, it is clear that neither the water balance nor the DIC concentrations would likely experience significant changes in the relatively short channel distance spanning the site. The introduction of the beaver wetland has increased water losses due to evaporation, and also greatly increased aquatic NPP and therefore created a large C sink that was previously not present in the landscape. When compared to the yearly rates of C sequestration in forests typical for the region, and assuming that carbon content in forest soils stay relatively constant, the C sink per year is roughly 3 times greater for the beaver wetland system. Although this change from forest to wetland provides an impressive increase in the size of the C sink, it is not necessarily unexpected, given wetlands are consistently found to provide more efficient C sinks relative to the local forests that would otherwise exist (Kolka et al. 2022).

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