

Modification and spatial variation of riverine nitrogen and dissolved organic carbon concentrations due to beaver damming across Switzerland

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Summary

Swiss streams, especially smaller ones, suffer from poor water quality (BAFU, 2022). The goal of this study was to assess the spatial and seasonal variability of beaver system impacts on nitrate and DOC (dissolved organic carbon) concentrations, as well as to determine whether there are clear physical characteristics of beaver systems that can help explain the extent of changes in these nutrients. This impact is assessed by comparing nitrate and DOC concentrations measured upstream and downstream of 164 beaver systems across Switzerland in two temporal windows, winter 2021/22 and summer 2022. Despite considerable variability, a predominant trend emerges from the data, indicating a prevalent decrease in nitrate levels during both summer and winter. Simultaneously, a substantial majority of the sites exhibit an increase in Dissolved Organic Carbon (DOC), with the most pronounced uptick occurring notably in the summer season. This constitutes a noteworthy result, underscoring the widespread occurrence of these trends on a large scale, albeit acknowledging substantial variability attributable to site-specific characteristics. We could not identify a significant beaver system character determining the extent of nitrate removal or DOC gain. However, land use analysis in the direct surroundings of the beaver dam reaches (buffer polygons of 5 m, 10 m, 25 m and 50 m) revealed that the extent of nitrate removal and DOC gain

is significantly determined or at least co-determined by the proportion of wetland conditions in these buffer areas. The extent of anaerobic conditions and vegetation in wetlands reduces nitrate concentrations and increases DOC concentrations due to enhanced ecosystem productivity. We interpret these findings that the ability of beaver systems to induce changes in water quality is not primarily dependent on specific beaver system characteristics such as length of the beaver reach, slope, water volume, water residence time, discharge, dam age or number of dams. Rather, it is primarily determined by the beavers' capability to influence the local floodplain through damming and raising water levels sufficiently to create lentic wetland habitat. In summary, beavers can reliably improve water quality if given the space in landscape settings with low river slopes and floodplains.

1.1 Introduction

The construction of dams by beavers creates a new mix of flowing and ponded water, which encourages new ecosystem habitats and biogeochemical pathways. In particular, there is an expansion in water interfaces that are anaerobic or depleted in dissolved oxygen. Given riverine water quality is highly dependent on these biogeochemical pathways, a key question is then how beaver dams may impact critical pollutants such as nitrogen in river systems. Beaver dam cascades and meadows are known to have the capacity to decrease nitrogen loads in river systems, yet the factors determining the extent of this decrease between different river systems remain unclear. The capacity for beavers to influence the concentrations of important pollutants is clear from the available literature (summarized in Larsen et al., 2021).

Nitrogen concentrations can be divided into nitrate (NO_3^-) and ammonia (NH_4^+). Nitrite is also an intermediate species that is negligible for nitrogen loads in natural rivers. Nitrate concentrations are consistently, though not uniformly, lower downstream of beaver dam systems. This can be attributed to a combination of 1) increased spatial extents of anaerobic metabolism and therefore denitrification, which converts NO_3^- to N_2 (gas), allowing nitrogen to be lost to the atmosphere, and 2) biomass uptake, especially by macrophytes and biofilms. High nitrate concentrations are a major pollution concern, especially across the fertilized regions of Switzerland, thus the potential capacity for beaver dammed river system to diminish this pollution load could be a large natural benefit that is essential for ecosystem and water quality managers to understand. Ammonia concentrations tend to increase downstream of beaver dams, likely due to the increased breakdown of organic matter in beaver ponds and wetlands which can also generate NH_4^+ . Given NH_4^+ is usually converted in well oxygenated rivers to NO_3^- via nitrification processes, this may offset to some extent the reductions in NO_3^- due to denitrification. However, the extent of this difference is poorly known, and the seasonal (winter vs summer) and Swiss wide sampling conducted by this project, in addition to sampling for organic nitrogen, provided critical information on the interplay between NO_3^- and NH_4^+ that then determines the overall impact that beaver systems have on nitrogen pollution.

Separately, although it is clear beaver dams have an impact on dissolved organic carbon in rivers, there is variation in the data and a need to understand the origin and quality of the dissolved organic carbon downstream to identify the benefits of beaver dam reaches for the aquatic food chain. In this project we establish the first large scale spatial analysis of water quality changes due to beaver dams. Given the increasing extent of beaver dams across Swiss river networks, the capacity for these dams to provide natural benefits to pollution problems, especially in the case of nitrogen loads, is essential information that can improve the decisions of beaver managers, policy makers, and land users in Switzerland.

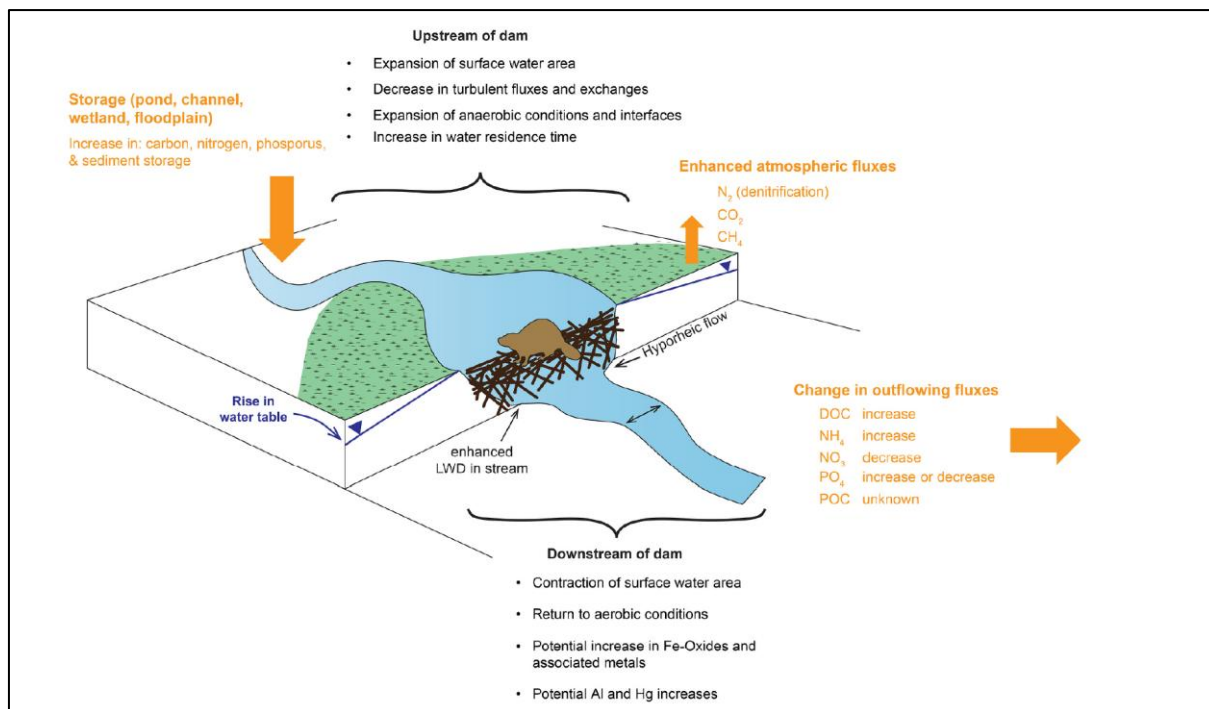


Figure 1: Conceptual model of beaver impacts on biogeochemistry and water quality (Larsen et al., 2021).

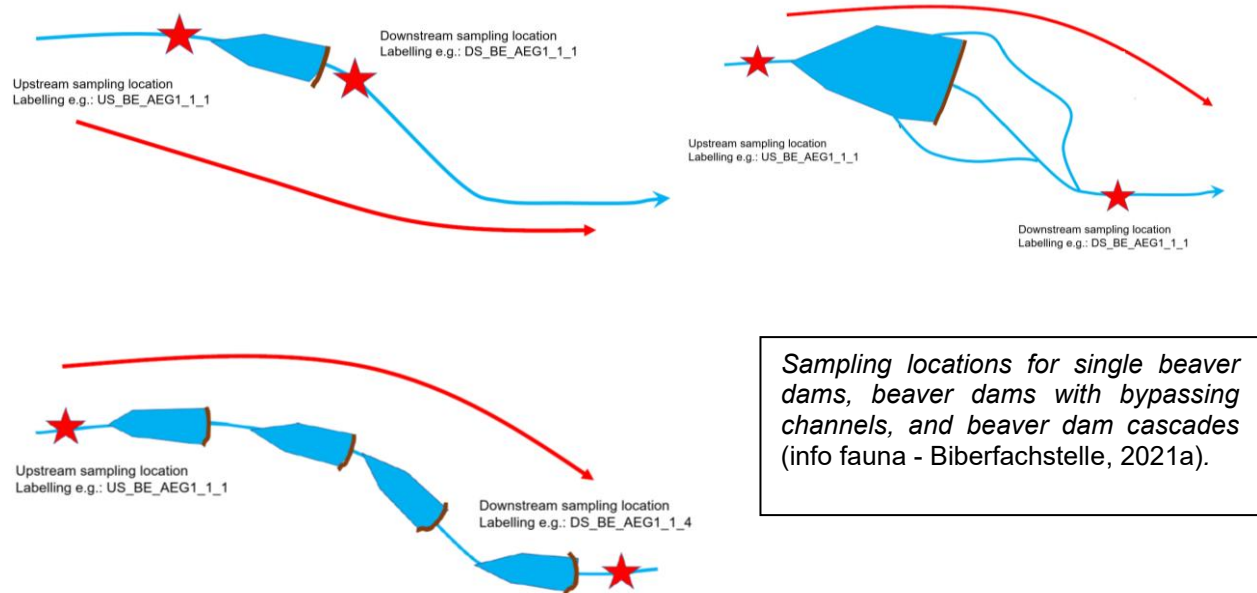
1.2 Objectives

This study was part of the national beaver project "Functionality of the beaver's damming activity in the landscape - a project to strengthen the ecological infrastructure" of the Federal Office for the Environment (Angst & 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 (assessment of the ecosystem services provided and clarification of the influence of the beaver on biodiversity in different types of water bodies). Here, we evaluate how much water quality is influenced by beaver systems, what the spatial variation is across Switzerland, and finally which beaver dam systems might be most effective in delivering the important ecosystem service of water quality improvement. More specifically, we determine what the spatial and seasonal patterns of riverine nitrate and DOC concentrations are upstream and downstream of beaver dam

systems throughout Switzerland, and which characteristics of beaver dam systems (water residence time, number of dams, slope of the beaver reach, etc.) determine the extent of beaver dam system impacts on riverine nitrate and DOC concentration.

1.3 Design of the field survey, laboratory measurements, spatial analysis and geostatistics

This study made use of the 2021/22 national beaver census (Angst et al. 2023). From December 2021 to April 2022, 313 volunteers surveyed 7'000 km of the Swiss river network to identify signs indicative of beaver presence. Following a citizen science approach, the volunteers also collected water samples upstream and downstream of beaver systems following a strict protocol, in-person training, and instructional videos. In order to examine seasonal variability, the same sites were resampled in summer 2022 by 4 student assistants/civil servants.



The nutrient and DOC winter samples were measured by EAWAG. During the summer campaign, EAWAG measured 261 samples, while 90 samples were measured at the cLab Berne. Nutrient and DOC samples required analysis within two weeks after being collected in order to minimize potential alterations caused by microbial processes. All ammonium samples were measured at EAWAG using colorimetric determination. All other nutrients were measured using ion chromatography, and encompassed Sodium (Na^+), Magnesium (Mg^{2+}), Calcium (Ca^{2+}), Potassium (K^+), Fluoride (F^-), Chloride (Cl^-), Bromide (Br^-), Nitrate (NO_3^-) and Sulfate (SO_4^{2-}). Dissolved organic carbon (DOC) was measured using catalytic combustion. Because 2 laboratories were used, 10 samples were measured in both laboratories to better understand potential discrepancies

between measurement devices. This exhibited a linear difference between DOC measurements, which could be correct through the factor 1.4. In order to better understand water residence time and evaporation in the beaver dam reaches, measurements of $\delta^{18}\text{O}$ (‰), $\delta^2\text{H}$ (‰), $\delta^{17}\text{O}$ (‰) and ^{17}O -excess composition for US (upstream) and DS (downstream) samples were conducted using a Cavity Ringdown Spectrometer (CRDS) at cLab Berne. Data was entered into a hydro calculator based on Skrzypek et al. (2015), which allows an estimation of evaporation based on the hydrogen and oxygen stable isotope composition of inflowing and outflowing water in a pond. Sediment load samples were filtered with a the 0.22 μm , dried and weighed. The weight was normalized by the water sample weight, from which sediment load was calculated.

For all DS sampling locations, catchments were delineated in order to estimate discharge during sampling times for each sampling location using the conceptual, processed-based PREVAH model following Brunner et al. (2019). Catchment delineation was based on the pre-existing dataset “Fliessgewässer” and the TLM3D from swisstopo (downloaded 2022) using ArcGIS10. Where catchment polygons were affected by urban canalization of surface water, catchments were modified manually based on the digital elevation model (DEM, see below for specification).

For nominal water residence time calculation, beaver pond volume was estimated using a high resolution lidar dataset and the beaver dam height, which was measured in the field. The volume between a designated plane height and the surface derived from the DEM was computed in both, ArcGIS10 and QGIS, which should represent the maximum water volume in the pond. This method was validated by field surveys of 6 very different beaver pond locations. In order to examine the potential impacts of river slope and length on water quality, distance and slope of the river reach between the US and DS sampling location was computed. As the main driver of reduced water quality is land-use, an existing dataset assigning each hectare in Switzerland to four main land-use categories (settlement areas, agricultural areas, forest areas and non-productive areas) and 72 subcategories (BFS, 2006) was clipped to the catchment area of each sampling point and quantified. Using the swissTLM3D from swisstopo (downloaded 2022) dataset, ratios of existing ‘wetlands’ per catchment area was calculated, and land-use in the immediate surroundings (50 m) of the beaver reach was quantified, merging the information into the 5 categories: stagnant water bodies, forest, wetland, anthropogenic, and agriculture. According to the product information of the swissTLM3D dataset, wetlands are defined as areas situated in the transitional zone between dry and permanently wet ecosystems. The term “wetland” encompasses various habitat types such as marshes, bogs, swamp forests, wet meadows, floodplains or fens. According to the information from swisstopo, wetlands were mapped in swissTLM3D based on older analogue maps, the peatland inventory from BAFU, cadastral surveys, and clearly visible wet areas mapped based on aerial photographs. In order to investigate the effect of different land use with various distances to the river, buffer polygons of 5 m, 10 m, 25 m and 50 m around the Swiss river network from swisstopo (downloaded 2022) was created. The proportion of the five land use categories within the buffer areas were determined using ArcMap and QGIS (see Appendix for more information). The time period during which the beavers having been occupying a site could also be relevant for water quality impact, but is difficult to estimate due to differences in beaver dam

monitoring of regional authorities, and inaccuracies of GPS-coordinates. However, it is possible to determine whether the beaver reach was already occupied by beavers in previous beaver surveys.

To analyze the statistical relationship between the environmental variables described above and the water quality measurements, we first compared winter and summer US concentrations, beaver dam reaches with increasing and decreasing concentrations in summer and in winter, the magnitude and spatial pattern of water quality indicator increase and decrease. To explore the dataset further, we then subdivided the beaver dam reaches into subdatasets with the goal to form categories with high contrasts such as “nitrate and DOC decreases in both seasons” and “nitrate and DOC increases in both seasons”. Following the Gewaesserschutzverordnung (Bundesrat 1998), the category “nitrate > 25 mg/l” was chosen in order to examine the characteristics of beaver systems with nitrate concentrations classified as ‘high’ for surface water. Please note that due to the citizen size approach and the complexity of water sample storage requirements, each analysis produced datasets which vary in number of beaver dam reaches. The category “All” in table 1 (153 beaver dam reaches) contain beaver dam reaches including all types of analysis, and are hence used for further comparison.

Table 1: Subdatasets

Subdatasets	Explanation	Number of beaver dam reaches
All	All beaver dam reaches with a complete dataset in summer and winter	153
NO3: --	Beaver dam reaches with decreasing nitrate concentrations in summer and winter	65
NO3: ++	Beaver dam reaches with increasing nitrate concentrations in summer and winter	32
NO3 (S, US) > 25 mg/l	Beaver dam reaches with US summer nitrate concentration > 25 mg/l (limit for Swiss rivers)	17
NO3: -- DOC: ++	Beaver dam reaches with decreasing nitrate and increasing DOC concentrations in summer and winter	24
DOC: ++	Beaver dam reaches with increasing DOC concentrations in summer and winter	47
DOC: --	Beaver dam reaches with decreasing DOC concentrations in summer and winter	31

Then, the dataset was separated into 3 categories to identify a relationship between US concentrations of nitrate/DOC, the increase/decrease of nitrate/DOC concentrations between the US and DS sampling location, and the land use in the buffer area of the river between US and DS. To determine the significance of the Pearson correlations a t-test was performed. A significance

level of 0.05 is considered. If the resulting p-value is lower than 0.05, the correlation is deemed significant.

Table 2: Overview over performed analysis

Characteristics of the catchment or the US sampling location which (may) control the US concentrations of nitrate or DOC	Beaver system characteristics which (may) cause an increase or decrease in nitrate and DOC concentration within the beaver system:	Land use in the direct surrounding of the river between US and DS
- Altitude of the US water sampling location - Mean catchment altitude - Discharge - Catchment size - Land use in catchment - Stable isotope composition - Ammonium, sodium, magnesium, calcium, potassium, fluoride, chloride, bromide and sulfate concentrations US	- Distance - Slope - Water volume - Water residence time - Discharge - Dam age - Number of dams - Temperature differences between US and DS - Differences in the stable isotope composition between US and DS - Change in sodium, magnesium, calcium, potassium, fluoride, chloride, bromide and sulfate concentrations from US to DS	- Stagnant water, Forest, Wetlands, Anthropogenic and Agriculture (buffer 50 m, 25 m, 10 m and 5 m) absolute area in the buffer polygon in m² - Stagnant water, Forest, Wetlands, Anthropogenic and Agriculture (buffer 50 m, 25 m, 10 m and 5 m) percentage of the buffer polygon area

Based on the initial findings, it became evident that wetlands within the buffer polygons of the beaver dam reaches have a significant impact on reducing nitrate concentrations and increasing DOC concentrations. 25 beaver dam reaches were identified as having a certain proportion of wetland area within the 50 m buffer polygon. These beaver dam reaches were categorized into two groups in order to investigate potential impacts of the connectivity between the wetland and river: Wetland directly connected to the water of the river (Figure 2 b), and wetland and river not directly connected, but separated by roads, trails, trees, etc. (Figure 2 a).

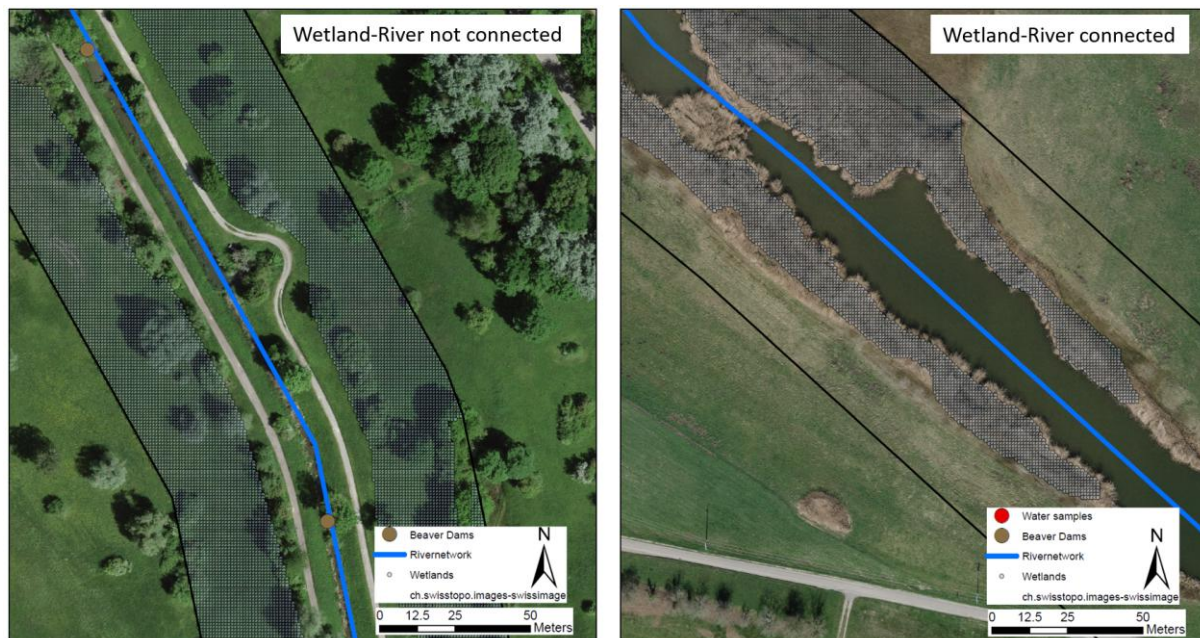


Figure 2a left, 2b right: Wetland-River connectivity. Classification of beaver dam reaches with wetlands in the 50 m buffer area into two categories. Background map: (swisstopo, 2018).

1.4 Descriptive statistics results

Analysis of beaver dam and reach data, water quality measurements, and environmental factors have highlighted that more than half of all beaver dams are located at an altitude between 400 to 500 m asl and are lower than 0.5 m (The largest recorded dam was 2.5 m high). The comparison of water temperature differences between US and DS has shown a large scatter, but a general increase in temperature from US to DS of 0.24°C . Most of beaver dammed catchments are smaller than 10 km^2 , and average discharge of all sites during the winter campaign was $0.7 \text{ m}^3/\text{s}$, and $0.2 \text{ m}^3/\text{s}$ in summer. The majority of land use in the catchments is agriculture (56 %, 73'332 hectares), 28 % is forest, 15 % settlements, and 1 % are rivers and lakes. The water volume estimation showed that most (107) of all 165 beaver dam reaches have a water volume up to 500 m^3 . The largest beaver dam reaches have a water volume between $3'000$ and $3'500 \text{ m}^3$. The analysis of beaver reach length, slope and number of dams shows that most beaver dam reaches are under 1 km length, and slope ranges between 0 and 7%, with a median at 0.6%. There is a tendency for the slope to decrease with increasing reach length, which is due to the backwater effect being larger the lower the slope. There are two beaver dams per beaver reach on average, with the highest recorded number of 19. From the 165 examined beaver dam reaches, 100 did not have any recorded presence of beaver dams in any previous surveys, and are hence considered 'new'. 15 reaches were already occupied by beavers during the national beaver census in winter 2007-2008. In 50 beaver dam reaches dams were mapped for the first time during cantonal surveys in the years from 2011 to 2020. The land use directly surrounding beaver dam reaches is predominantly composed of forest and agriculture. The proportion of forest tends to increase with

decreasing distance to the river, and the opposite is the case for agriculture. Stagnant water and wetland areas were mostly observed within 5 m to 10 m distance to the river.

1.5 Water quality

1.5.1 Nitrate

Overall, Nitrate contents in surface water was on average higher in winter (median: 16.34 mg/l) than in summer (median: 12.76 mg/l). However, the highest concentrations reaching up to 100 mg/l, occurred in summer season. When comparing nitrate concentrations US and DS of beaver dam reaches, nitrate concentrations can both, increase and decrease, but decreased more often. A decrease is more often observed during the summer season, where out of 158 nitrate measurements, 104 showed a decrease, while in winter, 89 out of 158 measurements indicated a decrease.

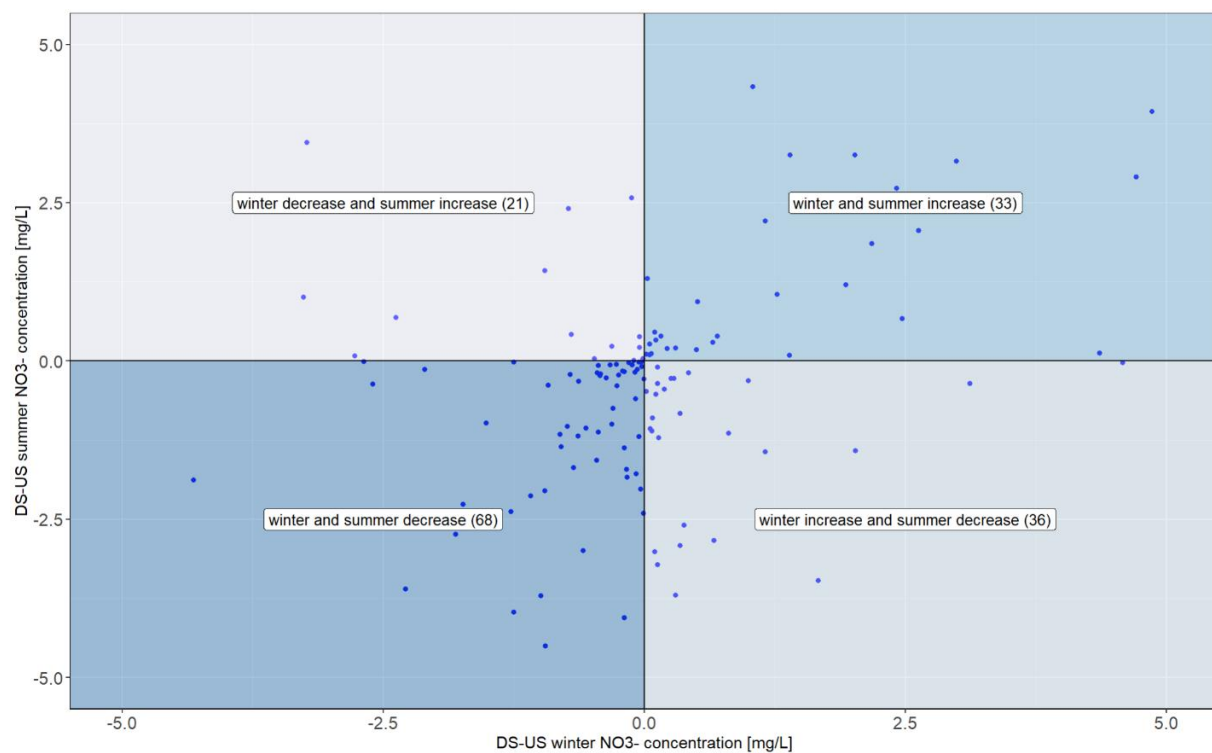


Figure 3: DS – US nitrate concentrations in winter and summer (all values ± 5 mg/l are not included for viability).

Overall, nitrate concentrations appear to be generally higher on the Swiss plateau compared to the St. Gallen Rhine Valley or the Valais. Locations with high or low nitrate concentrations during winter also tend to maintain lower values during summer.

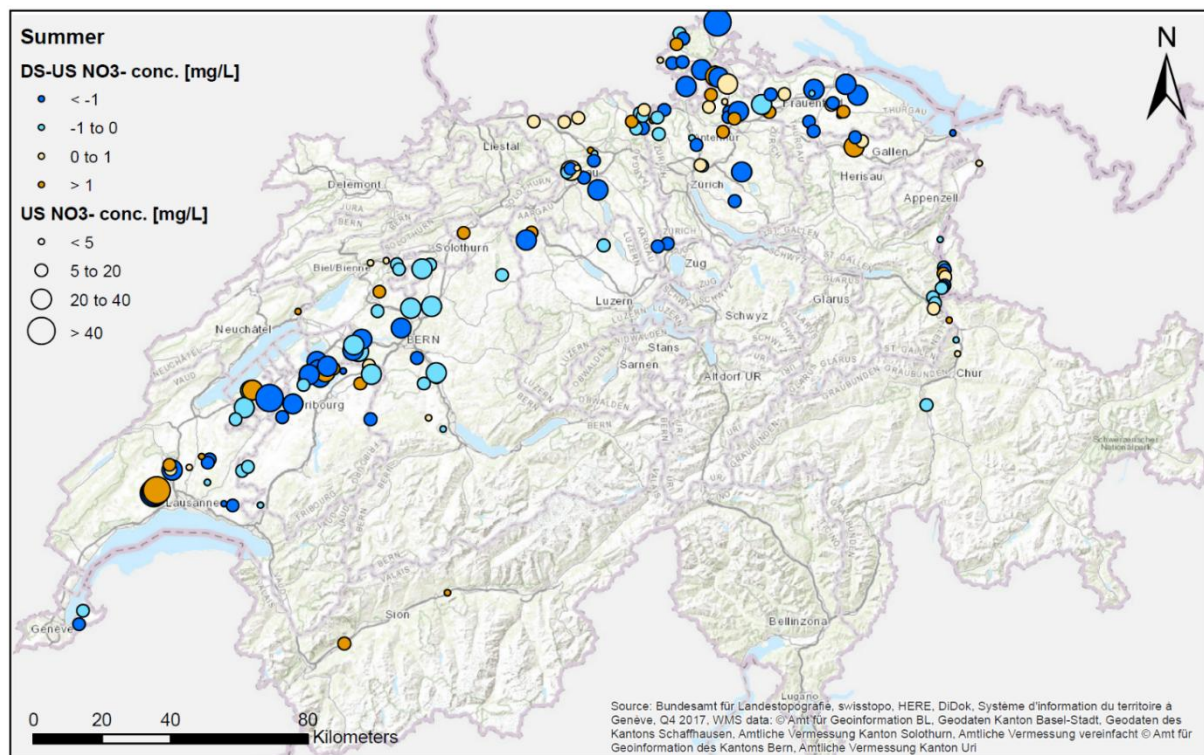
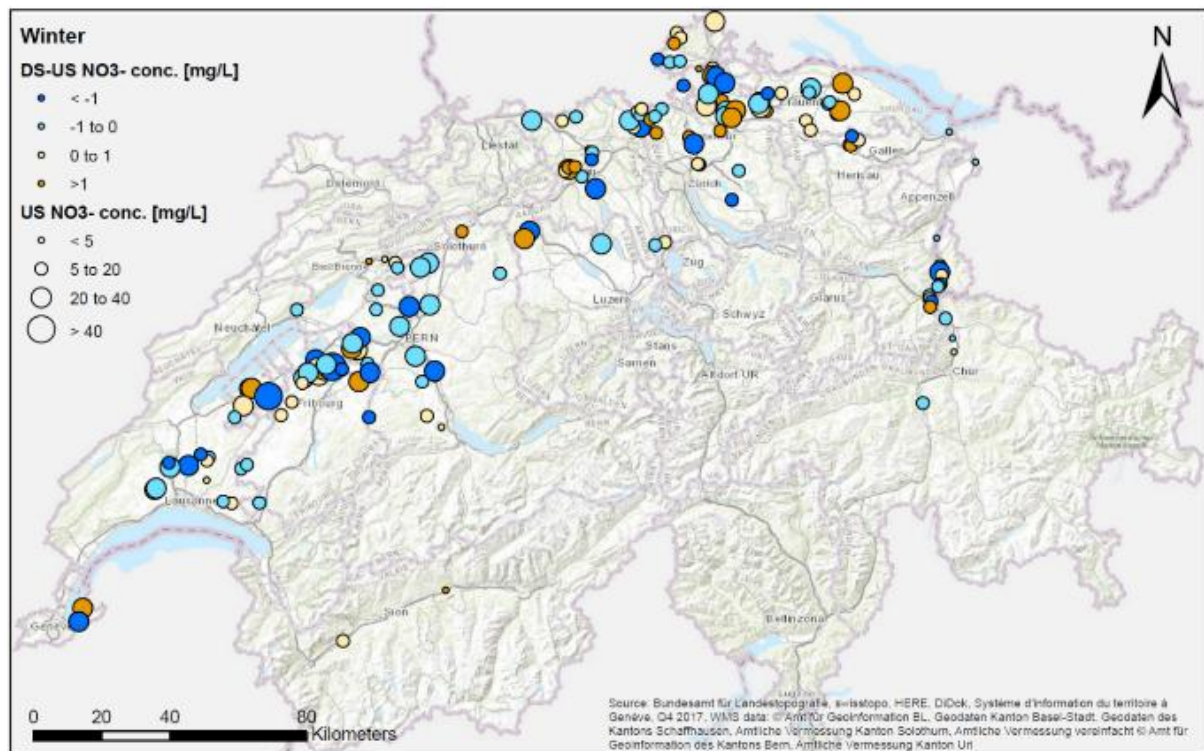


Figure 4: Change in upstream to downstream Nitrate concentration within all 164 measured beaver dam reaches in winter (top) and in summer (bottom). A general trend of decreasing nitrate is visible in summer as well as in winter, however in all areas both, increase and decrease of nitrate is possible.

1.5.2 Dissolved Organic Carbon (DOC)

Overall, DOC concentration in surface water is higher in summer (2.78 mg/l) than in winter (1.98 mg/l). In winter, beaver dam reaches have a negligible effect on DOC concentrations. In summer, most beaver dam reaches lead to an increase of DOC in the surface water

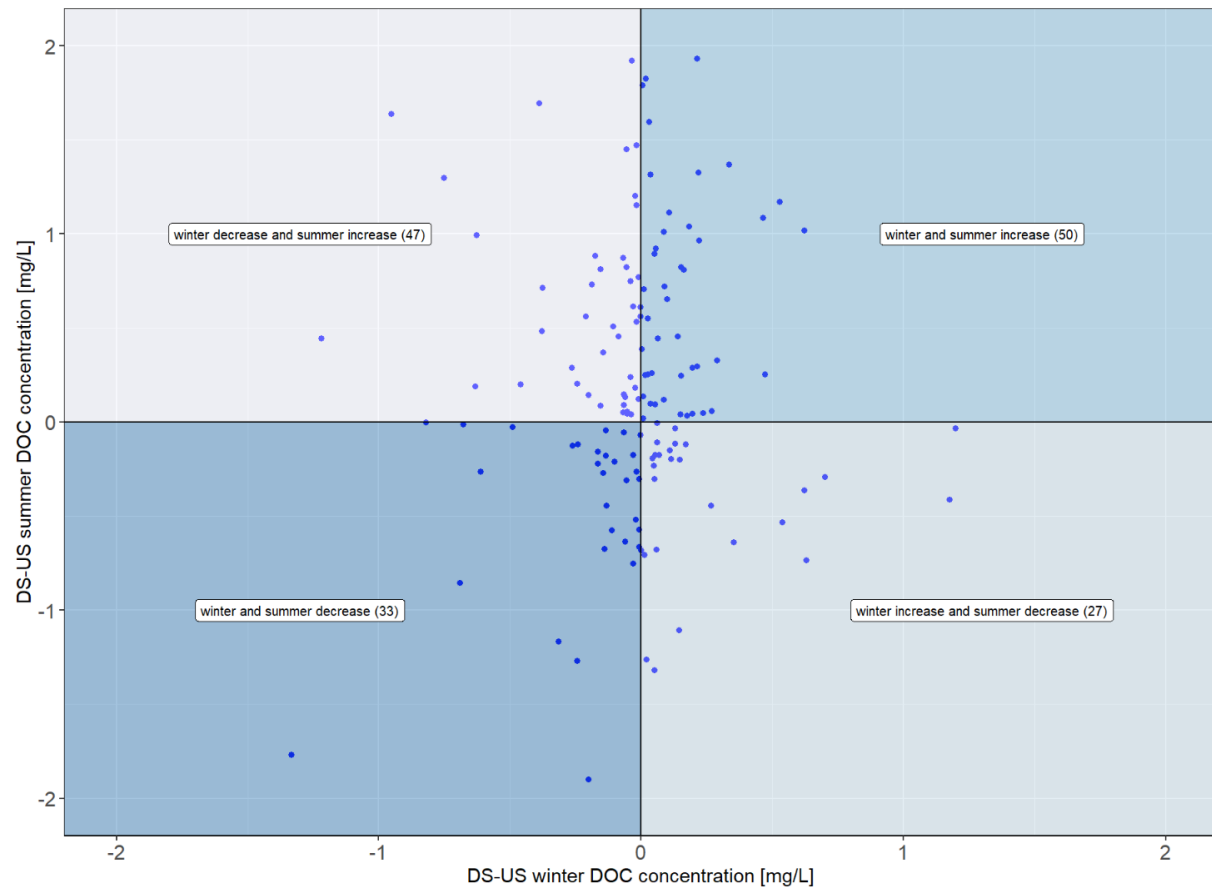


Figure 5: xxxxx

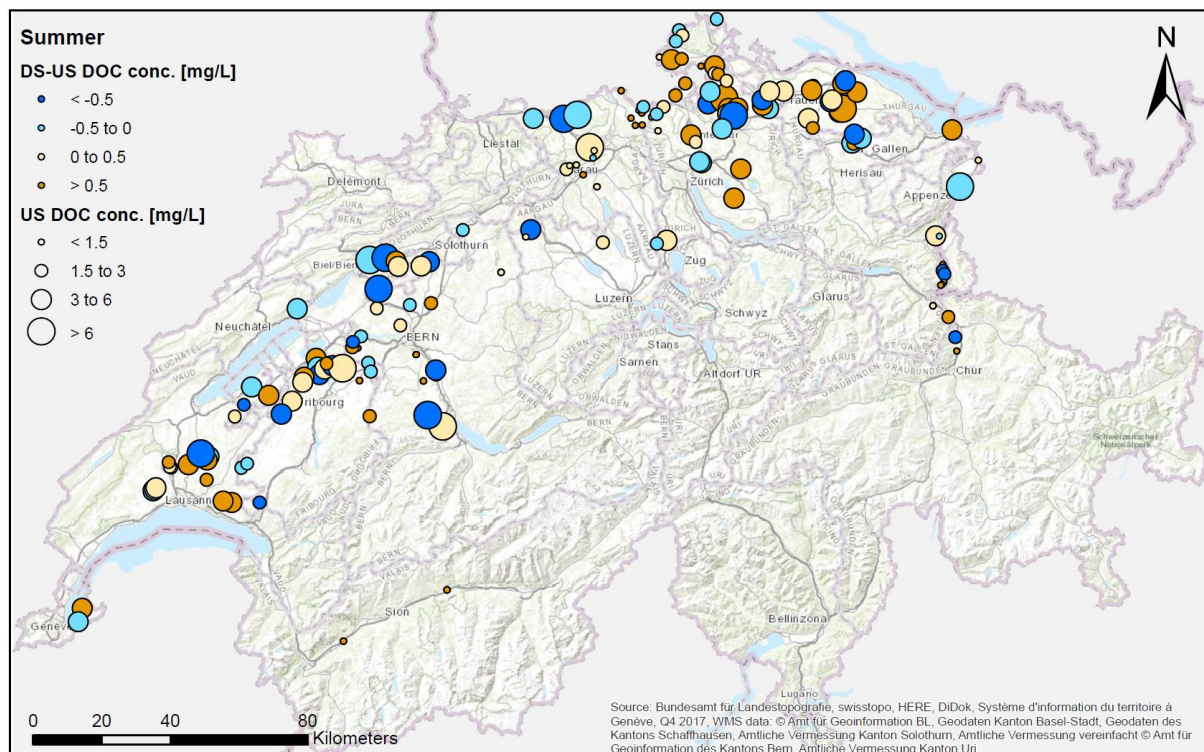
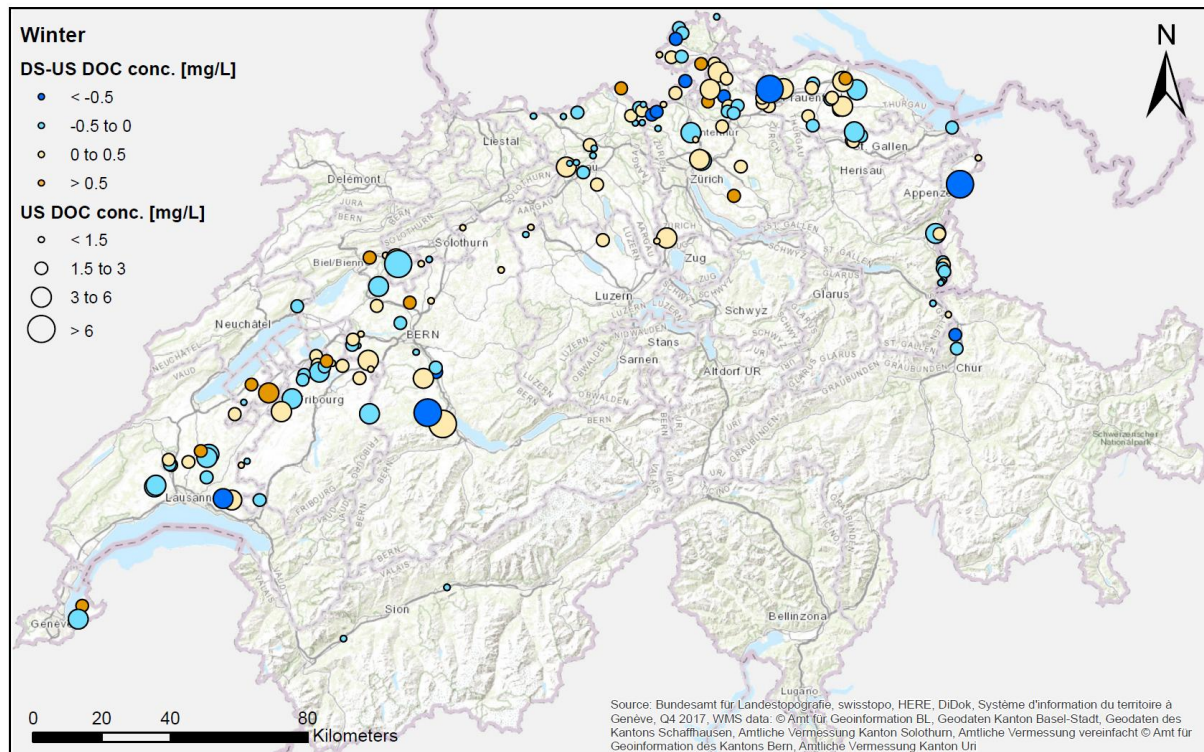


Figure 6: DOC concentrations and changes in winter (top) and in summer (bottom). The observed trend of increasing DOC downstream of beaver dam reaches is visible in summer. All areas show both, increasing and decreasing tendencies.

Interpretation

From the literature, we expected an increase in DOC concentrations through beaver systems. In this large-scale study, this increase was clearly observed in the summer data, where 97 out of 157 beaver dam reaches had higher DOC concentrations DS. However, in winter the number of beaver dam reaches with increasing (77) and decreasing (80) DOC concentrations is almost equal. This means, that higher DOC concentrations can be generally attributed to increased primary productivity in the beaver pond which is most pronounced during the summer months.

1.5.3 Suspended sediment load

134 beaver dam reaches in winter and 144 beaver dam reaches in summer were sampled for suspended sediment load. Low water levels prohibited the sampling in some cases. The median values in both seasons are slightly higher DS compared to US (US winter: 13.74 mg/l, DS winter: 14.41 mg/l and US summer: 12.65 mg/l, DS summer: 14.93 mg/l). In winter, 74 out of the 134 beaver dam reaches have a higher sediment load DS compared to US, while in summer, 86 out of the 144 beaver dam reaches showed higher sediment load DS. However, the differences between US and DS are in both seasons primarily below 10 mg/l, which may be within the error range of the method employed.

Interpretation

This means, that effects of beaver dam reaches on sediment loads are very small to negligible.

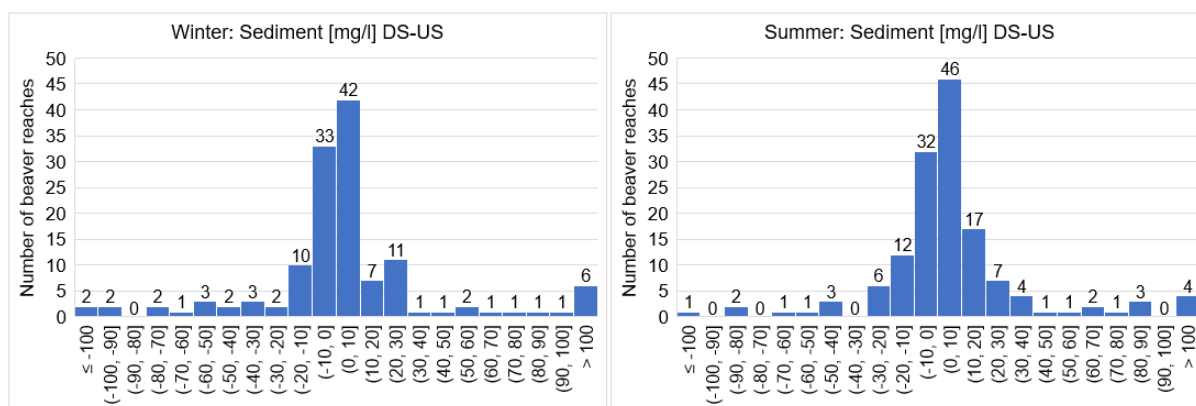


Figure 7 DS-US sediment load in winter (left) and summer (right). Positive values indicate higher sediment loads DS.

1.5.4 Stable water isotopes ($\delta^2\text{H}$ (deuterium), $\delta^{18}\text{O}$ (oxygen))

The stable isotope dataset encompasses 133 beaver dam reaches in summer and winter. The median values of $\delta^2\text{H}$ (deuterium) and $\delta^{18}\text{O}$ (oxygen) compositions are typically more enriched in summer compared to winter, which is to be expected. In most cases, there are minimal differences between the compositions of US and DS samples. Distance, slope, volume, and residence time were estimated to contribute to the enrichment of stable isotope composition from US to DS, due to increased exposure of the water to the sunlight. However, most correlations between changes in stable isotope composition and these characteristics were found to be insignificant. Nonetheless, a positive correlation of approximately 0.20 was observed between changes in stable isotope composition and water volume specifically for the summer samples. Additionally, DS samples tend to be enriched in areas with a high proportion of wetlands in the buffer polygon surrounding the river reach. This trend is significant ($p\text{-value} < 0.05$) in summer with correlations of 0.36 to 0.39 (in winter 0.18 to 0.23) (table 3).

Interpretation

Where beavers create wetlands, residence time and evaporation increases. In contrast, where beavers create no wetlands (e.g. beaver pond cascades), there is a small or no effect on residence time and evaporation. These results potentially also highlight a disconnected flow system typical for beaver wetlands, but this needs further testing, for example with tracers.

Table 3: Correlation matrix showing changes in stable isotope compositions and beaver system characteristics.

	DS- US $\delta^2\text{H}$ winter	DS-US $\delta^2\text{H}$ summer	DS-US $\delta^{18}\text{O}$ winter	DS-US $\delta^{18}\text{O}$ summer
Distance	0.08	0.08	0.05	0.11
Slope	0.10	-0.05	0.12	-0.04
Volume	0.12	0.19	0.06	0.21
Residence time winter	0.06		0.06	
Residence time summer		0.01		0.05
Wetland (abs.)	0.05	0.16	0.03	0.13
Wetland (%)	0.18	0.36	0.23	0.39

1.5.5 Other water chemistry parameters (including Ammonium)

The comparison of the median values US and DS in winter and summer for all measured water chemistry parameters excluding Nitrate and DOC show very small or no changes between US and DS of beaver dam reaches. Ammonium concentrations were of particular interest, as they can cause increases in nitrate concentrations downstream. However, Ammonium concentrations were

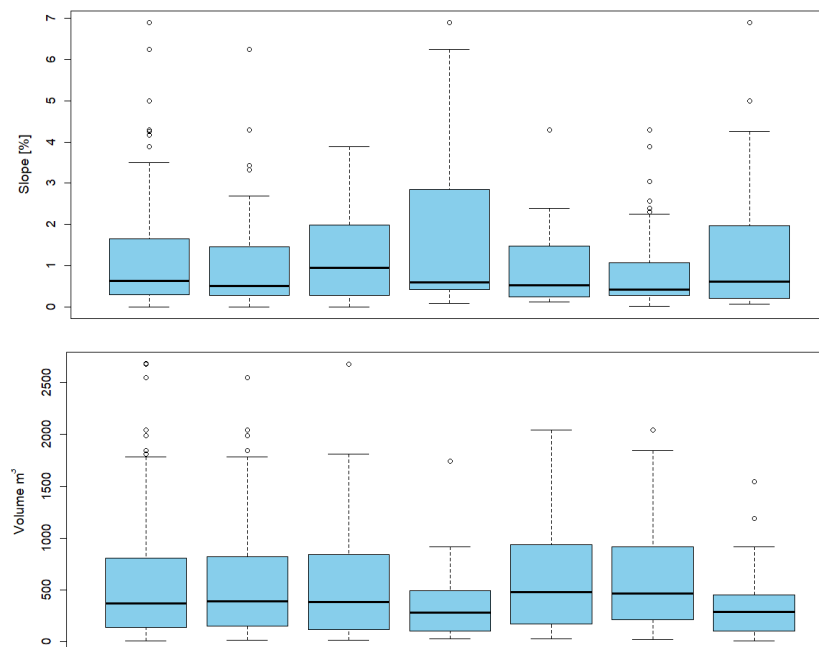
found to be mostly below detection limit (0.02 mg/l) and only slightly higher on average (0.03 mg/l) in summer DS of beaver dam reaches.

Interpretation

A widespread increase in ammonium production in beaver ponds that is followed by a re-nitrification to nitrate downstream of beaver ponds can be excluded.

1.5.6 The influence of beaver dam reaches on water quality

The data was separated into seven subdatasets with regards to nitrate and DOC concentrations. These classes are: “nitrate and DOC decreases in both seasons (NO3--, DOC--)”, “nitrate and DOC increases in both seasons” (NO3++, DOC++), “nitrate > 25 mg/l”, and “All” to allow a comparison with the entire dataset. These subdatasets were compared with regards to characteristics slope, water volume, distance, number of dams and dam age. The analysis of the median slope of the river revealed that it is steeper for NO3: ++ compared to NO3: --. In contrast, the median slope was found to be steeper for DOC: -- than for DOC: ++. These findings suggest that **beaver systems with lower slopes exhibit stronger nitrate removal and a larger increase of DOC**. The analysis revealed further that the median water volume is low in the subdataset in which DOC is reduced in summer and winter. This suggests that a **beaver system with a higher water volume has a greater potential for increasing DOC concentration**. Reach overall distance, number of dams, and dam age however exhibit minimal variations and do not provide any significant insights.



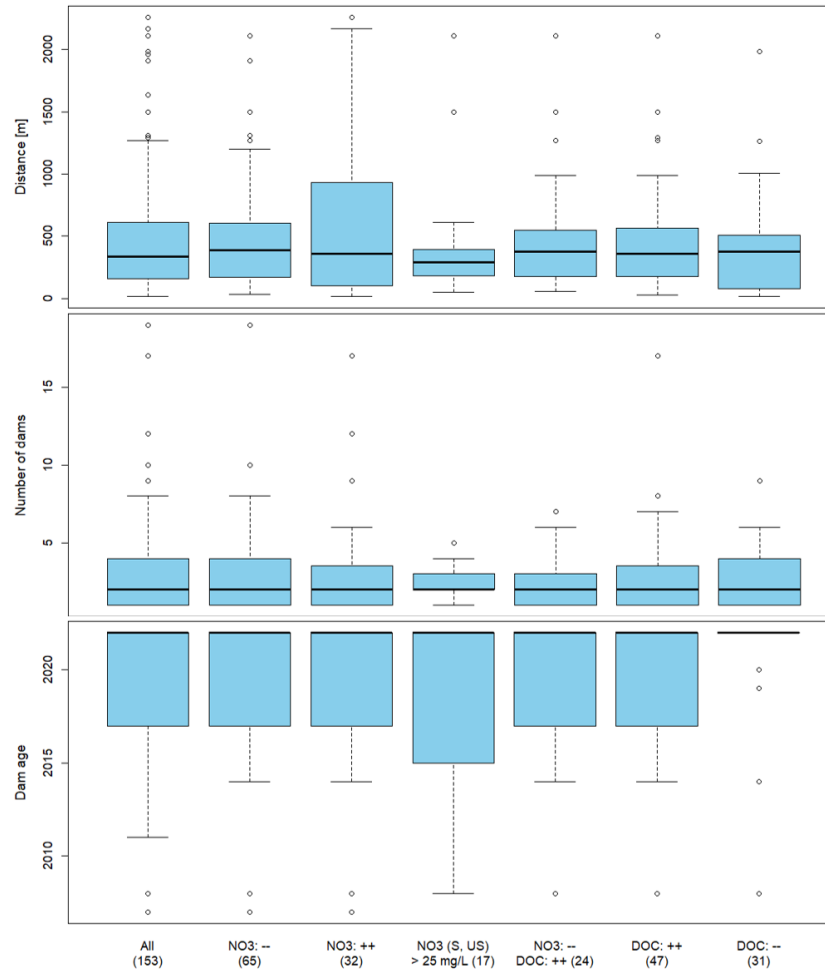


Figure 8: River slope, water volume, distance, number of dams and dam age: Boxplots for subdatasets of water quality

1.5.7 Correlation analysis

Correlation analysis reveals a positive correlation between nitrate concentrations in summer and winter (Corr.: 0.61), as well as between DOC concentrations in summer and winter (Corr.: 0.53), confirming the validity of the analysis. Additionally, there is a positive correlation (Corr.: 0.36) between DOC concentration and water temperature during summer. Positive correlations (Corr.: 0.17 to 0.34) are observed between DOC concentrations and the presence of wetlands in the catchments, while a negative correlation (Corr.: -0.20) is observed between the proportion of wetlands and nitrate concentration, but only in winter. Moreover, agricultural land use in the catchment shows a positive correlation with nitrate and DOC concentrations, while forest land use exhibits a negative correlation. Correlations are identified between the concentrations of nitrate and DOC and the stable isotope composition, indicating that higher concentrations are associated with enriched water. This relationship is particularly apparent between the stable isotope compositions and the DOC concentration in summer. Additionally, there are several correlations, predominantly positive, between the nitrate and DOC concentrations and the concentrations of other water quality parameters (see Figure 9 below).

The analysis reveals that there is no significant correlation between the concentration changes and any of the beaver system characteristics such as distance, slope, residence time, discharge, dam age and number of dams. However, a low positive correlation (Corr.: 0.22) is observed between the changes in DOC in summer and the water volume of the beaver reach. This suggests that a larger pond volume is associated with a higher increase in DOC concentration. Furthermore, there are low negative correlations (Corr.: -0.23 to -0.15) between the US concentrations and the changes, indicating that a higher initial concentration of nitrate or DOC results in greater removal rates within the beaver system. However, this negative correlation is not significant for DOC in summer. Additionally, a positive correlation is observed between the changes in ammonium and DOC concentrations (Corr.: 0.17 to 0.35), suggesting that increasing DOC concentrations are associated with increasing ammonium concentrations. There are also positive correlations between the DOC gain and stable isotope composition, as well as some positive and negative correlations with the changes of other water quality parameters.

Land-use (relative and absolute sizes of the land use types stagnant water, forest and agriculture in the catchment) shows no significant correlation (p -value < 0.05). There is a low positive correlation (Corr.: 0.17 to 0.29) between agriculture and changes in DOC concentrations in summer.

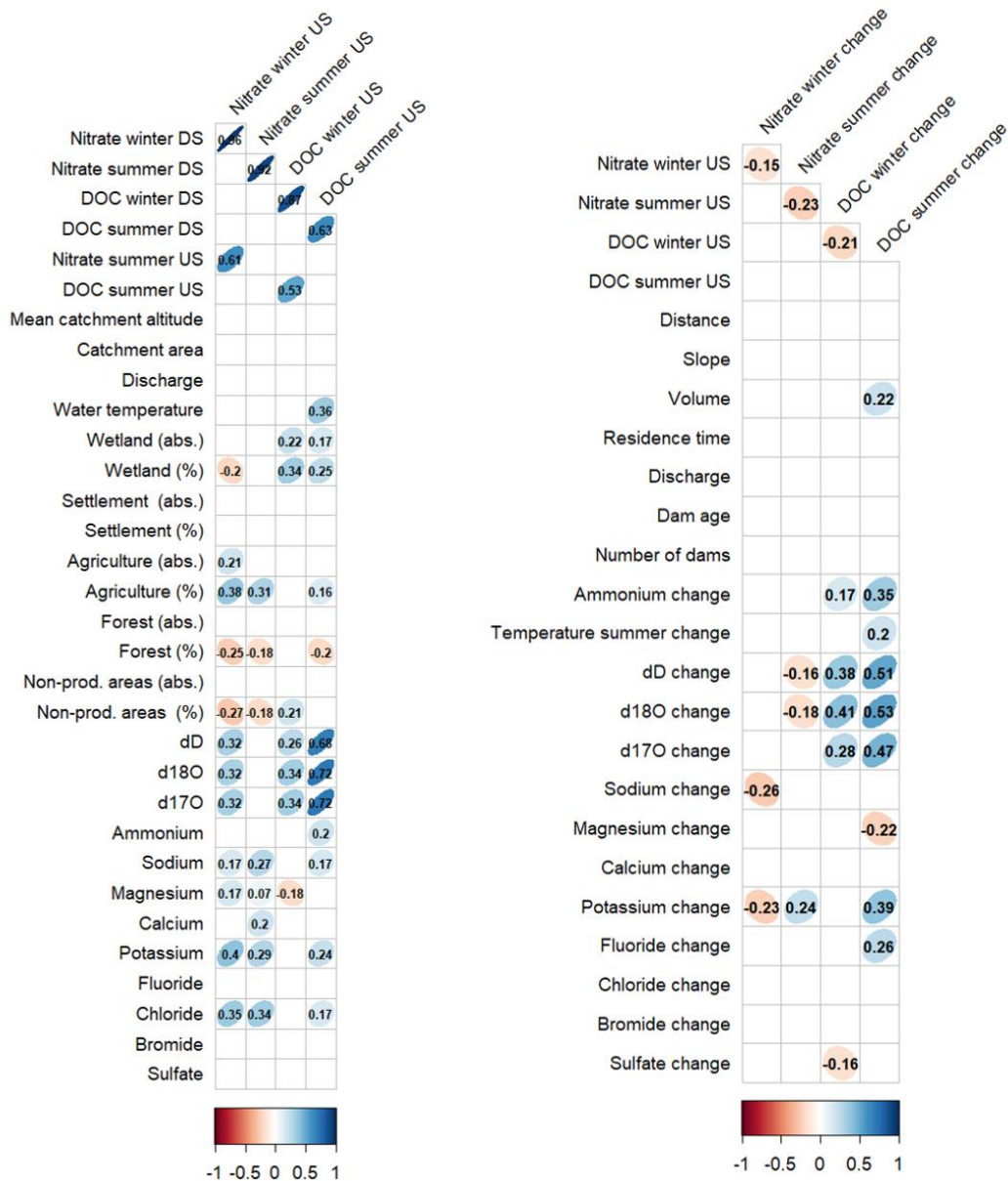


Figure 9: All significant (p -value < 0.05) Pearson correlation coefficient between the changes in nitrate and DOC concentrations in summer and winter (left), and from US to DS (positive values indicating an increase) (right), and catchment characteristics (left), and beaver system characteristics (right).

Interpretation

Greater ponds volumes exhibit a positive correlation with an elevated Dissolved Organic Carbon (DOC) concentration, a vital component in the aquatic food chain. The quality of DOC is equally crucial, dictating its pace of uptake as a food source. The observed downstream increase in DOC implies its probable derivation from decomposition of Particulate Organic Carbon (POC),

such as decaying vegetation, thereby constituting an enhancement for food webs downstream. Moreover, the dataset indicates the effectiveness of beaver wetlands in mitigating Nitrate in surface water improves with higher initial concentrations.

1.6 The role of connected beaver wetlands

Noticeable are the correlations of the relative and absolute sizes of wetland areas within the buffer polygons with a coherent decrease in nitrate and increase in DOC concentrations. Those correlations are stronger in summer than in winter. In summer the correlation is significant (p-value < 0.05).

Table 4: Correlations between wetlands and concentration changes. Correlations of the eight wetland categories (buffer 50 m, 25 m, 10 m and 5 m absolute and relative) with the changes in nitrate and DOC concentrations.

	Nitrate change winter	Nitrate change summer	DOC change winter	DOC change summer
Correlation	- 0.12 to 0.00	- 0.31 to - 0.18	0.05 to 0.15	0.25 to 0.39
Median:	- 0.08	- 0.25	0.12	0.32
Significant	No	Yes	No	Yes

Out of the 165 sampled beaver dam reaches, 25 beaver dam reaches were found to have wetlands within a 50 m buffer around the rivers. These 25 beaver dam reaches are distributed across Switzerland. The connectivity classification revealed that in 14 out of the 25 beaver dam reaches, the wetland is directly connected to the river. In terms of water quality, all these 14 beaver dam reaches with wetland-river connectivity show a consistent pattern of decreasing nitrate concentrations (median: -3.56 mg/l) and increasing DOC concentrations (median: 1.05 mg/l) in summer. Similarly, in winter, there is also a trend of decreasing nitrate concentrations (median: - 0.17 mg/l) and increasing DOC concentrations (median: 0.20 mg/l), although it is less pronounced compared to the summer season. Only two of the 14 wetlands are made by beavers, the remaining 12 are strongly influenced by beaver damming, and in the absence of beavers, these wetlands would likely not exist, or being much smaller in size.

In addition to the consistent finding that all fourteen beaver dam reaches with wetland-river connectivity exhibit a decrease in nitrate concentration and an increase in DOC concentration during the summer season, the size of the wetlands also has an influence on the magnitude of these changes. The size of the wetlands in these beaver dam reaches ranges from 511 and 23'828

m². Larger wetland sizes are associated with an increased concentration of DOC in both seasons as well as with decreased concentration of nitrate in summer.

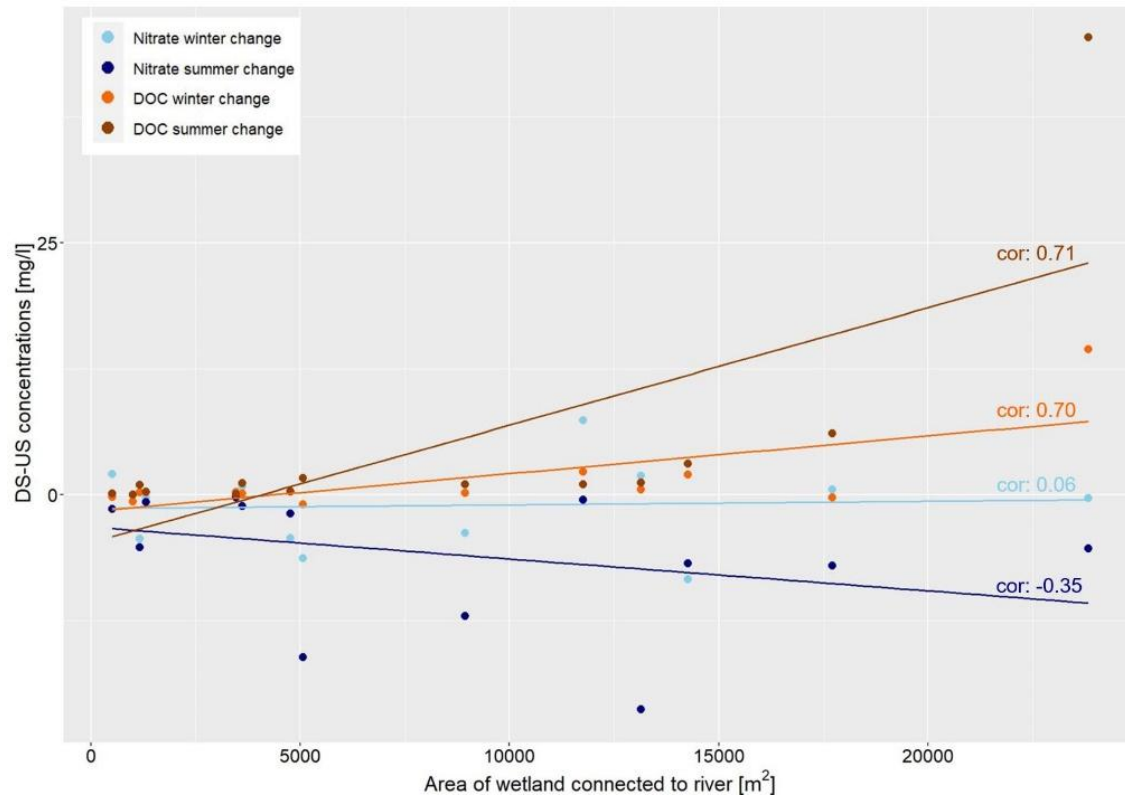


Figure 10: Wetlands size and changes in concentrations in nitrate and DOC from US and DS.

A comparative analysis between wetland connected beaver dam reaches with a reliable nitrate decrease and DOC increase in both seasons and 32 beaver dam reaches with increasing nitrate reaches in both seasons showed that wetland-river connected beaver dam reaches exhibit higher median values for variables such as distance of the beaver reach, water volume, water residence time and temperature change. On the other hand, beaver dam reaches with nitrate increases in both seasons tend to have higher median values for slope and discharge.

Table 5: Comparison between beaver wetlands and beaver dam reaches with increasing nitrate. Median values for 32 beaver dam reaches with nitrate increases in both seasons and 14 wetland-river connected

beaver dam reaches. Difference means that mean values of beaver dam reaches with increasing nitrates subtracted from beaver wetlands.

Variable	Nitrate increase in both seasons Median	Wetland-river connected Median	Difference	% change
Distance [m]	397	664	267	67
Slope [%]	0.82	0.34	-0.48	-59
Water volume [m ³]	413	939	526	127
Mean catchment altitude [m a.s.l.]	535	499	-37	-7
Residence time winter [h]	2.97	16.09	13.12	442
Residence time summer [h]	9.96	51.14	41.18	413
Discharge winter [l/s]	69.6	19.5	-50.1	-72
Discharge summer [l/s]	18.6	4.0	-14.6	-78
Dam age	2022	2021	-1	0
Number of dams	2	2	0	0
Temperature US [°C]	17.25	18.35	1.1	6
Temperature change [°C]	0.15	0.45	0.3	200

Connected beaver wetlands as a key for water quality improvement

It is well known that wetlands can reduce nitrate concentrations and increase DOC concentrations in aquatic systems. However, our analysis shows that beaver modifications of existing wetlands increase the ability of wetlands to remove nitrate from surface waters and increase DOC loads downstream. In general, the size and connectivity of the wetlands matter for the amount of nitrate removal and increase in DOC loads, and this trend is more pronounced in summer. Wetland beaver dam reaches were found to have a longer distance (+ 67 %), higher water volume (+ 127 %), and longer water residence time (+ 442 % in winter, + 413 % in summer) than beaver dam reaches with the opposite effect on water quality. Beaver wetlands also had a lower slope (- 59 %) and discharge (- 72 % in winter, - 78 % in summer). The lower slope and discharge, along with the extended water residence time, suggest reduced water turbulence, which increases the potential for anaerobic conditions and therefore a reduction of nitrate. Wetlands process nitrogen through a variety of biological, chemical and physical mechanisms and support most natural conversions of nitrogen. The close coupling of aerobic and anaerobic conditions in wetland soils combined with a high rate of plant productivity and organic metabolic activity creates conditions favorable for the conversion of nitrate to atmospheric gases by denitrification. The increase in DOC corresponds to the observations made by BAFU (Hrsg.) (2022), identifying wetlands as source of DOC due to enhanced aquatic net ecosystem production in the lentic environments.

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Appendix

Appendix A: Instructions water sampling (info fauna – Biberfachstelle 2020)

Nationale Biber-Bestandeserhebung 2021/2022 	Nationale Biber-Bestandeserhebung 2021/2022 
Anleitung zur Wasser Probennahme während der nationalen Biber-Bestandeserhebung 2021/2022 Ziel des Teilprojekts « Wasserqualität » Die Wasserstauung des Bibern verändert die Wasserqualität auf verschiedene Weise. Um diese Veränderungen erfassen und bewerten zu können, werden während der Biber-Bestandeserhebung 2021/22 auch Wasserproben genommen. Diese Wasserproben werden teilweise an der eawag (Wasserforschungsinstitut des ETH-Bereichs) in Dübendorf, und an der Universität Bern analysiert. Dabei werden vor allem Nährstoffe in den Fokus genommen (C, N, P). Diese Untersuchung wird zeigen, ob und wo Biberdämme die Wasserqualität beeinflussen, und wenn ja, wo sie am effektivsten sind und ob man Biber gezielt als Ökosystemdienstleister einsetzen kann. Die Grundsätze und Anforderungen an die Kartierenden für dieses Teilprojekt sind die gleichen wie die Anleitung für die Feldarbeit der nationalen Biber-Bestandeserhebung, da diese auch zusammen durchgeführt werden. Wichtig: Sicherheit kommt immer zuerst! Vorbereitung zu Hause Eine gute Vorbereitung der Behälter für die Wasserprobe ist Voraussetzung für eine erfolgreiche Durchführung der Probenahme. Hierzu gehört die Zusammenstellung der Materialien: 1. Falcon tubes (Plastik, blauer Deckel, Zentrifugenform) 3 Falcon Tubes pro Beprobungspunkt, also je drei Flaschen oberhalb eines Bibersees (Nährstoffe, Ammonium und DOC) und drei Flaschen unterhalb eines einzelnen Biberdamms oder einer ganzen Biberdammkaskade (Nährstoffe, Ammonium und DOC).  (zu Hause vorbereiten: mit Malertape umwickelt) Falcon Tube (Proben für Nährstoffe, Ammonium und DOC)	2. Kleine Glasflaschen, entweder mit schwarzem, grünem oder blauem Deckel (alle drei Farbvarianten vorhanden) – je 1x pro Beprobungspunkt, also je eine Flasche oberhalb und eine Flasche unterhalb eines einzelnen Biberdamms oder einer ganzen Biberdammkaskade. Vorsicht - diese Flaschen brechen leicht, und frieren auf, wenn sie Temperaturen unter 0 ausgesetzt sind, da sie nach der Beprobung komplett gefüllt sind (mit Malertape umwickelt).  Kleine Glasflaschen (Proben für Stabile Isotope) 3. Große Plastikflaschen mit rotem Deckel – 1x pro Beprobungspunkt, also je eine Flasche oberhalb und eine Flasche unterhalb eines einzelnen Biberdamms oder einer ganzen Biberdammkaskade (mit Malertape umwickelt).  Große Plastikflasche (Proben für Sedimenttransport) 4. Spritzen-Filter, steril – 1 bis 3 pro Beprobungspunkt, je nachdem wie schnell die Filter mit Sedimenten verstopfen. Bitte Filter in sauberer Plastiktüte aufbewahren, und nicht mit schmutzigen Fingern anfassen. Plastiktüten immer gut schließen. So sauber wie möglich halten.  Spritzen-Filter

5. Spritze (1 x pro Tag), Spritze wechseln, wenn Gewässer gewechselt werden



Spritze, steril verpackt

Beschriftung - Vorbereitung

1. Falcon Tubes und kleine Glasflaschen mit Malertape umwickelt, um eine Beschriftung zu ermöglichen.
2. Permanent marker/Eding in schwarz benutzen.
3. Deutlich (!) schreiben.
4. Protokollblatt für Wasserbeprobung während der Biber-Bestandserhebung 2021/2022 mitnehmen.
5. Koordinaten falls vorhanden mit GPS oder GPS-fähigem Smartphone oder möglichst genau aus Feldkarte 1:10'000 herauslesen.

Beschriftung – Im Gelände

1. Nicht vergessen: Protokollblatt für Wasserbeprobung während der Biber-Bestandserhebung 2021/2022 an jeder Beprobungsstelle ausfüllen, und den Ort der Probenahme mit Name des Beprobungsortes (siehe Punkt 2) in die Feldkarte 1:10'000 eintragen (das ist wichtig, da GPS-Koordinaten besonders im Wald oft sehr ungenau sind).
2. Name des Beprobungsorts. Die Beschriftung der Wasserproben folgt der *Anleitung zur Beschriftung der verschiedenen Spurentypen und Proben*. Zusammengefasst gilt: Die Wasserproben werden oberhalb des ersten Damms genommen, wo der Bach noch fließt, also bevor der Staubeereich des Biberdamms beginnt (zum Beispiel US_BE_AEG1_1_9). Die zweite Probe liegt unterhalb des letzten Damms wieder in der Fließstrecke (zum Beispiel DS_BE_AEG1_1_1). Um es etwas deutlicher zu machen, WO und WIE Wasserproben zu nehmen, bitte folgende Videos anschauen:
- [Standortwahl für Wasserprobenentnahme](#)
- [Verschiedene Wasserprobenentnahmen](#)
3. Probenotyp. Es gibt 5 verschiedene Probenotypen, die unterschiedliche Beprobung und Aufbewahrung verlangen. Daher müssen die Proben auch mit der Abkürzung des Namens des Probenotyps (Punkt 3) versehen werden - und nicht nur mit dem Beprobungsort (Punkt 2). Diese Abkürzungen können auch auf dem « Protokollblatt für Wasserbeprobung während der Biber-Bestandserhebung 2021/2022 » gefunden werden. Es handelt sich um folgende:

- 3 -

Probenotyp	Beschriftung auf Flasche	Flaschentyp	Beprobungstyp
Sediment Transport	Sediment	Grosse Flasche mit rotem Deckel	unfiltriert
Stabile Isotope	SI	Kleine Glasflasche mit blauen und schwarzen Deckeln	unfiltriert
Nährstoffe/Nitrat	N	Falcon tube	filtriert
Ammonium	A	Falcon tube	filtriert
Dissolved Organic Carbon	DOC	Falcon tube	filtriert

4. Datum und Uhrzeit im Format: 25/12/21, 12:35

Auf einer fertig beschrifteten Falcon Tube in der DOC aufbewahrt wird und oberhalb des Biberreichs in der frei fließenden Strecke beprobt wurde, würde demnach das Folgende geschrieben sein:

DOC US_BE_AEG1_1_9 25/12/2021 12:35

5. Auf dem Protokollblatt werden dann folgende Informationen für diese Probe eingetragen:

Nationale Biber-Bestandserhebung 2021/2022

Protokollblatt für Wasserbeprobung während der Biber-Bestandserhebung 2021/2022

Bachabschnitt (Adresse): Ort: Koordinate: Datum: Uhrzeit: Probenotyp: Flaschentyp: Beprobungstyp: Beobachtung:

1. US_BE_AEG1_1_9 25/12/2021 12:35 DOC US_BE_AEG1_1_9 25/12/2021 12:35

Aufbewahrung der Proben

Probenotyp	Beschriftung auf Flasche	Flaschentyp	Aufbewahrung	Aufbewahrung bis wann
Sediment Transport	Sediment	Grosse Flasche mit rotem Deckel	Ohne Sonnenlicht, kühl (z.B. Keller)	März 2022 (wird abgeholt)
Stabile Isotope	SI	Kleine Glasflasche	Kühlschrank	März 2022 (wird abgeholt)
Ammonium	A	Falcon tube	-20°C Gefrierschrank	März 2022 (wird abgeholt)
Nährstoffe/Nitrat	N	Falcon tube	4°C Kühlschrank	Maximal 1 Woche
Dissolved Organic Carbon	DOC	Falcon tube	4°C Kühlschrank	Maximal 1 Woche

- 4 -

Versenden der Proben

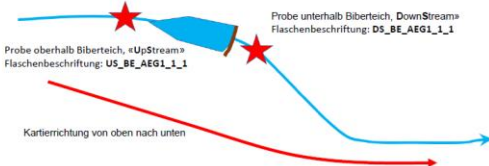
1. DOC und N Proben müssen mit einem Kühlaggregat (Kühlaggregate im Gefrierfach vorkühlen) als Paket verschickt werden (wenn keine Schachtel vorhanden ist können entweder PostPac Öko 0 (2.50) oder PostPac Öko 1 (2.70) verwendet werden. Pakete bis 2 kg als A-Post versenden). Einen kleinen Zettel beilegen, auf dem der Probenname der mitgeschickten Proben nochmals geschrieben steht, um Missverständnisse durch Handschrift zu vermeiden.
2. Proben müssen Montag, Dienstag oder Mittwoch am Nachmittag/Abend mit der letzten Post in Richtung eawag (Dübendorf) raus gehen. Spätestens sollen sie aber eine Woche nachdem sie beprobt wurden abgeschickt werden. Die Proben sollen sich so kurz wie möglich im Transport befinden, daher sollen sie mit der letzten Fracht am Tag in Richtung Labor aufbrechen, da sie dann am nächsten Morgen im Labor eintreffen. Die letzte Postabholung kann regional unterschiedlich sein. Wir empfehlen die Proben kurz vor 16 h auf die Post zu bringen, oder eben kurz bevor die letzte Fracht am Tag abgeholt/versendet wird.
3. Bitte alle DOC und N Proben an folgende Adresse versenden:

Eawag
AuA Labor (FX-D13) (Biber Projekt)
Überlandstrasse 133
8600 Dübendorf

Wo beproben? (Beprobungsort/Flaschenbeschriftung)

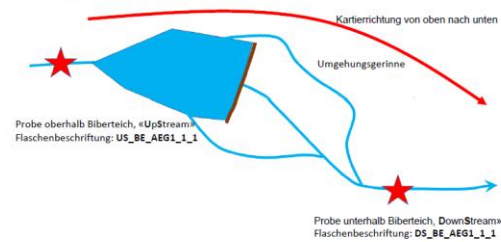
Die Wasserproben werden oberhalb des ersten Damms eines Reviers genommen, wo der Bach noch frei fließt, also bevor der Rückstaubeereich des Biberdamms beginnt (« backwater effect »). Die zweite Probe liegt unterhalb des letzten Damms in der Fließstrecke (entweder ist nur ein Dam in der Biberrevier oder mehrere Dämme, also eine Dammkaskade). Bitte aufpassen, dass unterhalb/bachabwärts von vom Biber angelegten Seitengewässern beprobt wird. Um das etwas anschaulicher zu machen, bitte das Video zur [Wahl der Beprobungsstandorte](#) anschauen.

Bachabschnitt mit 1 Biberdamm

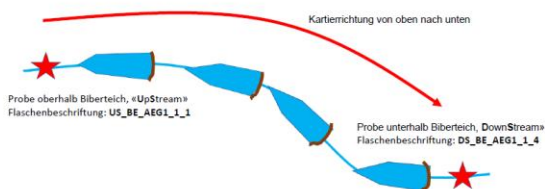


- 5 -

Bachabschnitt mit 1 Biberdamm und Umgehungsgerinne



Bachabschnitt mit mehreren Biberdämmen, Biberdammkaskade



Wie beproben? (5 Wasserproben im Gelände beproben)

Sedimenttransportprobe: Die große Flasche mit dem roten Deckel erst beschriften, dann 3 x am Beprobungsort ausspülen (wird im Video im Abschnitt [Sedimenttransport](#) gezeigt), indem Bachwasser bachaufwärts im Stromstrich in die Flasche genommen wird, die Deckel zugemacht werden, die Flasche geschüttelt wird, und das Wasser bachabwärts wieder in den Bach zurück geschüttet wird. Anschließend aus dem Stromstrich/aus dem fließenden Wasser eine Probe entnehmen, dabei aufpassen, dass keine Verunreinigung des Wassers (Aufwirbelung von Sediment) durch einen selbst entsteht, Deckel drauf machen, und kühl und dunkel lagern.

- 6 -

Stabile Isotope: Die kleine Glasflasche mit blauem und schwarzem erst beschriften, dann 3x ausspülen (genau wie bei der Sedimenttransportprobe, wird im Video im Abschnitt [Stabile Isotope](#) gezeigt). Für die Probennahme die kleine Flasche aufrecht im fließenden Wasser komplett versenken, so dass alle Luft entweichen kann. Dabei kein Sediment aufwirbeln. Durch die Spannung des Wassers bildet das Wasser eine uhrglasförmige Oberfläche auf der Flasche. Vorsichtig den Deckel draufschräuben, und durch das Umdrehen der Flasche überprüfen, ob sich eine Luftblase in der Flasche gebildet hat. Falls ja – die Probennahme bitte wiederholen. Es darf keine Luft eingeschlossen sein. SI-Proben sollen im Kühlschrank aufbewahrt werden. Am besten in einem Container (da sie leicht umfallen und brechen) – und auf keinen Fall bei Minusgraden, da sie sofort auffrieren und zerbrechen.

Falcon Tubes (DOC, A, N): Zugespitzte Plastikflaschen mit blauem Deckel. Alle drei Proben werden mit der gleichen Methode genommen – sie werden filtriert. Bitte erst alle Falcon Tubes beschriften. Falcon Tubes und Filter sind steril, und müssen nicht gewaschen werden. Die Spritze 3x im fließenden Wasser auswaschen (genau wie bei der Sedimenttransportprobe, wird im Video im Abschnitt [Ammonium, Nährstoffe, DOC](#) gezeigt). Die Spritze kann wieder verwendet werden, solange man sich im gleichen Gewässer aufhält. Man sollte sie aber maximal einen Tag lang benutzen. Nach dem Waschen der Spritze mit Bachwasser, wird Wasser in die Spritze gesaugt, und anschließend der Drehfilter drauf geschraubt. Der Filter sollte dabei möglichst trocken und sauber gehalten werden. Dann werden ein paar Tropfen Wasser aus der Spritze durch den Filter gedrückt, um diesen zu reinigen. Anschließend wird das Wasser in der Spritze durch den Filter in die Falcon Tubes gedrückt, bis diese circa dreiviertel voll sind. Filter können sich durch Sediment zusetzen – dann geht kein

Wasser mehr durch. In diesem Falle bitte einen neuen Filter benutzen. Wenn das nicht der Fall ist, kann für alle drei Falcon Tubes der gleiche Filter benutzt werden: Er wird einfach abgeschraubt, neues Wasser in die Spritze gezogen, der Filter wieder draufgeschraubt, und weiter beprobt. Anschließend ist der Filter verschmutzt und muss entsorgt werden. Bitte den Filter auf keinen Fall am nächsten Beprobungspunkt nochmal benutzen! DOC und N werden im Kühlschrank aufbewahrt, A tiefgekühlt.

Appendix B: Catchment delineation

Table B1: Different methods to calculate the catchment polygons.

Program	Tools	Resolution DTM	Preprocessing DTM?	Outlet point	Quality of resulting polygon
ArcMap	Spatial Analyst	0.5 m	No	DS coordinate	Poor
ArcMap	Spatial Analyst	0.5 m	Yes	DS coordinate	Good
ArcMap	Spatial Analyst	2 m	Yes	DS coordinate	Good
QGIS	GRASS	2 m	Yes	manually, in the region of the DS coordinate	Good

Table B2: Preprocessing (burning) of DTM for catchment delineation.

Preparation	- Open Q-GIS with GRASS - Add DEM and polyline river layer
Rasterize the river network	- Tool: Rasterize (vector to raster) - Input layer: Polyline river network - A fixed value to burn: 1 - Output raster size units: Georeferenced units - Width/Height: 2 m (pixel size) - Output Extent: DEM - Output data type: Byte - Save to file: Rasterized.tif - Other parameters: default
Reclassify	- Tool: Reclassify by table - Raster Layer: Rasterized.tif - Reclassification table: Min. 1 / Max. 1 / Val. 1 - Range boundaries: min <= value <= max - Save to file: Rasterize_reclass.sdat - Other Parameters: default
Statistics	- Tool: Raster Layer Statistics - Input: DEM - Save to temporary file - Open html file and note min. and max. value
Standardized DEM	- Tool: Raster Calculator - Expression: ("DEM"- min. value)/(max. value – min.value) - Output Layer: standardized_dem.tif
Burn river in DEM	- Tool: Raster calculator - Expression: "standardized_dem.tif"- "Rasterize_Reclass.dat" - Output Layer: Standardized_burn
DEM_burned	- Tool: Raster calculator - Expression: "DEM"*"Standardized_burn" - Output Layer: DEM_burned

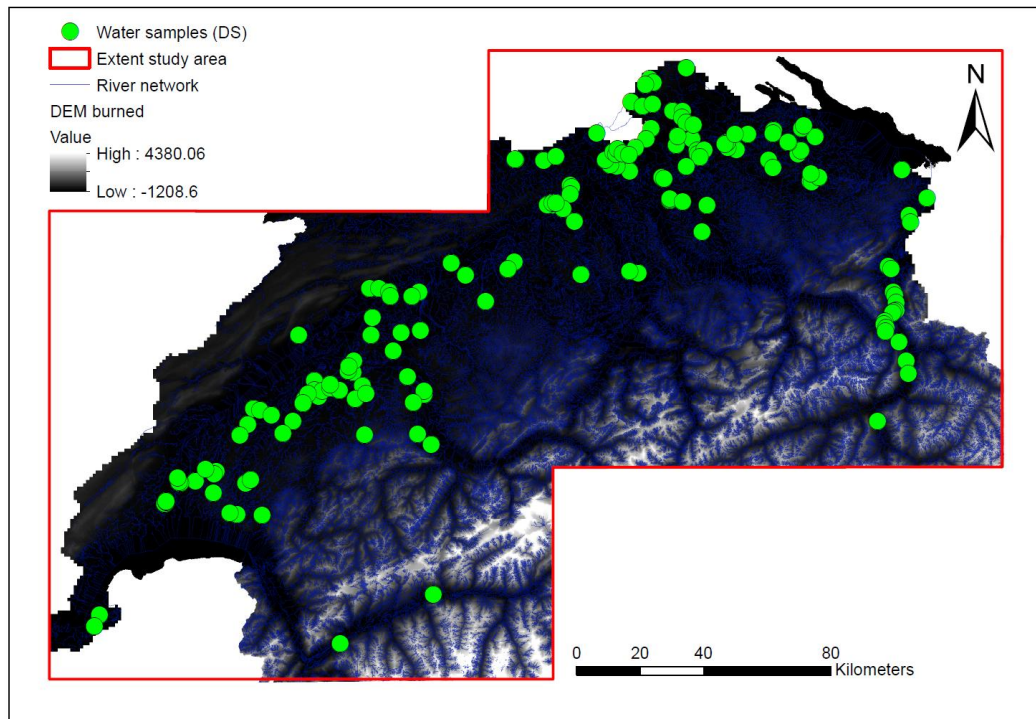


Figure B1: Data basis for catchment area calculations in QGIS. DEM burn calculated on the basis of (swisstopo, 2022 (Basemap: (swisstopo, 2022)).

Table B3: ArcMap steps for catchment delineation.

Preparation	- Open ArcMap 10.7.1 - Add DEM_burned - Add the point shapefile of the DS coordinate
Filling sinks	- Tool: Fill (spatial analyst) - Input surface raster: DEM_burned - Output surface raster: DEM_filled.tif - Z limit: default
Calculate the Flow Direction to the steepest downslope neighbour raster cell	- Tool: Flow direction (spatial analyst) - Input surface raster: DEM_filled.tif - Output flow direction raster: FlowDir.tif - Other parameters: default
Calculate the accumulated flow into each cell	- Tool: Flow Accumulation (spatial analyst) - Input flow direction raster: FlowDir.tif - Output accumulation raster: FlowAcc.tif
Snap points to the cell of highest flow accumulation in 2 m distance	- Tool: Snap Pour Point (spatial analyst) - Input raster or feature pour point data: Point shapefile of the DS water sample coordinate - Input accumulation raster: FlowAcc.tif - Output raster: spp.tif - Snap distance: 2
Calculate the upslope water contributing area	- Tool: Watershed (spatial analyst) - Input flow direction raster: FlowDir.tif - Input raster or feature pour point data: spp.tif - Output Raster: watershed.tif
Converting the watershed raster into polygons	- Tool: Raster to Polygon (conversion) - Input raster: watershed.tif - Output polygon features: catchment_poly - Other parameters: default

Appendix C: GIS volume calculation tools

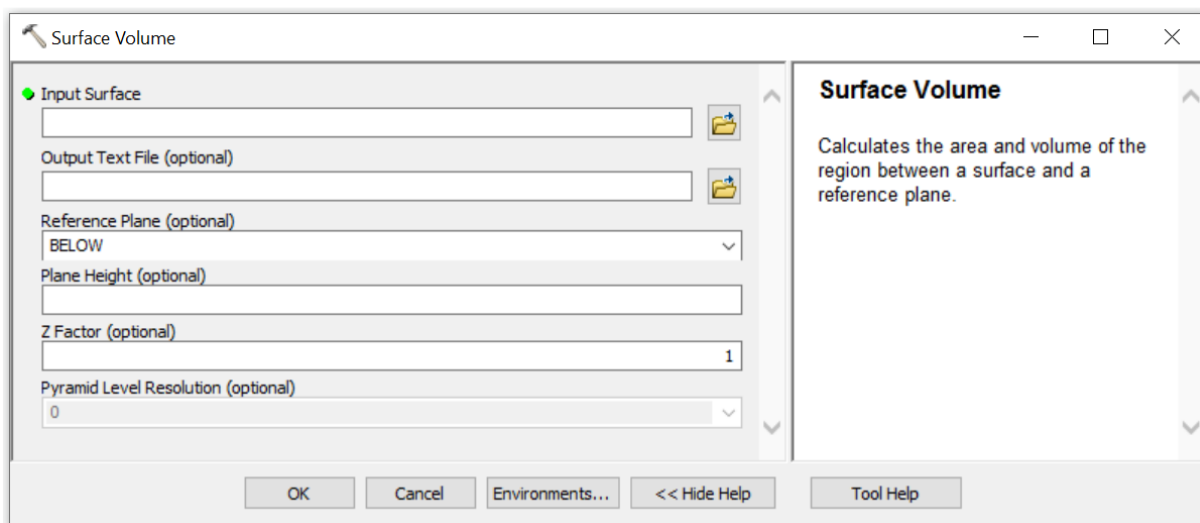


Figure C1: Surface Volume tool in ArcMap. The input surface is the DEM clipped to the beaver reach area and the plane height is the altitude of the top of the beaver dam.

Volume Calculation Tool

Input Layers

Areas (Polygon Layer): [Dropdown]

DEM Height Layer: [Dropdown] Band: [Dropdown]

Define base level height

Choose type of base height: [Dropdown] (Manually enter base level)

DEM Base Layer: [Dropdown] Band: [Dropdown]

0.00 [Spin] Base Level (m)

Type of Volume Calculation

☐ Simple Mean Value (fast, but problematic at cut/fill)

☒ Accurate Approximation (slower, but more options)

Counting Method: [Dropdown] (Count only below (eg. gravel pit))

Sampling Step Size: X: 0.20 [Spin] Y: 0.20 [Spin]

Decimal Places in Output: 1 [Spin]

Optional Output Options

☒ Add/Update Volume As Field

Above Name: V_above [Text]

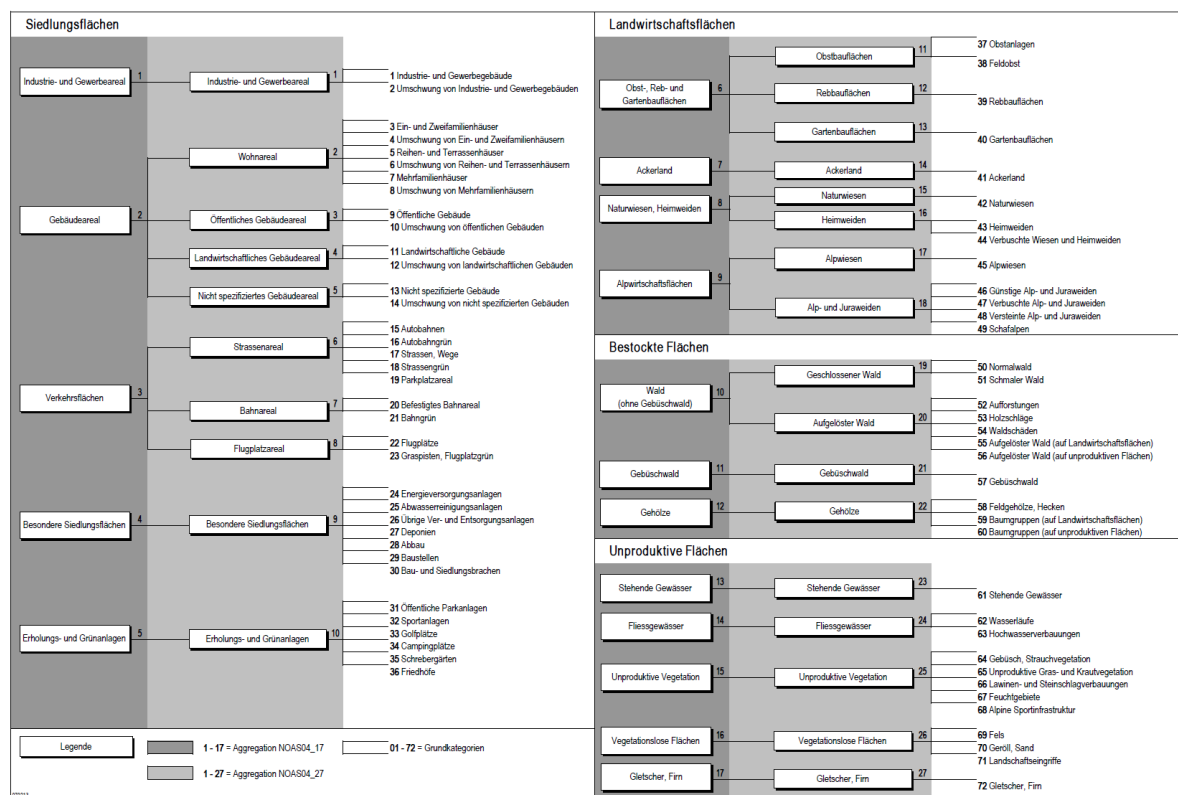
Below Name: V_below [Text]

Log

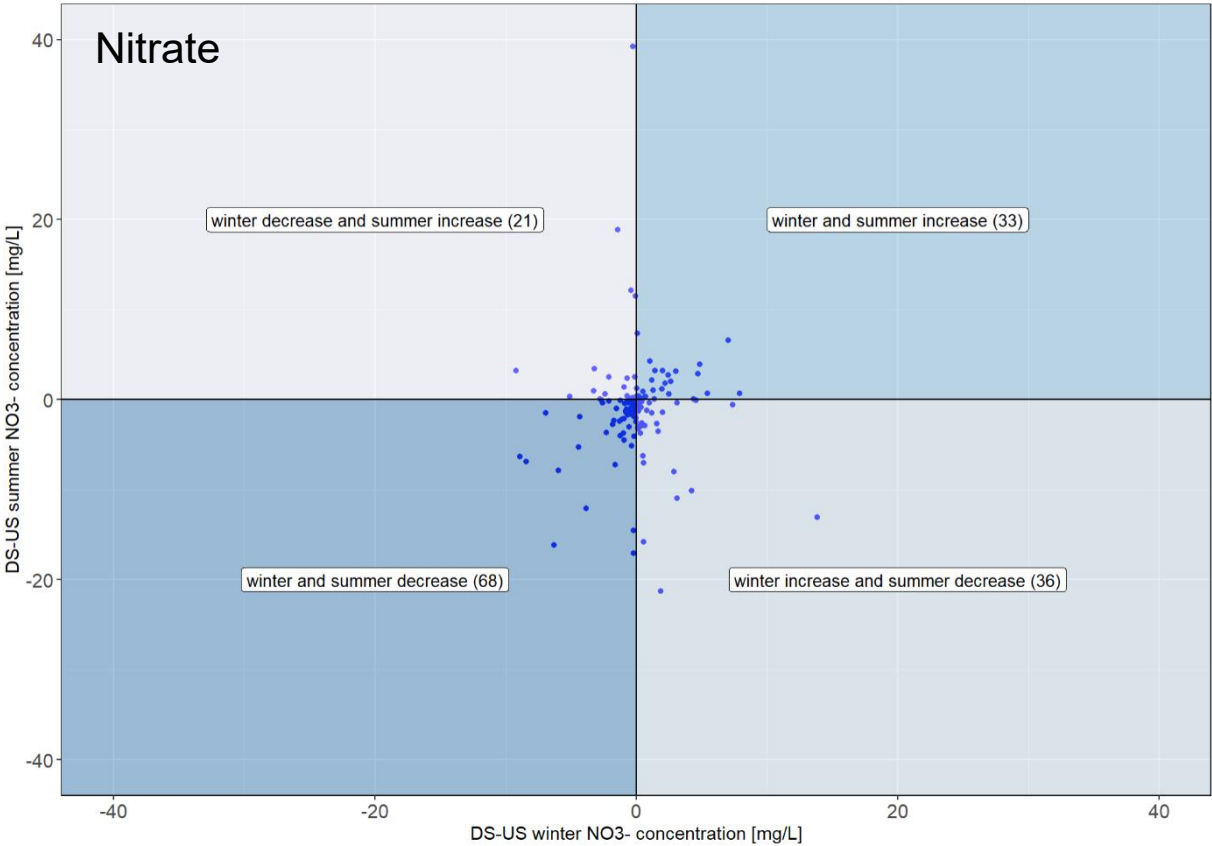
[Run] [Cancel] [Save Log] [Clear Log] [Help] [About] [Close]

Figure C2: Volume Calculation Tool from QGIS. The area is a polygon around the beaver reach extracted from the aerial image and the DEM height layer is the DEM clipped to this polygon. The base level is identical to the plane height in the ArcMap.

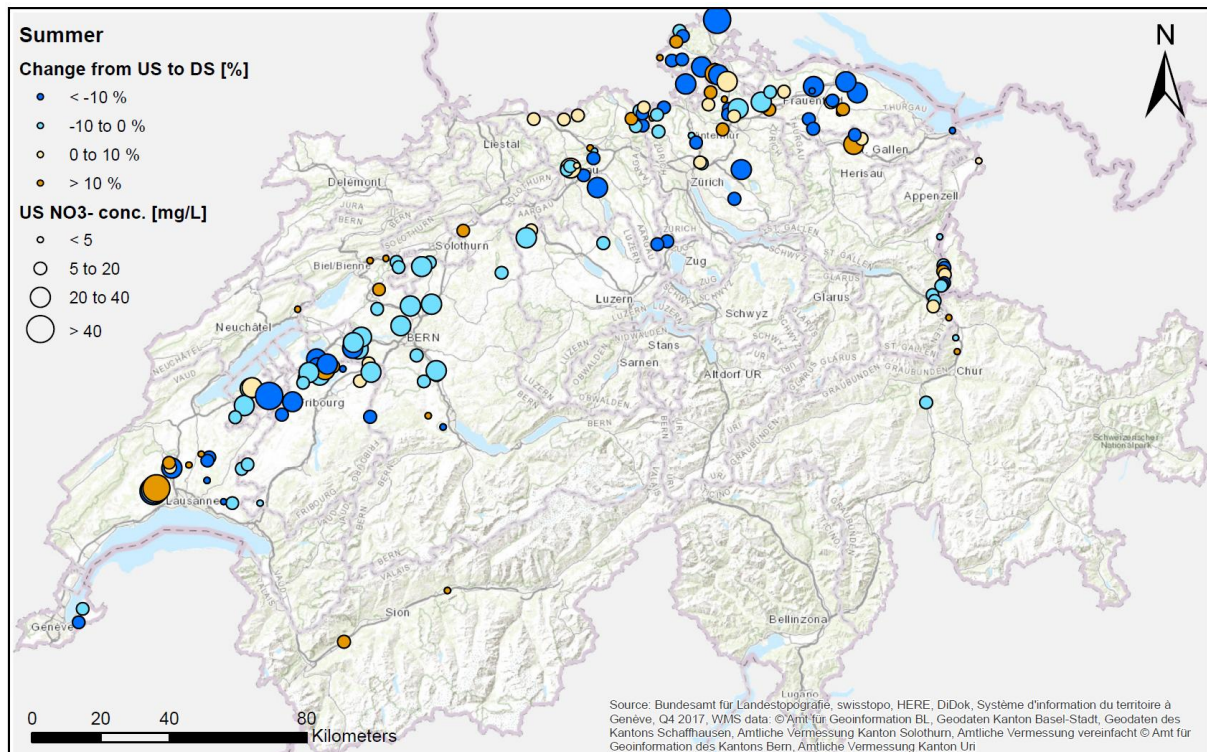
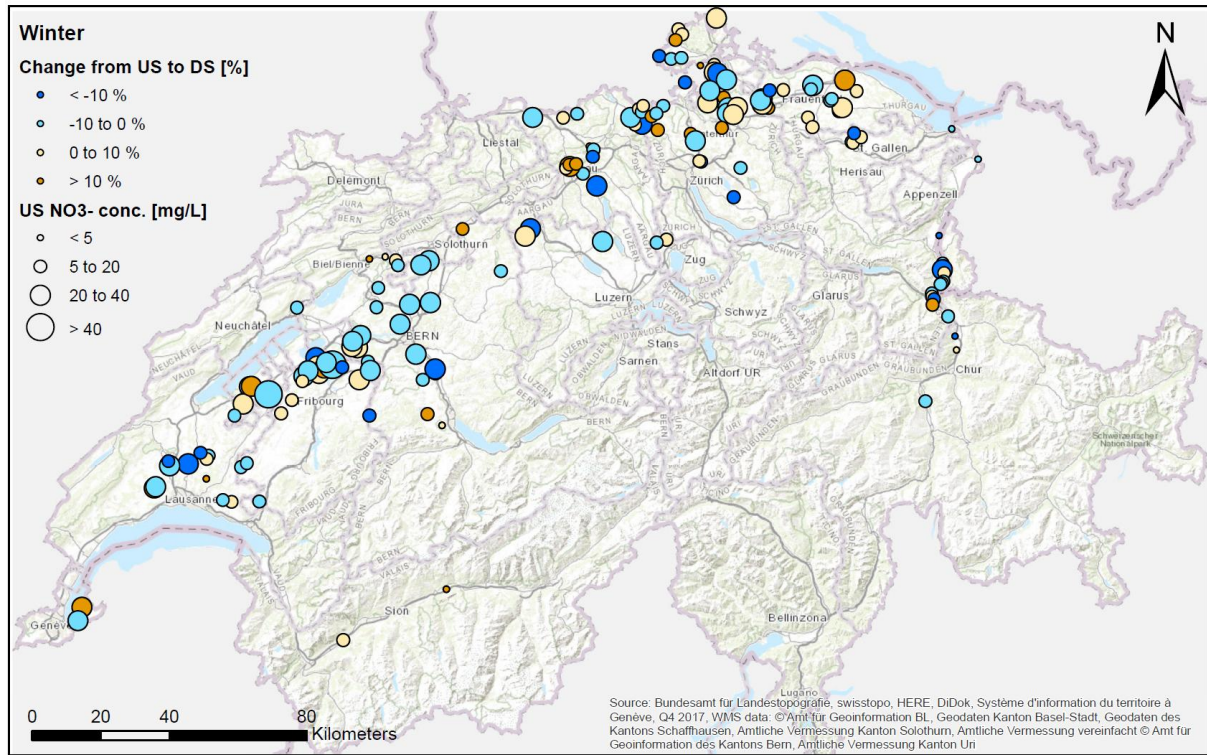
Appendix D: Area statistics Switzerland - Standard nomenclature NOAS04



Appendix E: DS - US nitrate concentrations in winter and summer (with outliers)



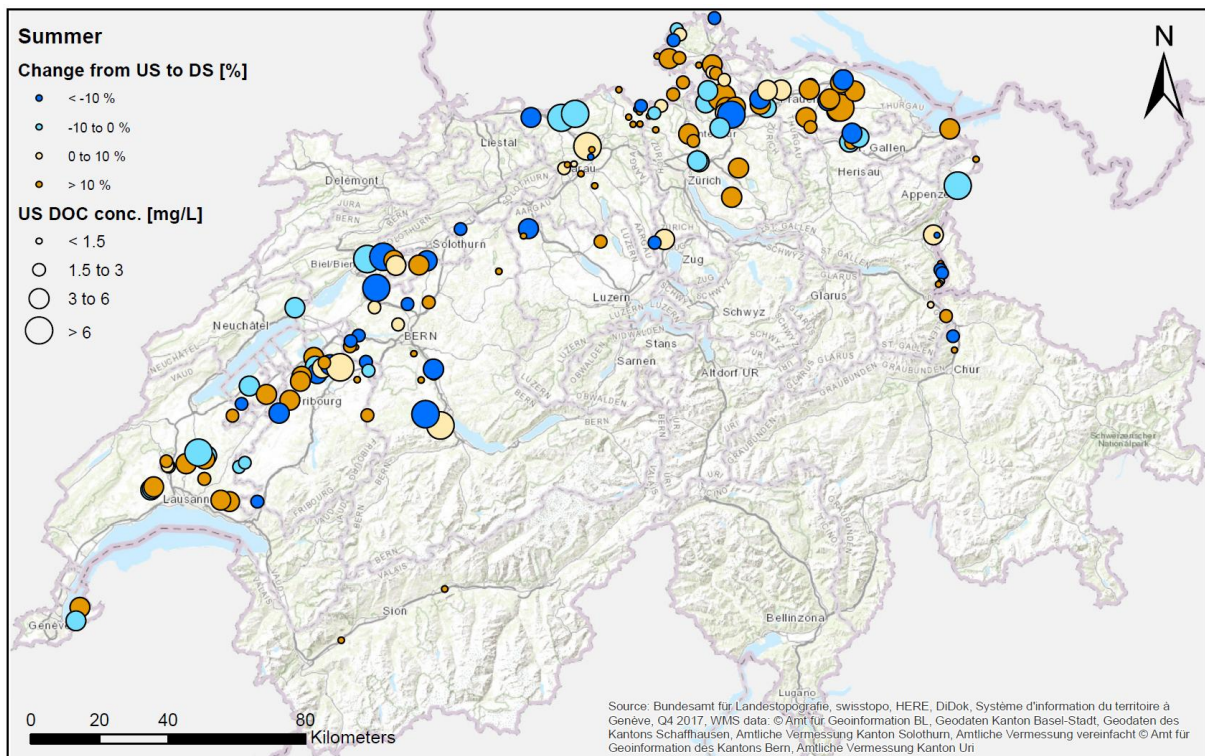
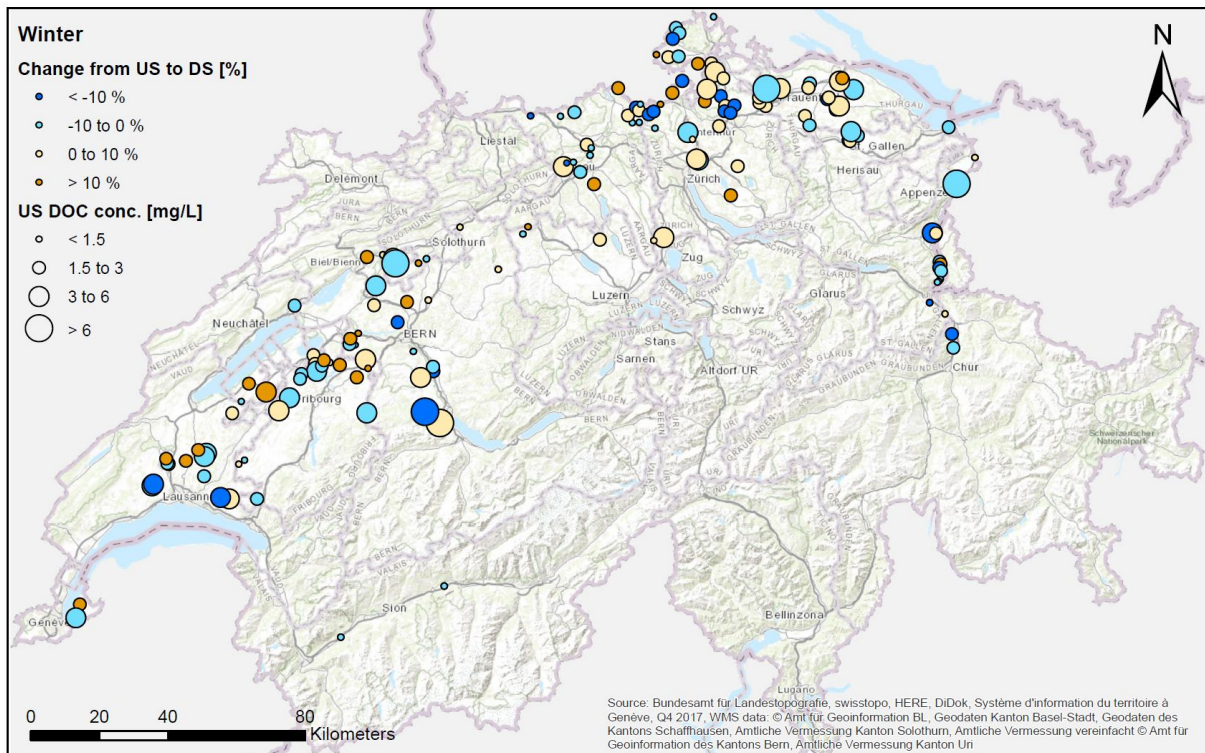
Appendix F: Relative changes in nitrate concentrations



Appendix G: DS - US DOC concentrations (outlier values > 2 mg/l)

Beaver reach	decrease: ↓ increase: ↑	Season (W/S)	Difference (DOC DS-US) [mg/l]
10	↓	S	-2.59
19	↑	S	3.06
36	↑	S	6.07
67	↑	W & S	14.39 / 45.37
81	↑	S	2.89
83	↑	S	2.05
86	↑	S	2.02
93	↑	S	3.23
95	↑	W	2.24
107	↑	W	2.26
141	↑	S	2.35
151	↑	S	2.35
155	↑	S	2.49

Appendix H: Relative changes in DOC concentrations



Appendix I: Results ammonium analysis

From the 660 measured ammonium samples, 242 samples (78 US winter, 68 DS winter, 56 US summer and 40 DS summer) were below the detection limit of 0.02 mg/l. For the purpose of analysis, a value of 0.02 mg/l was assigned to these 242 samples. Consequently, no change from US to DS could be observed for these samples, as both measurements were below the detection value (Figure I1). The median US ammonium concentration in summer is 0.005 mg/l higher than in winter. In both seasons the median is only slightly over the detection limit of 0.02 mg/l (Figure).

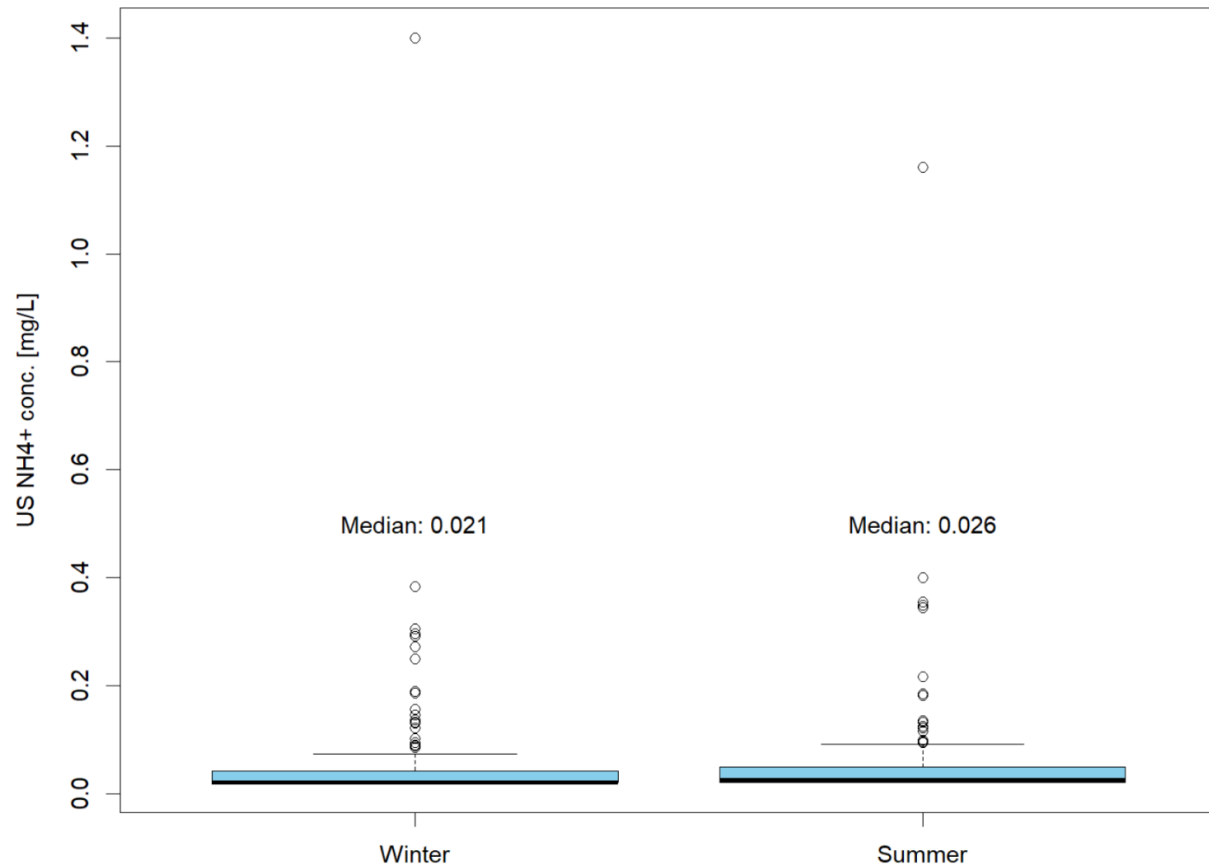


Figure I1: US ammonium concentrations in winter and summer.

In winter, a comparable number of beaver dam reaches show an increase or decrease in ammonium concentrations from US to DS, while in over a third of the reaches, no change between the US and DS concentration is observed. In summer, there is a tendency for higher ammonium concentrations DS compared to US (Figure I2).

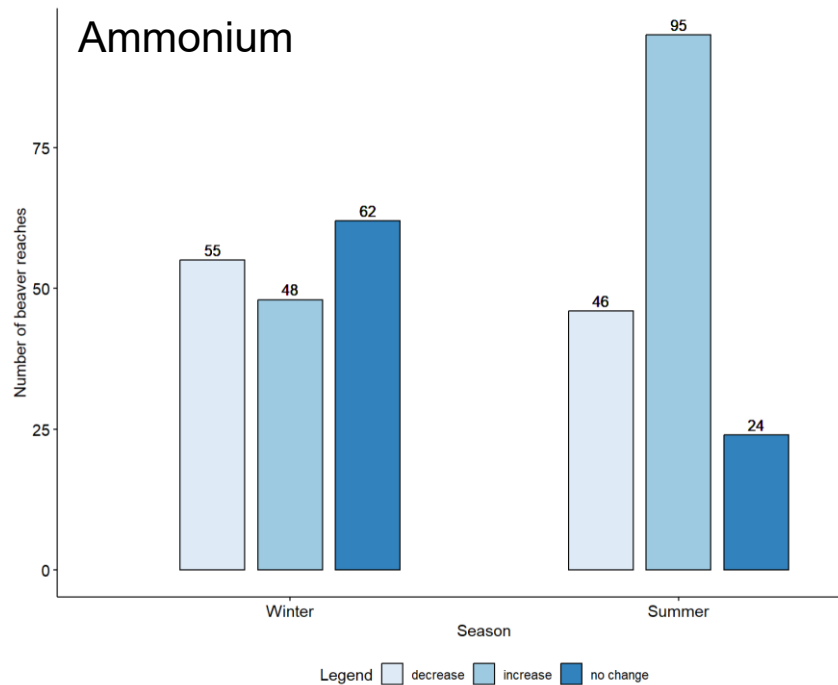


Figure I2: Change in ammonium concentrations within beaver systems. Decrease means that the DS NH_4^+ concentration is lower.

The differences in ammonium concentrations US and DS of beaver systems are mainly below 0.3 mg/l, with winter differences frequently being less than 0.05 mg/l. The majority of reaches fall into the categories where the DS summer concentration is increased (Figure I3).

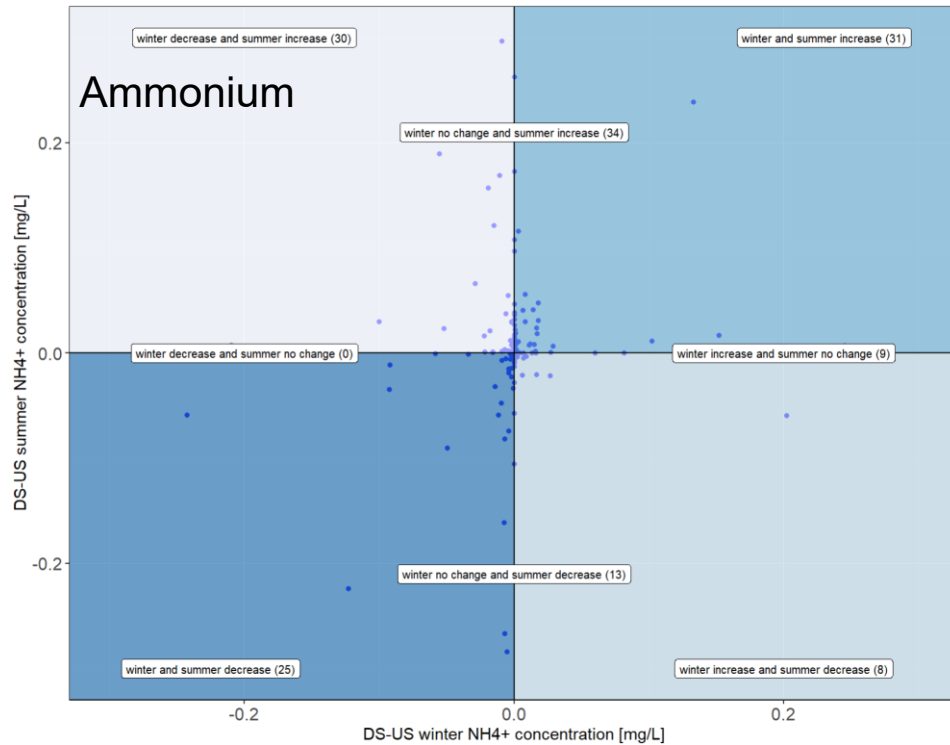


Figure I3: DS – US ammonium concentrations in winter and summer. For the sake of clarity, only differences of ± 0.3 mg/l are depicted in this graph. The outlier differences (> 0.3 mg/l) are presented in Table, with notably high differences in beaver reach Nr. 67.

Out of all the beaver dam reaches, only six of them exhibit differences in ammonium concentrations greater than 0.3 mg/l. Interestingly, all of these differences exceeding 0.3 mg/l are observed in the summer season (Table).

Table I1: Ammonium concentrations differences > 0.3 mg/l.

Beaver reach	decrease: ↓ increase: ↑	Season (W/S)	Difference (NH4+ DS-US) [mg/l]
27	↑	S	0.83
45	↑	S	0.31
65	↓	S	-0.50
67	↑	S	1.87
149	↑	S	0.75
164	↑	S	0.39

Figures below do not reveal any discernible spatial pattern in terms of US ammonium concentrations and the changes in ammonium concentrations within the beaver systems.

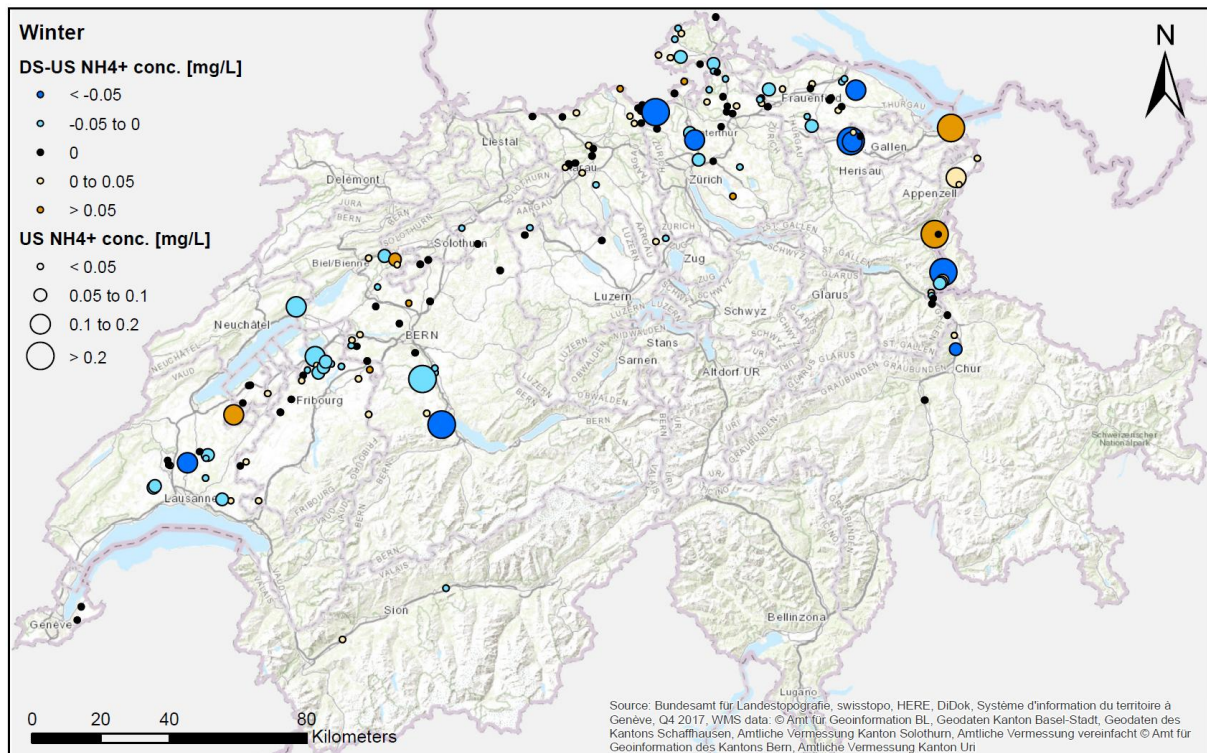


Figure 14: US ammonium concentration and concentration changes in winter. Negative values indicate lower DS concentrations. Background map: (swisstopo, 2021).

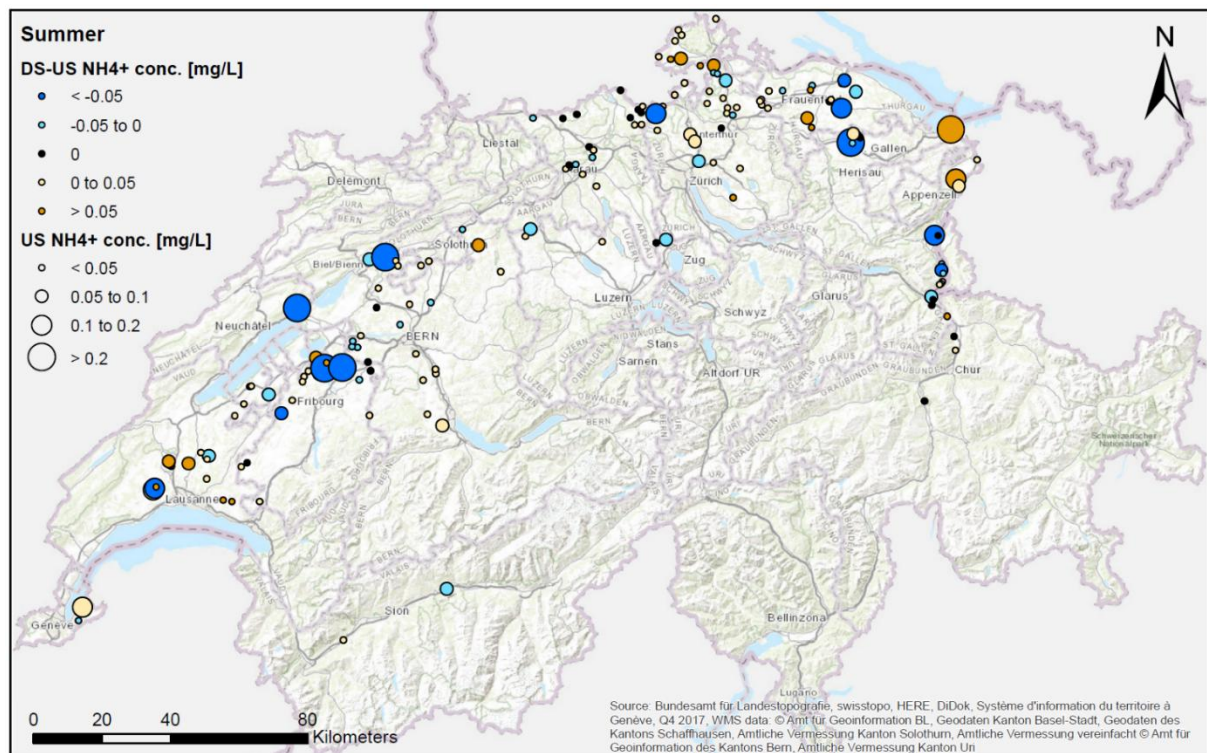


Figure 15: US ammonium concentration and concentration changes in summer. Negative values indicate lower DS concentrations. Background map: (swisstopo, 2021).

Appendix J: Concentrations in beaver dam reaches only sampled in one season

In this chapter, the results for nitrate and DOC concentrations of the beaver dam reaches which were only sampled in winter (72 reaches) or summer (7 reaches) are presented.

For the 72 beaver dam reaches sampled only in winter, the median nitrate concentration shows an increase within the beaver system of 0.04 mg/l (Figure). This is in contrast to the findings for the beaver dam reaches sampled in both seasons, where the median nitrate concentration is 0.08 mg/l lower downstream.

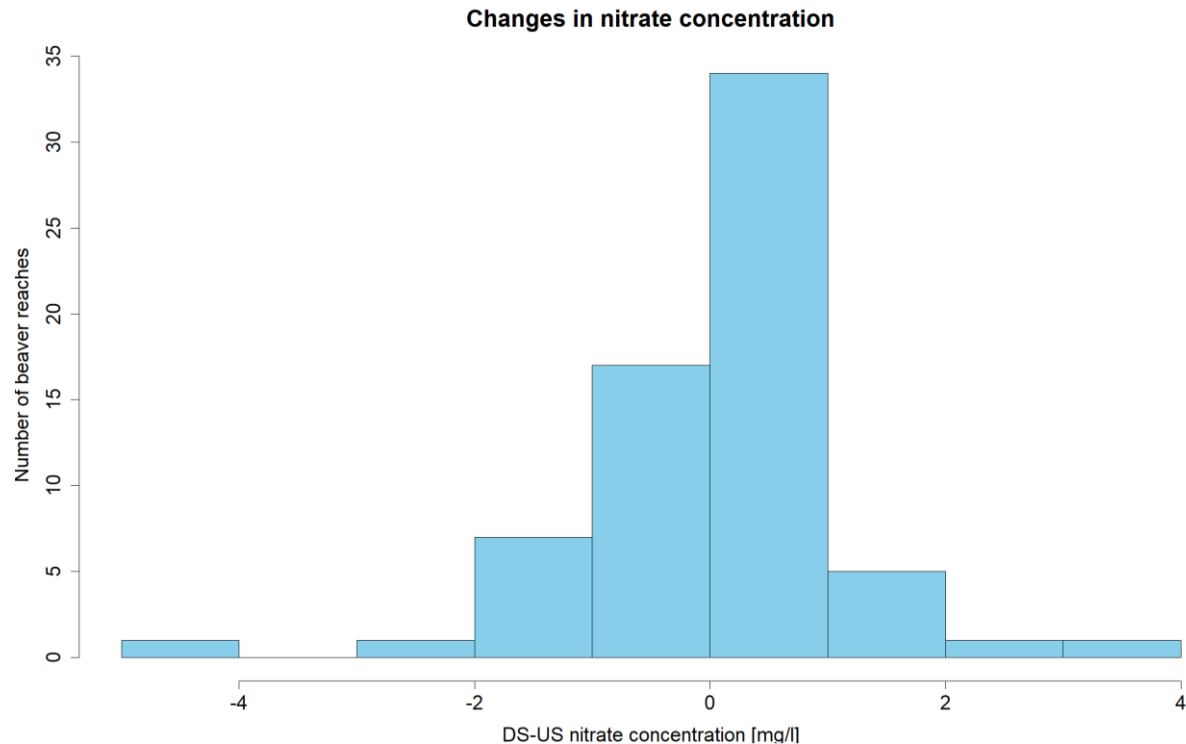


Figure J1: Nitrate changes from US to DS. Positive values represent an increase in nitrate concentration. This plot presents the changes in 68 beaver dam reaches. In four beaver dam reaches the US to DS difference (DS-US) was more than 5 mg/l (-29.90, -10.58, -7.49 and +10.52 mg/l).

The majority of the beaver dam reaches sampled only in one season undergo an increase in DOC concentration within the beaver system. The differences are mainly < 0.5 mg/l.

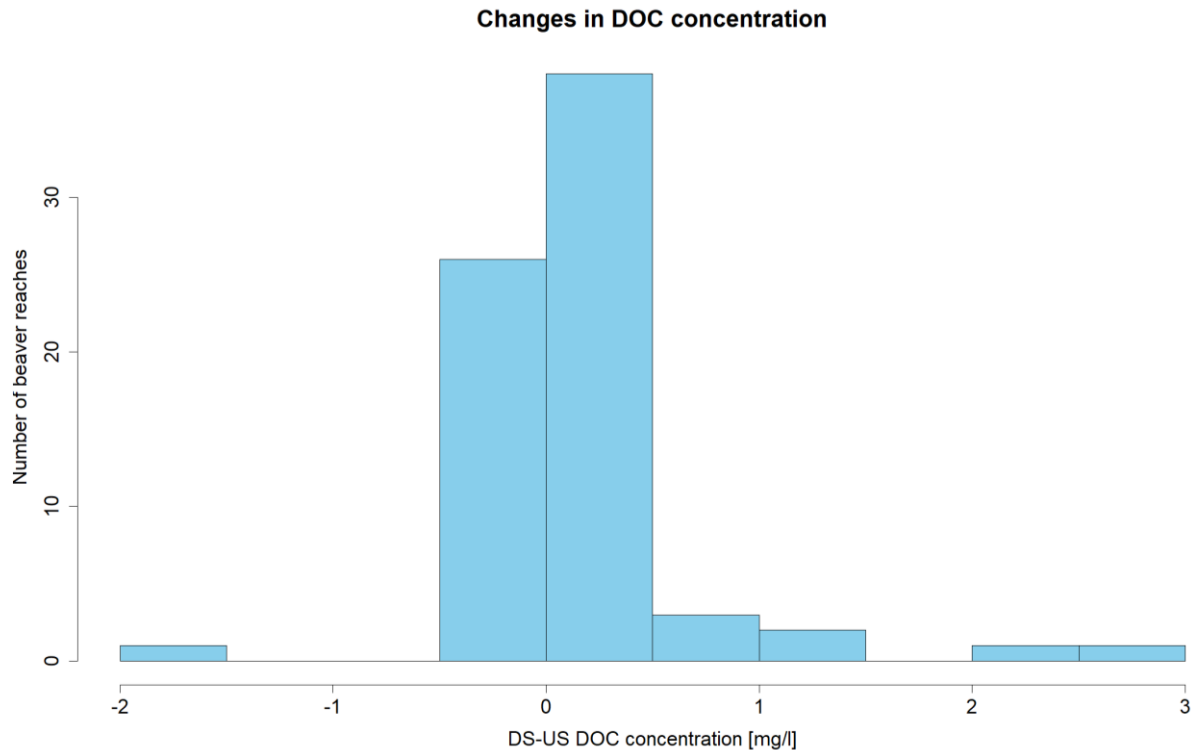


Figure J2: DOC changes from US to DS. Positive values represent an increase in DOC concentration. This plot presents the changes in 72 beaver dam reaches.

The US and DS water quality parameters from the 7 beaver dam reaches only samples in summer were compared (Nitrate and DOC, other parameters). The first beaver reach with notably high nitrate concentrations is the Chriesbach, north of Dübendorf (Coord.: 2'689'823 / 1'251'753). The second beaver reach is close to Herzogenbuchsee (Coord.: 2'621'625 / 1'228'246). The remaining five beaver dam reaches only sampled in summer are located in Liechtenstein. Among these reaches, nitrate concentrations were found to decrease downstream in five out of the seven locations. As for DOC concentrations, they increased in four beaver dam reaches. Regarding the other water quality parameters, no clear trends in increasing or decreasing concentrations were observed for the seven beaver dam reaches (Figure J3).

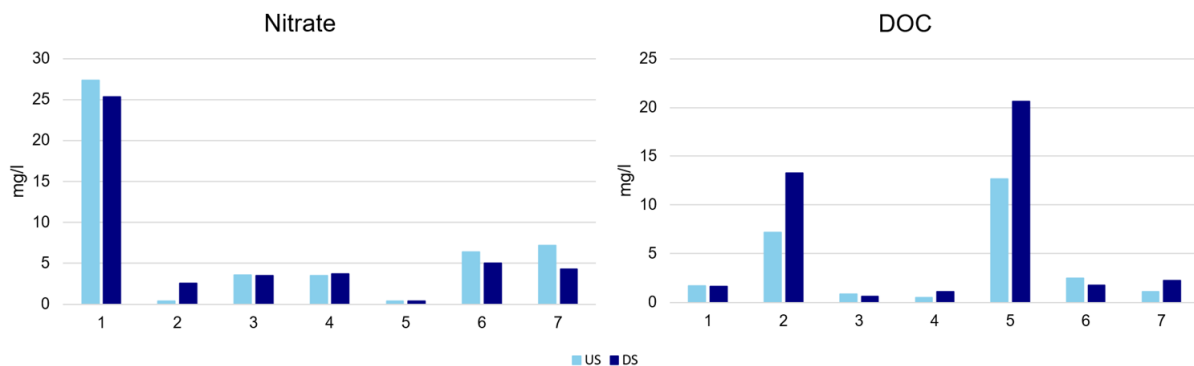


Figure J3: Comparison of the US and DS nitrate and DOC concentrations from the seven beaver dam reaches only sampled in summer.

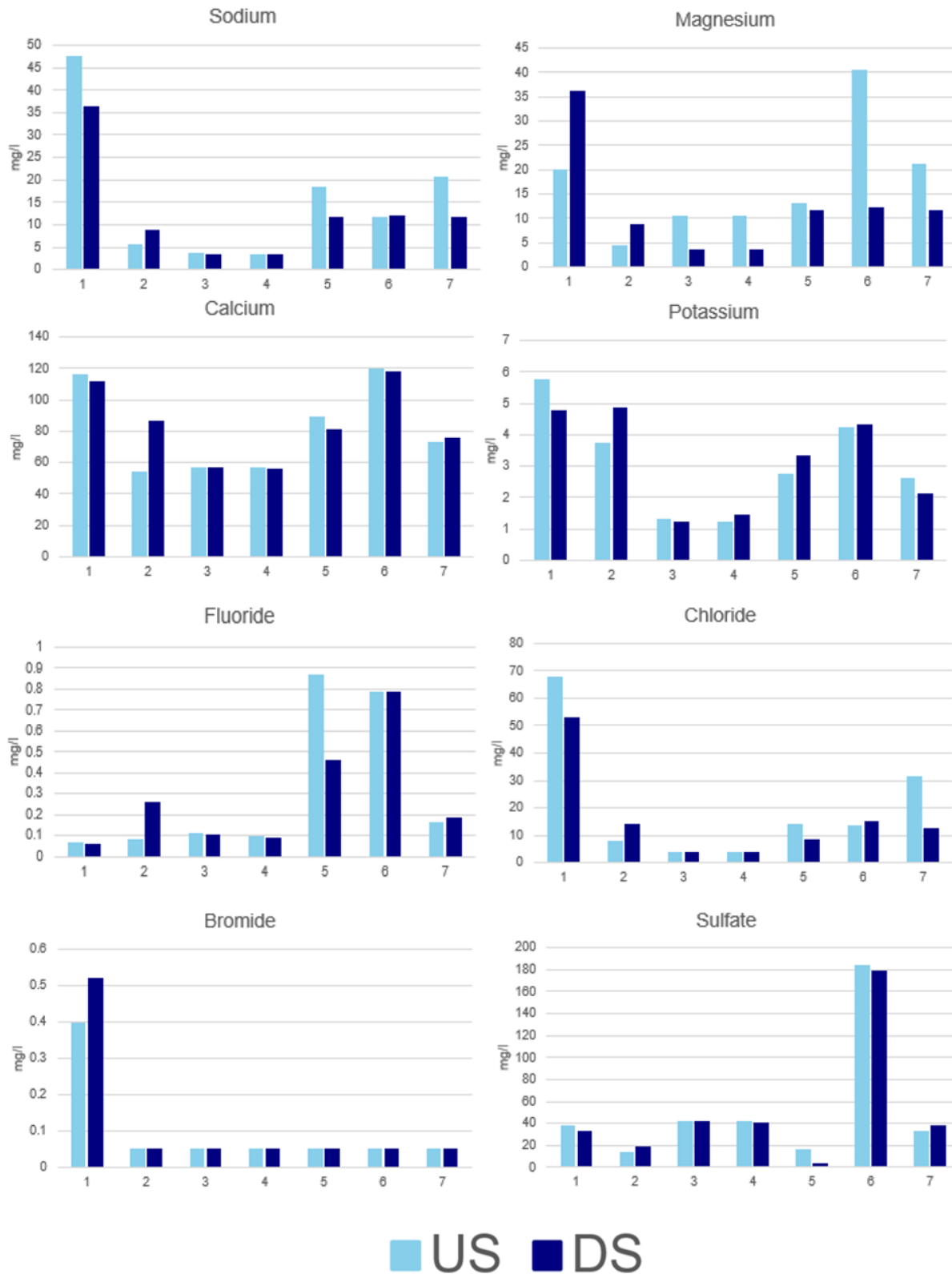


Figure J4: Comparison of the US and DS concentrations (Bromide etc.) from the seven beaver dam reaches only sampled in summer.

Appendix K: Results stable isotope analysis

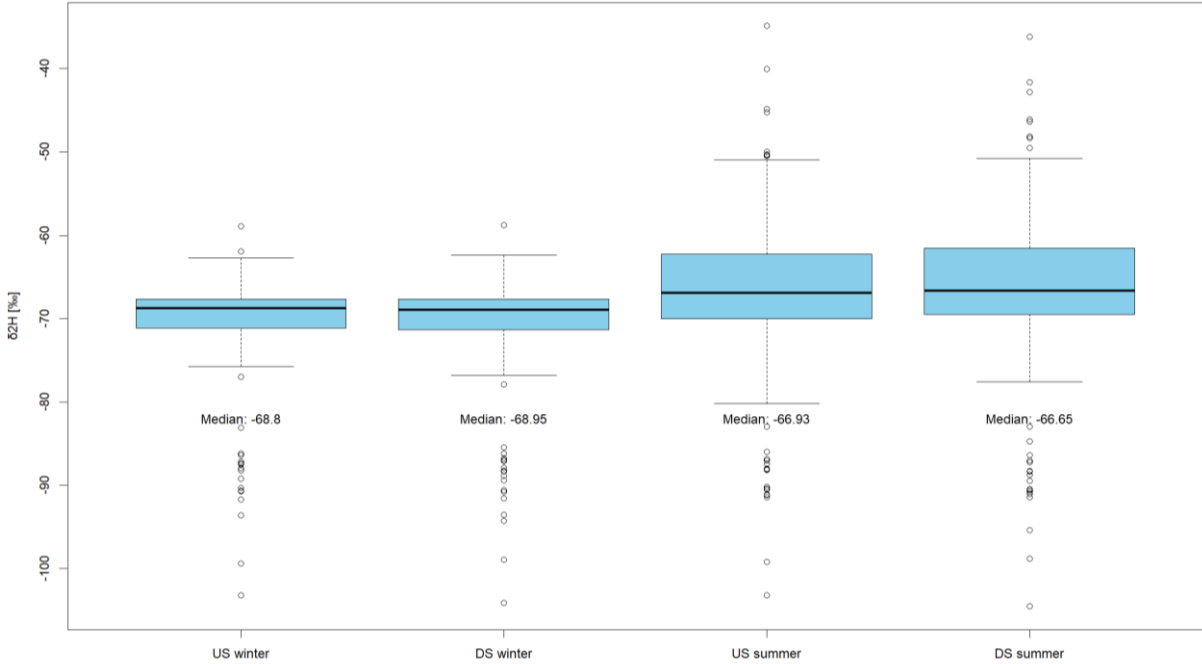


Figure K1: $\delta^2\text{H}$ composition US and DS in winter and summer.

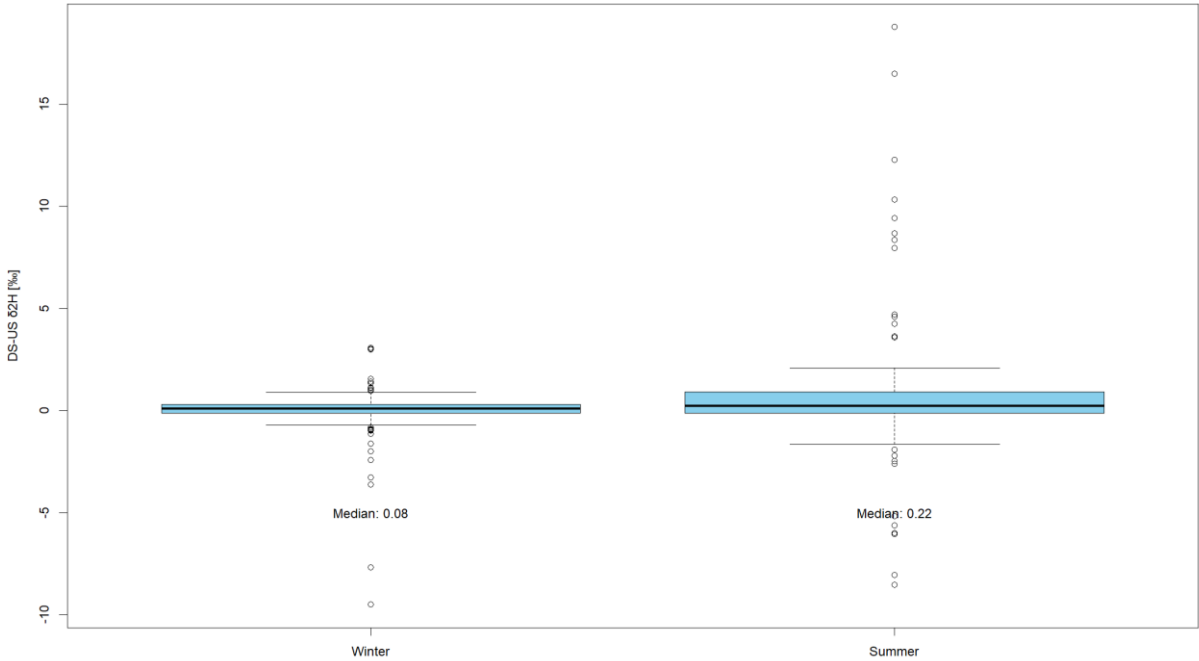
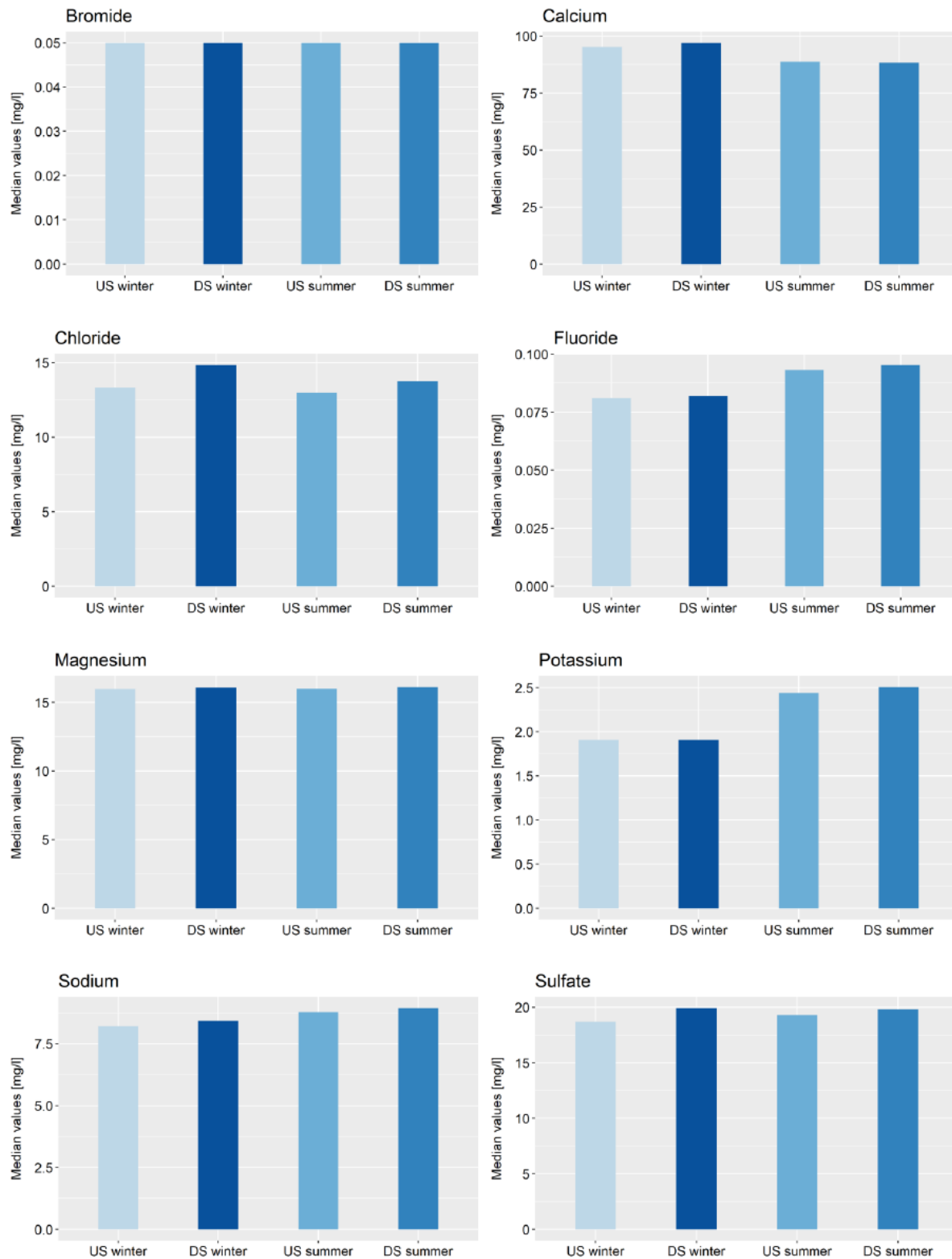


Figure K2: DS minus US $\delta^2\text{H}$ compositions in winter and summer.

Appendix L: Median water quality concentrations



Appendix M: Corr. US concentrations and catchment characteristics

Variable	Median Winter Summer	Unit	Observations	NO3 winter US Median: 16.24 mg/l Correlation P-value	NO3 summer US Median: 12.70 mg/l Correlation P-value	DOC winter US Median: 1.95 mg/l Correlation P-value	DOC summer US Median: 2.66 mg/l Correlation P-value
Altitude US water sampling location	470.50	m a.s.l.	163 / 165	-0.01	0.90	0.09	0.01
Mean catchment altitude	536.20	m a.s.l.	163 / 165	-0.12	0.12	-0.04	-0.10
Discharge winter	38.70	l/s	153	0.06	0.47	-0.03	0.68
Discharge summer	10.12	l/s	157				0.00
Catchment area	4.24	km²	163 / 165	0.12	0.13	0.00	0.04
Temperature summer US	17.20	°C	159		0.14		0.36
DOC winter US	1.95	mg/l	163	-0.14	0.07		
NH4 winter US	0.02	mg/l	163	-0.13	0.09	0.15	0.06
NO3 summer US	12.70	mg/l	163	0.61	< 0.05		
NO3 winter DS	16.42	mg/l	163	0.96	< 0.05		
NH4 summer US	0.03	mg/l	165				-0.01
DOC summer US	2.66	mg/l	163				0.20
NO3 summer DS	12.05	mg/l	165		0.92	< 0.05	
DOC winter DS	1.97	mg/l	163			0.53	< 0.05
DOC summer DS	3.18	mg/l	165			0.87	
US wetland (abs.)	0.00	m²	163	0.04	0.59		0.63
US wetland (%)	0.00	%	163	-0.20	< 0.05	0.22	< 0.05
US Settlement (abs.)	46.00	hectares	163	0.10	0.19	0.34	< 0.05
US Settlement (%)	9.95	%	163	-0.11	0.15	0.04	0.65
US Agriculture (abs.)	228.00	hectares	163	0.21	< 0.05	-0.03	0.69
US Agriculture (%)	60.98	%	163	0.38	< 0.05	0.04	0.63
US Forest (abs.)	117.00	hectares	163	-0.02	0.81	0.13	0.09
US Forest (%)	23.64	%	163	-0.25	< 0.05	-0.05	0.57
US non productive areas (abs.)	2.00	hectares	163	-0.01	0.93	-0.15	0.05
US non productive areas (%)	0.37	%	163	-0.27	< 0.05	0.10	0.19
dD US	-68.77	‰	146 / 154	0.32	< 0.05	0.21	< 0.05
d18O US	-9.76	‰	146 / 154	0.32	< 0.05	0.26	0.68
d17O US	-5.04	‰	146 / 154	0.32	< 0.05	0.34	< 0.05
Sodium US	8.20	mg/l	163 / 165	0.17	< 0.05	0.34	< 0.05
Magnesium US	15.96	mg/l	163 / 165	0.17	< 0.05	-0.02	0.17
Calcium US	95.33	mg/l	163 / 165	0.13	< 0.05	-0.18	-0.08
Potassium US	1.91	mg/l	163 / 165	0.40	< 0.05	0.07	-0.09
Fluoride US	0.08	mg/l	163 / 165	-0.13	0.09	0.14	0.24
Chloride US	13.36	mg/l	163 / 165	0.35	< 0.05	-0.11	0.04
Bromide US	0.05	mg/l	163 / 165	0.02	< 0.05	-0.02	0.17
Sulfate US	18.76	mg/l	163 / 165	-0.12	0.13	-0.04	0.10
						-0.09	0.22
						0.25	0.27

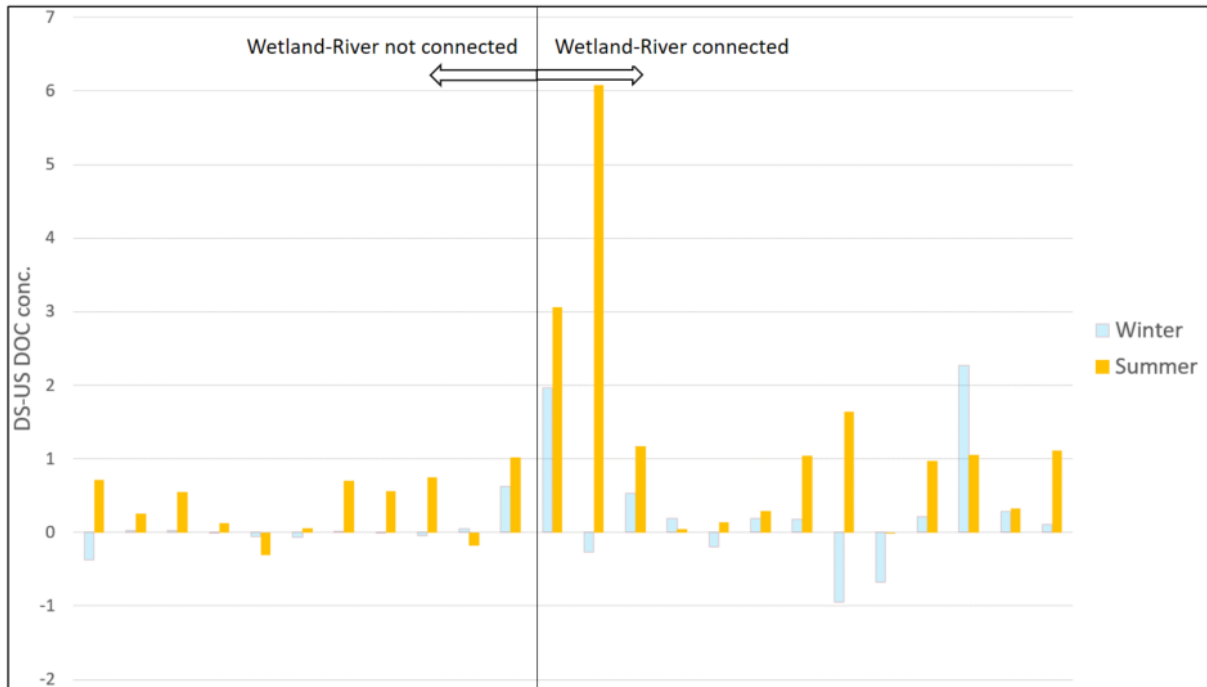
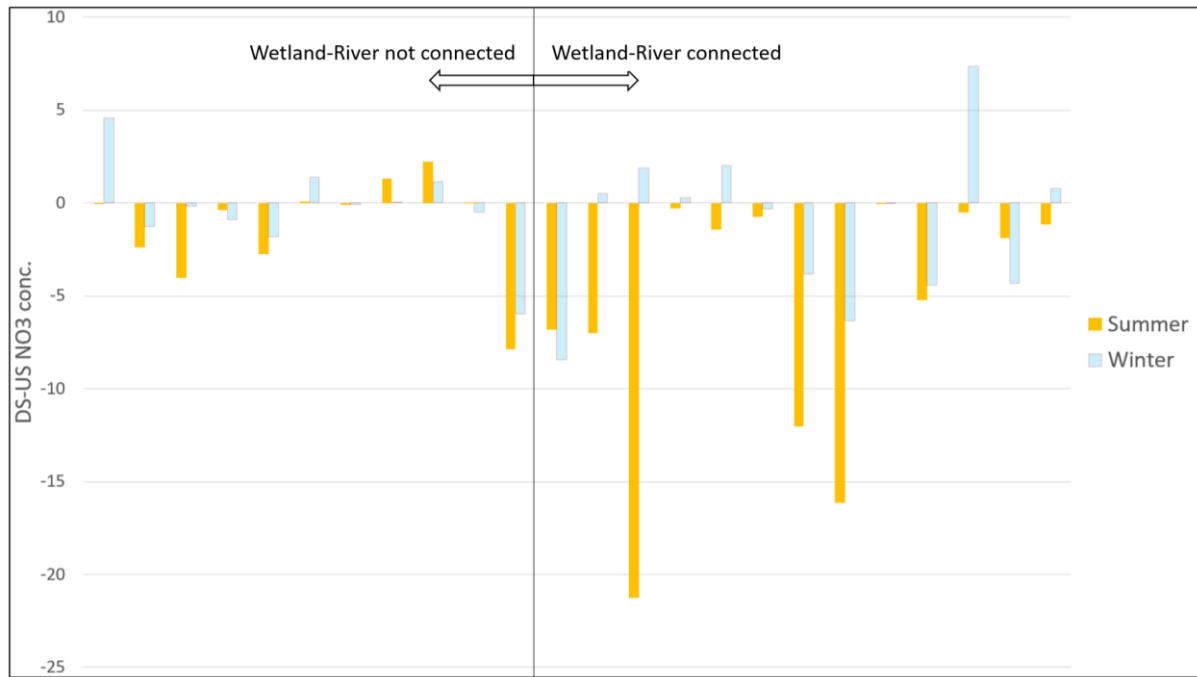
Appendix N: Corr. concentration changes and beaver reach characteristics

Variable	Winter	Median	Summer	Unit	Observations	NO3 change winter Median: -0.07 mg/l Correlation P-value	NO3 change summer Median: -0.27 mg/l Correlation P-value	DOC change winter Median: 0 mg/l Correlation P-value	DOC change summer Median: 0.13 mg/l Correlation P-value
Distance		336.63		mg/l	162-165	0.01	-0.07	0.07	0.11
Slope		0.598		%	162-165	0.08	-0.02	-0.04	-0.15
Volume		379.7		m³	162-165	0.11	-0.09	0.05	0.22
Residence time winter	2.5			h	153 / 152	-0.03		0.07	< 0.05
Residence time summer		10.3		h	157 / 156		0.01		0.04
Discharge winter	38.74			l/s	153 / 152	0.06		-0.07	0.40
Discharge summer		10.12		l/s	157 / 156		0.13		-0.08
Dam age		2022		year	162-165	-0.12	0.13	-0.10	0.08
Number of dams		2		count	162-165	-0.13	-0.06	-0.12	0.09
NO3 winter US	16.24			mg/l	163	-0.15	< 0.05		0.26
NO3 summer US		12.7		mg/l	165		-0.23	< 0.05	
DOC winter US	1.954			mg/l	162			-0.21	< 0.05
DOC summer US	-0.07	2.614		mg/l	164		0.04	-0.05	-0.09
NO3 summer change		-0.27		mg/l	163 / 164	0.04			0.23
DOC winter change	0			mg/l	163	-0.03			-0.14
DOC summer change		0.136		mg/l	162 / 165		-0.10	0.10	0.10
NH4 winter change	0			mg/l	163 / 162	-0.08		0.17	0.20
NH4 summer change		0.002		mg/l	165 / 164		-0.05	< 0.05	
Temperature summer US		17.2		°C	158		-0.01		0.35
Temperature summer change		0.2		°C	158		-0.06		< 0.05
dD change	0.082	0.217		‰	144-150	0.06	-0.16	0.38	0.20
d18O change	0.009	0.047		‰	144-150	0.04			< 0.05
d17O change	0.004	0.018		‰	144-150	0.06	< 0.05	< 0.05	< 0.05
Sodium change	0.016	-0.001		mg/l	162-165	-0.26	-0.15	0.28	< 0.05
Magnesium change	-0.007	0.014		mg/l	162-165	0.03	0.08	-0.09	0.04
Calcium change	0.085	-0.065		mg/l	162-165	0.04	0.13	-0.12	< 0.05
Potassium change	-0.001	0.014		mg/l	162-165	-0.23	0.14	-0.10	-0.07
Fluoride change	0	-0.05		mg/l	162-165	-0.06	< 0.05	0.12	0.39
Chloride change	0.014	0.008		mg/l	162-165	-0.13	-0.05	-0.07	0.26
Bromide change	0	0		mg/l	162-165	-0.06	0.13	-0.05	0.06
Sulfate change	0.021	-0.069		mg/l	162-165	-0.05	0.01	-0.02	-0.03
							0.00	< 0.05	0.03
							0.99		0.72

Appendix O: Corr. with land use in buffer polygon

Variable	Median	Unit	Observations	NO3 change winter Median: -0.07 mg/l		NO3 change summer Median: -0.27 mg/l		DOC change winter Median: 0 mg/l		DOC change summer Median: 0.13 mg/l	
				Correlation	P-value	Correlation	P-value	Correlation	P-value	Correlation	P-value
Stagnant water (buffer 50 m) (abs.)	0	m²2	162-165	-0.10	0.23	-0.06	0.46	0.05	0.57	0.14	0.09
Stagnant water (buffer 50 m) (%)	0	%	162-165	-0.06	0.42	-0.02	0.81	0.05	0.53	0.14	0.08
Stagnant water (buffer 25 m) (abs.)	0	m²2	162-165	-0.12	0.12	-0.01	0.89	0.13	0.11	0.12	0.14
Stagnant water (buffer 25 m) (%)	0	%	162-165	-0.06	0.49	0.01	0.88	0.06	0.45	0.11	0.16
Stagnant water (buffer 10 m) (abs.)	0	m²2	162-165	-0.02	0.83	0.00	0.99	0.05	0.52	0.09	0.28
Stagnant water (buffer 10 m) (%)	0	%	162-165	-0.01	0.95	0.02	0.81	0.02	0.85	0.08	0.32
Stagnant water (buffer 5 m) (abs.)	0	m²2	162-165	0.03	0.76	0.01	0.95	0.02	0.85	0.08	0.31
Stagnant water (buffer 5 m) (%)	0	%	162-165	0.01	0.89	0.02	0.76	0.00	0.99	0.07	0.40
Forest (buffer 50 m) (abs.)	4876	m²2	162-165	-0.11	0.18	-0.08	0.32	-0.06	0.48	0.15	0.06
Forest (buffer 50 m) (%)	15.85	%	162-165	-0.05	0.50	0.01	0.90	-0.02	0.80	0.04	0.65
Forest (buffer 25 m) (abs.)	3621	m²2	162-165	-0.08	0.29	-0.05	0.51	0.00	0.99	0.10	0.18
Forest (buffer 25 m) (%)	23.765	%	162-165	-0.03	0.67	0.03	0.73	0.02	0.83	-0.03	0.68
Forest (buffer 10 m) (abs.)	2332	m²2	162-165	-0.03	0.69	-0.01	0.90	0.05	0.50	0.06	0.44
Forest (buffer 10 m) (%)	44.89	%	162-165	0.00	0.96	0.09	0.27	0.03	0.67	-0.10	0.22
Forest (buffer 5 m) (abs.)	1416	m²2	162-165	0.00	0.97	0.01	0.93	0.06	0.48	0.06	0.46
Forest (buffer 5 m) (%)	67.35	%	162-165	0.02	0.77	0.13	0.11	0.01	0.89	-0.12	0.14
Wetlands (buffer 50 m) (abs.)	0	m²2	162-165	0.00	0.99	-0.20	< 0.05	0.05	0.54	0.25	< 0.05
Wetlands (buffer 50 m) (%)	0	%	162-165	-0.02	0.78	-0.18	< 0.05	0.08	0.34	0.27	< 0.05
Wetlands (buffer 25 m) (abs.)	0	m²2	162-165	-0.03	0.69	-0.31	< 0.05	0.11	0.18	0.37	< 0.05
Wetlands (buffer 25 m) (%)	0	%	162-165	-0.04	0.61	-0.26	< 0.05	0.12	0.14	0.39	< 0.05
Wetlands (buffer 10 m) (abs.)	0	m²2	162-165	-0.12	0.11	-0.30	< 0.05	0.14	0.07	0.34	< 0.05
Wetlands (buffer 10 m) (%)	0	%	162-165	-0.12	0.13	-0.25	< 0.05	0.15	0.06	0.37	< 0.05
Wetlands (buffer 5 m) (abs.)	0	m²2	162-165	-0.12	0.14	-0.24	< 0.05	0.13	0.10	0.28	< 0.05
Wetlands (buffer 5 m) (%)	0	%	162-165	-0.11	0.16	-0.19	< 0.05	0.13	0.10	0.29	< 0.05
Anthropogenic (buffer 50 m) (abs.)	854	m²2	162-165	0.05	0.51	0.08	0.33	-0.09	0.29	0.21	< 0.05
Anthropogenic (buffer 50 m) (%)	2.9	%	162-165	0.05	0.57	0.11	0.14	-0.07	0.38	0.17	< 0.05
Anthropogenic (buffer 25 m) (abs.)	348	m²2	162-165	0.10	0.21	0.08	0.30	-0.04	0.60	0.22	< 0.05
Anthropogenic (buffer 25 m) (%)	3.17	%	162-165	0.08	0.31	0.08	0.31	-0.02	0.77	0.21	< 0.05
Anthropogenic (buffer 10 m) (abs.)	89	m²2	162-165	0.14	0.07	0.09	0.27	0.03	0.74	0.21	< 0.05
Anthropogenic (buffer 10 m) (%)	1.34	%	162-165	0.12	0.14	0.06	0.48	0.06	0.46	0.17	< 0.05
Anthropogenic (buffer 5 m) (abs.)	11	m²2	162-165	-0.03	0.67	0.08	0.32	0.02	0.78	0.27	< 0.05
Anthropogenic (buffer 5 m) (%)	0.34	%	162-165	-0.07	0.41	0.07	0.38	0.11	0.16	0.29	< 0.05
Agriculture (buffer 50 m) (abs.)	21301	m²2	162-165	0.06	0.49	-0.04	0.64	0.10	0.20	0.00	0.97
Agriculture (buffer 50 m) (%)	74.09	%	162-165	0.03	0.66	-0.01	0.89	0.03	0.73	-0.12	0.14
Agriculture (buffer 25 m) (abs.)	8501	m²2	162-165	0.05	0.57	-0.04	0.63	0.06	0.45	0.00	0.96
Agriculture (buffer 25 m) (%)	67.93	%	162-165	0.01	0.93	0.01	0.94	-0.04	0.62	-0.13	0.11
Agriculture (buffer 10 m) (abs.)	2358	m²2	162-165	0.03	0.73	-0.07	0.38	0.00	0.96	0.03	0.71
Agriculture (buffer 10 m) (%)	46.02	%	162-165	-0.03	0.75	-0.04	0.59	-0.09	0.25	-0.05	0.55
Agriculture (buffer 5 m) (abs.)	710	m²2	162-165	0.03	0.71	-0.09	0.25	-0.02	0.77	0.03	0.72
Agriculture (buffer 5 m) (%)	26.8	%	162-165	-0.01	0.92	-0.08	0.28	-0.07	0.41	-0.02	0.83

Appendix P: Nitrate and DOC concentration changes for wetlands



Appendix Q: 14 wetland beaver dam reaches

Beaver reach	Distance [m]	Wetlands [m^2]	X_Coord_US	Y_Coord_US	X_Coord_DS	Y_Coord_DS	Created by beavers damming activity	Nitrate winter change [mg/l]	Nitrate summer change [mg/l]	DOC winter change [mg/l]	DOC summer change [mg/l]
19	606	14262	2695582	1241577	2695945	1242032	No	-8.43	-8.83	1.97	3.06
36	564	17707	2731472	1272478	2731459	1272021	No	0.53	-7.03	-0.26	6.08
46	723	13139	2686025	1279958	2686673	1280183	No, but strongly influenced	1.86	-21.27	0.53	1.17
52	805	3470	2646838	1249994	2647164	1250558	Yes	0.28	-0.27	0.20	0.04
53	1011	511	2647813	1251020	2648775	1251238	No, but without beaver no stagnant water	2.02	-1.41	-0.20	0.14
55	282	1324	2657424	1228698	2657691	1228728	No, but without beaver no stagnant water	-0.30	-0.74	0.20	0.29
60	1500	8941	2690996	1277655	2690986	1276386	No, river was re-naturalized in 2004	-3.83	-12.05	0.18	1.04
67	727	23828	2760617	1246966	2761190	1247365	No	-0.32	-5.34	14.40	45.37
92	1910	5061	2681425	1275004	2679829	1274499	No	-6.33	-16.14	-0.95	1.64
98	374	1007	2673107	1265983	2672976	1266275	No	-0.03	-0.02	-0.68	-0.01
99	359	1171	2573917	1194899	2573926	1195234	No	-4.40	-5.24	0.22	0.97
107	868	11763	2505800	1122216	2506267	1121622	No, pond was there before the beavers damming activity	7.36	-0.52	2.27	1.05
136	457	4764	2581567	1192065	2581870	1192177	Yes	-4.32	-1.88	0.29	0.33
149	533	3616	2549409	1152905	2549618	1153271	No	0.81	-1.14	0.11	1.12

Appendix R: Comparison wetland vs. nitrate source beaver dam reaches

