

Master thesis at the Faculty of Science at the University of Berne

Modification and spatial variation of riverine water quality due to beaver damming across Switzerland

Kaspar Berger

2023

Master thesis director

Prof. Dr. Bettina Schaefli

Institute of Geography, University of Berne, Switzerland

Master thesis supervision

Dr. Annegret Larsen

Soil Geography and Landscape, Wageningen University and Research, Netherlands

Acknowledgments

I would like to express my thanks to everybody who has supported me throughout my master's thesis. This master's thesis is a result of the collaboration of an ingenious team. I am thankful for all the suggestions, feedbacks, data collection assistance, lab work assistance, proofreading of the work, mental support and helpful discussions.

First and foremost, I would like to thank my supervisors:

Dr. Annegret Larsen

Prof. Dr. Bettina Schaefli

Furthermore, I would like to express my gratitude to (in alphabetic order):

Christof Angst

Cécile Auberson

Elisabeth Berger

Dr. Natalie Ceperley

Civil servants Infofauna

cLab Berne team

Raphael d'Epagnier

EAWAG team

Dr. Mauro Fischer

Ladina Gaudy

Dr. Joshua Larsen

Sibylle Wilhelm

Abstract

This study was conducted as a part of a Swiss national beaver project launched in 2021 in order to estimate the ecological potential of beaver systems in relation to the continuously increasing beaver population. Beaver systems are recognized as nitrate sinks and DOC sources. However, the factor(s) determining the degree of nitrate removal and DOC gain within the beaver systems has not been established. This study aimed to demonstrate the seasonal and spatial variability of beaver system impacts on nitrate and DOC concentrations and to identify the factor(s) that determine the extent of nitrate removal and DOC gain. The data collection involved citizen science and a dataset of over 200 beaver systems was compiled. Locations of beaver systems throughout Switzerland were mapped in a national beaver survey. Additionally, water samples were taken upstream and downstream of beaver systems in winter 2021/22 and summer 2022. The beaver systems were characterized with a variety of methods, primarily GIS analysis. While no distinct spatial pattern was observed, the results showed that the impacts of beaver systems on nitrate and DOC concentrations were generally more apparent in summer than in winter. The increased nitrate removal in summer is attributed to nitrate uptake by pond vegetation, while enhanced primary productivity in summer is responsible for the increased DOC gain. A variety of analysis, mainly quantitative, were conducted, but no beaver system characteristics, determining the extent of nitrate removal or DOC gain, could be identified. 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. However, land use analysis showed that the presence of wetlands in the surroundings (50 m buffer area) of the beaver systems determine or co-determine the extent of nitrate removal and DOC gain. Further analysis has shown that the size of the wetland area is a determining factor for the extent of nitrate removal and DOC gain. Wetlands are known as DOC sources due to a high primary productivity, and nitrate removal in wetlands is attributed to enhanced anaerobic conditions promoting denitrification (nitrate conversion to atmospheric gases) as well as nitrate uptake by wetland vegetation. Therefore, the important ecosystem benefit of nitrate removal in beaver systems is primarily determined by the beavers' capability to create dams that can cause water levels to rise and potentially create wetlands.

Table of contents

Acknowledgments	I
Abstract	II
Table of contents	III
List of figures	VI
List of tables	VIII
Abbreviations	IX
1. Introduction	1
1.1 Context and relevance of the research field	1
1.1.1 Nitrate	2
1.1.2 Dissolved Organic Carbon (DOC)	6
1.2 Excursion: The Beaver (in Switzerland)	7
1.3 State of the research	10
1.3.1 Hydrology	10
1.3.2 Geomorphology	11
1.3.3 Ecosystems	12
1.3.4 Biogeochemistry	12
1.3.4.1 Summary of two literature synthesis (nitrate and DOC)	12
1.3.4.2 Impacts of beaver systems on the nitrogen cycle (focus nitrate)	14
1.3.4.3 Impacts of beaver systems on the carbon cycle (focus DOC)	16
1.3.4.4 Other impact on biogeochemical processes	16
1.4 Research objectives	17
2. Study setup	18
3. Data	20
4. Methods	21
4.1 Beaver survey and water sampling by volunteers	21
4.1.1 Beaver survey	21
4.1.2 Water sampling	22
4.2 Summer water sampling campaign	28
4.2.1 Teams and sampling locations	28
4.2.2 Beaver dam height documentation	29
4.2.3 Water temperature measurement	30
4.3 External lab measurements (EAWAG & GIUB)	30
4.3.1 Nutrient measurements	30
4.3.2 DOC measurements	32
4.3.3 Ammonium measurements	33
4.3.4 Comparison of EAWAG and cLab Berne measurements	34
4.4 Stable isotope analysis	35
4.4.1 Cavity Ringdown Spectroscopy (CRDS)	36
4.4.2 Measuring techniques for stable isotopes	37
4.5 Sediment load analysis	38
4.6 Catchment delineation	39
4.7 Water residence time estimation by volume and discharge	41
	III

4.7.1	Discharge estimations	41
4.7.2	Water volume estimation	41
4.7.2.1	Field measurement for validation.....	41
4.7.2.2	Quantitative approaches	43
4.7.2.3	Comparison and validation	46
4.8	Determination of river slope and distance.....	46
4.9	Land use in catchments	47
4.10	Land use in the direct surroundings.....	47
4.11	Dam Age	51
4.12	Water quality analysis	53
4.12.1	General summary water chemistry	53
4.12.2	Comparing areas of interest	53
4.12.3	Correlations between characteristics and (change in) nitrate and DOC concentrations	54
4.12.4	Wetlands	55
5.	Results	57
5.1	Characterizations of study sites.....	57
5.1.1	Locations.....	57
5.1.2	Altitudes of mapped beaver dams	57
5.1.3	Dam heights (summer)	58
5.1.4	Water temperature (summer)	59
5.1.5	Catchment characterization.....	60
5.1.5.1	Catchment size	60
5.1.5.2	Land use in catchments	60
5.1.6	Discharge.....	61
5.1.7	Water volume estimation	62
5.1.8	River sector between US and DS water sample	63
5.1.8.1	Distance	63
5.1.8.2	Slope.....	63
5.1.8.3	Dams per reach.....	63
5.1.8.4	Land use in the direct surroundings.....	64
5.1.9	Dam age	64
5.2	General summary water chemistry	65
5.2.1	Nitrate	65
5.2.2	Dissolved Organic Carbon DOC.....	69
5.2.3	Total suspended sediment	73
5.2.4	Stable isotope composition.....	74
5.2.5	Other water chemistry parameters	76
5.3	Areas of interest	77
5.4	Correlation analysis.....	79
5.4.1	Characteristics controlling the general US concentrations	79
5.4.2	Correlations with beaver system characteristics	80
5.4.3	Correlations with land use	82
5.5	Wetlands	82
5.6	Comparison between wetland-river connected beaver reaches and beaver reaches with nitrate increase in both seasons	86

6.	Discussion.....	87
6.1	Highest measured nitrate and DOC concentrations on the Swiss plateau	87
6.2	Higher nitrate concentrations in winter and more apparent nitrate decrease in summer 89	
6.3	Higher DOC concentrations and DOC increase in summer	90
6.4	No spatial pattern for beaver system impacts on nitrate and DOC concentrations throughout Switzerland identified	90
6.5	No specific beaver system characteristics determining the extent of nitrate and DOC decreases and increases identified	91
6.6	Nitrate removal and DOC gain in beaver reaches situated in wetland areas	92
6.7	Beaver system characteristics of wetland beaver reaches compared to nitrate source beaver reaches.....	94
6.8	Limitations.....	94
6.8.1	Citizen science.....	94
6.8.2	Estimations in discharge and volume	94
6.8.3	Semi-comparable US and DS water samples.....	94
6.8.4	Concentrations instead of fluxes.....	94
7.	Conclusion	96
	Outlook	97
	References.....	98
	Appendix	103
	Appendix A: Case study for nitrate removal in beaver systems.....	103
	Appendix B: Instructions water sampling.....	106
	Appendix C: Catchment delineation	108
	Appendix D: Email swisstopo (lidar)	110
	Appendix E: GIS volume calculation tools.....	111
	Appendix F: Area statistics Switzerland - Standard nomenclature NOAS04.....	112
	Appendix G: Email swisstopo (wetlands)	112
	Appendix H: DS - US nitrate concentrations in winter and summer (with outliers).....	113
	Appendix I: Relative changes in nitrate concentrations	114
	Appendix J: DS - US DOC concentrations (outlier values > 2 mg/l)	115
	Appendix K: Relative changes in DOC concentrations.....	116
	Appendix L: Results ammonium analysis.....	117
	Appendix M: Concentrations in beaver reaches only sampled in one season	121
	Appendix N: Results stable isotope analysis	124
	Appendix O: Median water quality concentrations.....	125
	Appendix P: Corr. US concentrations and catchment characteristics	126
	Appendix Q: Corr. concentration changes and beaver reach characteristics.....	127
	Appendix R: Corr. with land use in buffer polygon.....	128
	Appendix S: Nitrate and DOC concentration changes for wetlands.....	129
	Appendix T: 14 wetland beaver reaches	130
	Appendix U: Comparison wetland vs. nitrate source beaver reaches.....	131
	Appendix V: Beaver reach Nr. 67.....	136

List of figures

Figure 1: Stream conditions and nitrogen inputs.....	2
Figure 2: Nitrate concentrations and intense agriculture.....	3
Figure 3: Simplified illustration of the nitrogen cycle..	5
Figure 4: NAWA DOC measurements.....	6
Figure 5: Examples of beaver dam types.....	8
Figure 6: Distribution of beavers in Switzerland in 2008.....	9
Figure 7: Impacts of beaver systems on hydrology.....	11
Figure 8: Impacts of beaver systems on geomorphology.....	11
Figure 9: Impacts of beaver systems on ecosystems.....	12
Figure 10: Synthesis by Grudzinski et al. (2022).....	13
Figure 11: Synthesis by Larsen et al. (2021).....	13
Figure 12: Conceptual model of beaver impacts on biogeochemistry and water quality.....	14
Figure 13: Denitrification rates in different types of wetlands	15
Figure 14: Beaver dams and the sampling locations	18
Figure 15: Flow chart of the data generation process.....	20
Figure 16: Signature legend for the mapping of the beaver occurrences	21
Figure 17: Differentiation of new gnawing tracks (left) and old gnawing tracks (right)	22
Figure 18: Sampling locations for a single beaver dam.....	22
Figure 19: Sampling locations for river sections with bypass channel.....	23
Figure 20: Sampling locations for beaver dam cascades.....	23
Figure 21: Four types of water samples.....	24
Figure 22: Protocol sheet for water sampling.....	25
Figure 23: Collecting points for ammonium samples.....	26
Figure 24: Locations of 482 usable winter samples.....	28
Figure 25: Measurement of dam height	29
Figure 26: Summer sampling locations and beaver dams	30
Figure 27: Methrohm 930 Compact IC Flex.....	31
Figure 28: Shimadzu TOC-L CSH	33
Figure 29: Skalar San++ Autoanalyzer	33
Figure 30: DOC concentrations measured by EAWAG and cLab Berne.....	34
Figure 31: Adjustment of the cLab Berne DOC concentrations.....	35
Figure 32: Cavity Ringdown Spectroscopy (CRDS).....	36
Figure 33: Cavity Ringdown Spectrometer L2140-I (left) and run architecture (right).....	38
Figure 34: Setup for the sediment analysis.....	39
Figure 35: Different catchment delineation and preprocessing methods.....	40
Figure 36: Cécile Auberson (Infofauna) measuring pond depth.....	42
Figure 37: Ortho view (left) and cross profile (right) illustrating length, width and depth.....	42
Figure 38: ArcMap surface volume tool (esri, 2016).....	44
Figure 39: LiDAR and shallow water.....	44
Figure 40: Illustration on plane height determination.....	45
Figure 41: Polygons for volume calculation	45
Figure 42: Volume estimations from six test sites with different methods.....	46
Figure 43: Subcategories of the swissTLM3D	47
Figure 44: Categories from the swissTLM3D.....	48
Figure 45: Land use and buffer polygons.....	50
Figure 46: Beaver dam locations from previous and current surveys.....	52

Figure 47: Comparison with previous surveys	52
Figure 48: Categories for correlation analysis.....	55
Figure 49: Wetland-River connectivity	56
Figure 50: Size of wetland area.	56
Figure 51: Overview map.	57
Figure 52: Beaver dam altitudes.....	58
Figure 53: Height of the beaver dams documented in summer.....	58
Figure 54: Water temperature measurements	59
Figure 55: Distribution of the catchment areas.	60
Figure 56: Land use in catchments.....	61
Figure 57: Discharge in winter and summer	61
Figure 58: Water volume in the beaver reaches.	62
Figure 59: Slope, length and beaver dams per beaver reach.....	63
Figure 60: Ratio of land use categories for different buffer width.	64
Figure 61: Number of beaver reaches occupied by beavers in previous surveys.....	65
Figure 62: Boxplots US nitrate concentrations in winter and summer.	66
Figure 63: Nitrate increases and decreases	66
Figure 64: DS – US nitrate concentrations in winter and summer	67
Figure 65: Nitrate concentrations and changes in winter	68
Figure 66: Nitrate concentrations and changes in summer	68
Figure 67: Boxplots US DOC concentrations in winter and summer.	69
Figure 68: Comparison of DOC concentrations US and DS of beaver reaches	70
Figure 69: DS – US DOC concentrations in winter and summer	71
Figure 70: DOC concentrations and changes in winter	72
Figure 71: DOC concentrations and changes in summer.....	72
Figure 72: Sediment load boxplots for US and DS in both seasons	73
Figure 73: DS-US sediment load in winter (left) and summer (right)	73
Figure 74: $\delta^{18}\text{O}$ composition US and DS in winter and summer.....	74
Figure 75: DS minus US $\delta^{18}\text{O}$ compositions in winter and summer.	74
Figure 76: Ammonium: Median concentrations US and DS in winter and summer.	76
Figure 77: Slope: Boxplots for Areas of Interest.....	77
Figure 78: Water volume: Boxplots for Areas of Interest.....	77
Figure 79: Distance, number of dams and dam age: Boxplots for Areas of Interest.....	78
Figure 80: Significant correlations between concentrations and characterizations.....	80
Figure 81: Significant correlations between concentrations and characterizations.....	81
Figure 82: Spatial distribution of beaver reaches with wetland area.....	83
Figure 83: Change in nitrate and DOC concentrations in 14 wetland beaver reaches.....	84
Figure 84: Wetlands size and changes in concentrations (with Nr. 67).	85
Figure 85: Wetlands size and changes in concentrations (without Nr. 67).	85
Figure 86: Recapitulation of the research questions.	87
Figure 87: US nitrate concentration in winter and summer	88
Figure 88: US DOC concentration in winter and summer	88
Figure 89: Nitrate concentrations in Marthalen.	90
Figure 90: US and DS water sampling location of beaver reach Nr. 67	93
Figure 91: Nitrate and DOC fluxes in winter and summer.	95
Figure 92: Water residence time and nitrogen fractional change	103
Figure 93: Study setup from Dewey et al. (2022).....	104

Figure 94: Expansion of aerobic zone and nitrification.....	105
Figure 95: Nitrate removal along the flow path.....	105
Figure 96: Data basis for catchment area calculations in QGIS	109
Figure 97: Surface Volume tool in ArcMap	111
Figure 98: Volume Calculation Tool from QGIS.	111
Figure 99: US ammonium concentrations in winter and summer.	117
Figure 100: Change in ammonium concentrations within beaver systems	118
Figure 101: DS – US ammonium concentrations in winter and summer	118
Figure 102: US ammonium concentration and concentration changes in winter	119
Figure 103: US ammonium concentration and concentration changes in summer.....	120
Figure 104: Nitrate changes from US to DS.....	121
Figure 105: DOC changes from US to DS.	122
Figure 106: Comparison of the US and DS nitrate and DOC concentrations.	122
Figure 107: Comparison of the US and DS concentrations (Bromide etc.).....	123
Figure 108: $\delta^2\text{H}$ composition US and DS in winter and summer.....	124
Figure 109: DS minus US $\delta^2\text{H}$ compositions in winter and summer.	124
Figure 110: Beaver reach Nr 67 and DOC measuring station	136
Figure 111: DOC measuring station from the office for water and energy.....	137

List of tables

Table 1: Extract from the water protection ordinance.....	1
Table 2: Sample types, storage conditions and analysis laboratory.	24
Table 3: Examples of sampling errors.	27
Table 4: Reasons for the incomplete summer sampling.	29
Table 5: Laboratory techniques for nutrient analysis by EAWAG	31
Table 6: Conversion from NO_3^- -N to NO_3	31
Table 7: Laboratory techniques for nutrient analysis by cLab Berne.	32
Table 8: Laboratory technique EAWAG for DOC	32
Table 9: Method EAWAG to measure the ammonium concentration.	33
Table 10: Analysis setup for CRDS.	37
Table 11: Criteria for manual water volume measurement.....	41
Table 12: Water volume calculation.....	43
Table 13: Categories for the land use analysis.	48
Table 14: Buffer around polylines from the swissTLM3D.	49
Table 15: GIS land use analysis in direct surroundings	50
Table 16: Cantonal and national beaver surveys from previous years.	51
Table 17: Seven areas of interest.	53
Table 18: US vs. DS stable isotope composition	75
Table 19: Changes in stable isotope compositions and beaver system characteristics.....	75
Table 20: Correlations between wetland land use and concentration changes.	82
Table 21: Comparison wetlands and nitrate increasing beaver reaches	86
Table 22: Different methods to calculate the catchment polygons.	108
Table 23: Preprocessing (burning) of DTM for catchment delineation.....	108
Table 24: ArcMap steps for catchment delineation.	109
Table 25: Ammonium concentrations differences $> 0.3 \text{ mg/l}$	119
Table 26: Water quality parameters in beaver reach Nr. 67.....	136

Abbreviations

cLab Berne	= Laboratory of the Institute of Geography, University of Bern
Corr.	= Pearson correlation coefficient
CRDS	= Cavity ring down spectroscopy
DEM	= Digital Elevation Model
DOC	= Dissolved Organic Carbon
DOM	= Dissolved Organic Matter
DS	= Downstream
EAWAG	= Swiss Federal Institute of Aquatic Science and Technology
LiDAR	= Light detection and ranging
N	= Nitrogen
NAQUA	= National Groundwater Monitoring
NAWA	= National Surface Water Quality Monitoring
NH₄⁺	= Ammonium
NO₃⁻	= Nitrate
US	= Upstream

1. Introduction

1.1 Context and relevance of the research field

Swiss rivers and streams build a branched network that spans a total length of 65'000 kilometers. Since the 1980s, investments in wastewater treatment and the prohibition of phosphates in detergents improved water quality. Nevertheless, various substances from urban and industrial areas, traffic infrastructure and intensive agriculture continue to pollute Swiss surface waters, contributing to the loss of aquatic biodiversity and the contamination of drinking water (BAFU (Hrsg.), 2022). The deficits in water quality are especially prominent in small watercourses (Strahler stream order 1 or 2), which constitute up to 75 % of the Swiss river network (BAFU (Hrsg.), 2016).

In 2021, the parliament implemented additional measures aimed at enhancing water quality, which included a directive that wastewater treatment plants should improve their removal of nitrogen and micropollutants from wastewater. The Swiss water protection legislation aligns with UN goals for sustainable development (BAFU (Hrsg.), 2022), with Goal 6 of the agenda stating that water quality must improve globally, and water connected ecosystems must be protected and restored (UN, 2015).

To evaluate water quality, the *Nationale Beobachtung Oberflächengewässerqualität (NAWA)* conducts surveys on nutrients, micropollutants and biological indicators at around 170 measuring sites (BAFU (Hrsg.), 2013). BAFU (Hrsg.) (2022) assess water quality based on the water protection ordinance (*Gewässerschutzverordnung, GSchV*), with annex 2 of the water protection ordinance outlining the requirements for surface water quality (Table 1).

Table 1: Extract from the water protection ordinance. Requirements to the water quality of surface waters (Bundesrat, 1998).

Parameter	Requirements
Nitrate (NO_3^- - N)	5.6 mg/l NO_3^- - N $\approx$ 25 mg/l nitrate For waters which serve as a source of drinking water.
Dissolved organic carbon (DOC)	1 to 4 mg/l The lower value applies to waters which are naturally only slightly polluted.
Ammonium (sum of NH_4^+ - N and NH_3 - N)	at temperatures: - above 10 °C: 0.2 mg/l N - below 10 °C: 0.4 mg/l N

1.1.1 Nitrate

Nitrate is the largest contributor to the nitrogen export from Switzerland via rivers to oceans, leading to over-fertilization of marine ecosystems (BAFU (Hrsg.), 2022). Hürdler et al. (2015) developed a model to estimate the nitrogen inputs into Swiss waters. Nitrogen inputs are distinct in point sources of pollution (sewage treatment plants and precipitation overflows) and diffuse sources (primarily agriculture and natural background loads). The model revealed annual diffuse nitrogen input of 51'493 t. Intensively cultivated areas on the Swiss plateau and large river valleys experience the highest nitrogen losses. Diffuse sources account for 68 % of the total nitrogen inputs, while point sources contribute 32 %. 35 % of the diffuse inputs are from natural background loads, while the remaining 65 % (33'000 t) are from anthropogenic sources. Cropland ($48 \text{ kg ha}^{-1} \text{ a}^{-1}$ and 38 % of the diffuse nitrogen inputs), horticulture ($42 \text{ kg ha}^{-1} \text{ a}^{-1}$), and viticulture ($33 \text{ kg ha}^{-1} \text{ a}^{-1}$) are the primary sources of nitrogen inputs per area among diffuse sources, while forested areas ($6 \text{ kg ha}^{-1} \text{ a}^{-1}$) contribute a relatively small amount, but due to their high areal distribution, they account for 14% of the diffuse nitrogen inputs. The input pathways for nitrogen are dominated by leaching to groundwaters (65 %), while leaching to surface waters is relevant as well (16 %) (Hürdler et al., 2015).

Nitrate concentrations in surface water (Figure 1) and groundwater (Figure 2) are highest in areas with intense agricultural land use and corresponding high nitrogen losses.

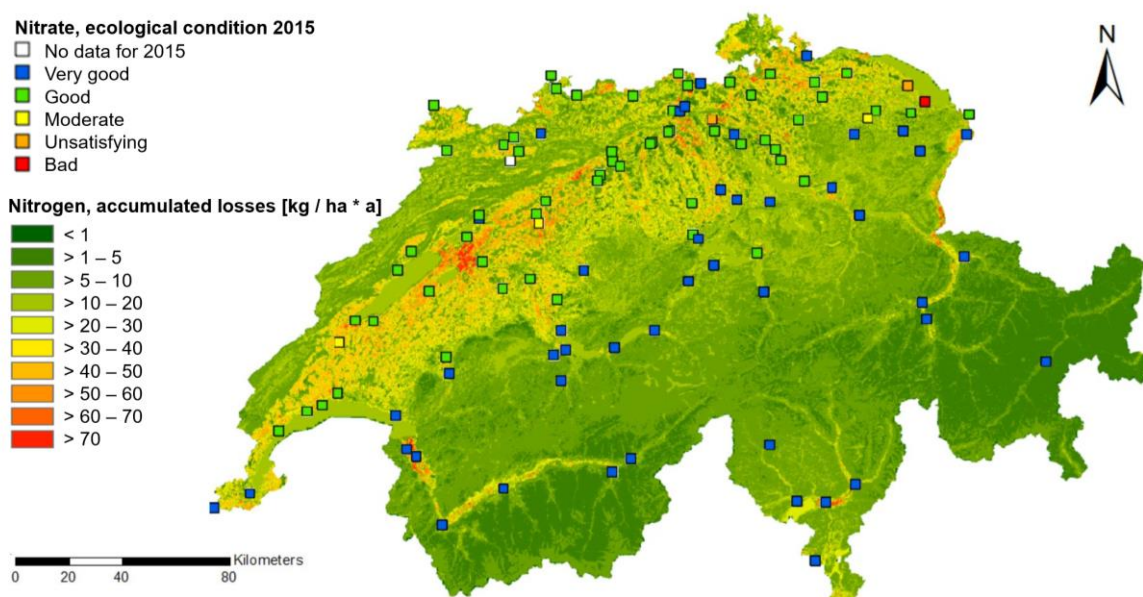
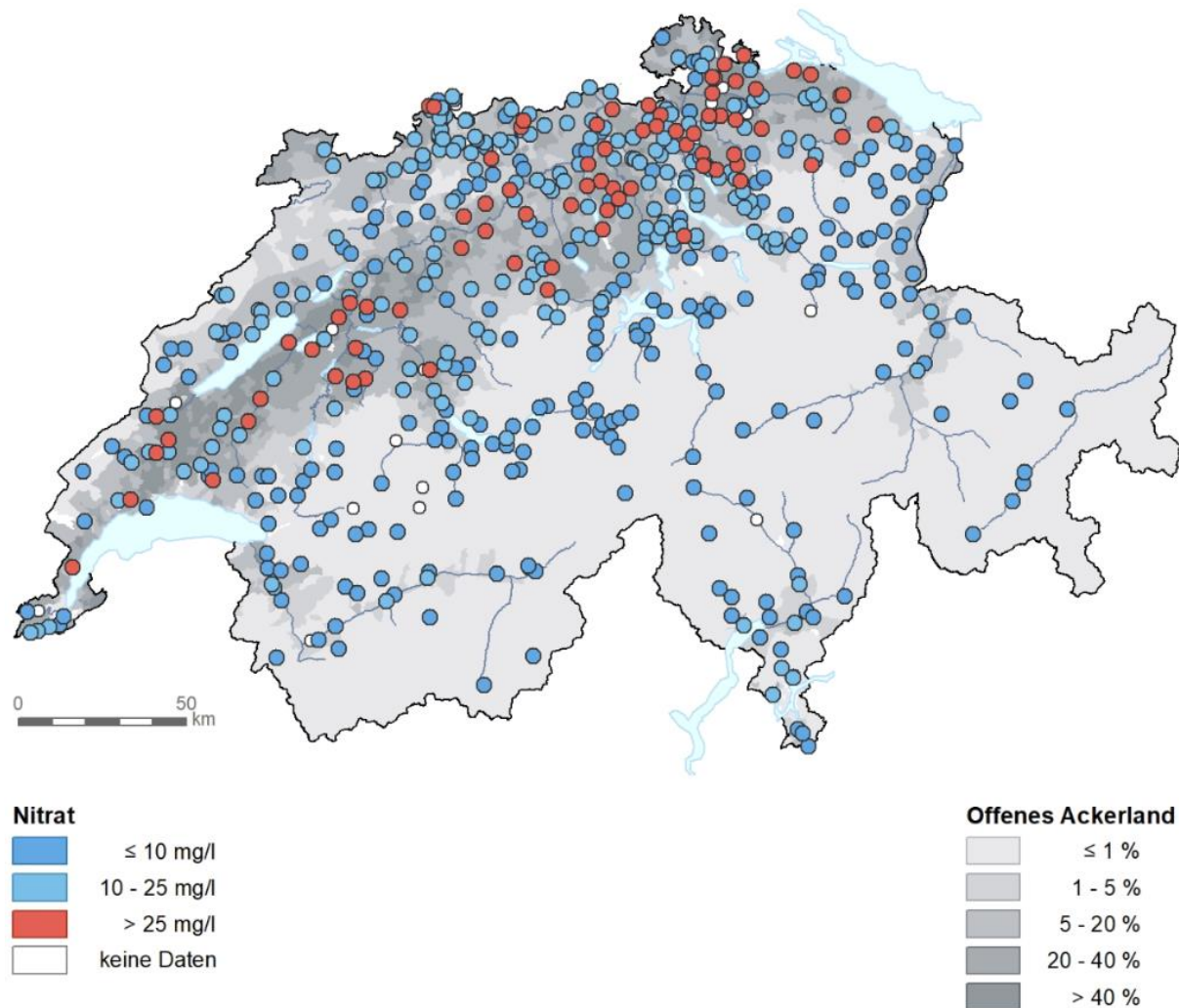


Figure 1: Stream conditions and nitrogen inputs. Assessment of stream conditions based on NAWA results from 2015. The evaluation from “Bad” to “Very good” corresponds to the European water framework directive (BAFU (Hrsg.), 2013). The background map represents the diffuse nitrogen inputs to water bodies (Hürdler et al., 2015).



Numerische Anforderung GSchV: 25 mg/l

Figure 2: Nitrate concentrations and intense agriculture. Nitrate concentration in groundwater measured in the NAQUA (BAFU (Hrsg.), 2019) project (Data from 2020) compared to the areas with intense agricultural land use. The nitrate threshold for groundwater is often exceeded in areas with a higher proportion of open cropland. Nearly 15 percent of the national groundwater monitoring sites exceeded the nitrate threshold for groundwater (25 mg/l). Graphic: (BAFU (Hrsg.), 2022).

Excursion nitrogen cycle:

The earth's atmosphere is composed of approximately 78 % nitrogen, mostly in the nonreactive form (dinitrogen, N_2). Nitrogen is essential because plants and animals need it as nutrient to grow and survive (Bashir et al., 2013). Living organisms require reactive forms of nitrogen, such as nitrate (NO_3^-) or ammonium (NH_4^+) (Medford & Hatzell, 2017). Unfortunately, excessive amounts of nitrogen released into the environment can cause environmental problems. "Excess fixed nitrogen, in various guises, augments the greenhouse effect, diminishes stratospheric ozone, promotes smog, contaminates drinking water, acidifies rain, eutrophies bays and estuaries, and stresses ecosystems" (Socolow, 1999).

Atmospheric nitrogen enters the biosphere through wet or dry **deposition** (Pan et al., 2012). Moreover, N_2 can be oxidized by lightnings. Schumann & Huntrieser (2007) estimated the global nitrogen mass of lightning-induced nitrogen on 2-8 Tg / a. In **nitrogen-fixation** bacteria convert atmospheric nitrogen (N_2) to ammonia (NH_3) by combining the nitrogen with hydrogen

(Mus et al., 2016). During the **ammonification** process organic nitrogen from dead plants, animals or manure is reduced to ammonium by bacteria and fungi (Stein & Klotz, 2016). Furthermore, there is an anthropogenic input of nitrogen in form of ammonia to soils: 1909 the **Haber-Bosch** process where nitrogen is industrially fixed into ammonia used as fertilizer was discovered. The usage of fertilizer increased agricultural productivity and averted a food crisis in the 20th century. The flipside of fertilizing soils is an over contribution of nitrogen to the environment and therefore degradation (Stein & Klotz, 2016). Prior anthropogenic intervention into the nitrogen cycle microorganisms were able to recycle almost all of the reactive nitrogen. Today more than half of the total global fixed nitrogen originates from anthropogenic sources (> 150 Tg) (Medford & Hatzell, 2017).

Nitrification is an aerobic process where ammonia is oxidized by microorganisms to nitrite and nitrate (Stein & Klotz, 2016). As this process happens readily the ammonia and ammonium concentration in soils is normally rather low (Di & Cameron, 2002). The nitrite and nitrate can be respired to the atmosphere through the denitrification process or it can be **assimilated** by plants (Stein & Klotz, 2016). **Denitrification** is an anaerobic process where nitrate acts as electron acceptor for oxidation of organic matter and is consequently converted to atmospheric gases (N_2). Denitrification is probably the most important removal mechanism for nitrate in surface waters (Burgin & Hamilton, 2007).

As nitrate is one of the most mobile ions in agricultural systems it is very susceptible to leaching (Follett & Delgado, 2002). **Leaching** causes nitrate in soils to enter groundwater through percolation or surface water through runoff. The requirements for leaching is an excess of nitrate in soil and a high water drainage (Di & Cameron, 2002). The potential for nitrate leaching for different land use analyzed by Di & Cameron (2002) “[...] followed the order: forest < cut grassland < grazed pastures < arable cropping < ploughing of pasture < market gardens”. The leaching losses of nitrate are further depending on the soil and the climate conditions as for example coarse-textured soils have a faster drainage and lower potential for denitrification which results in increased leaching (Di & Cameron, 2002). The amount of leaching in autumn and winter is higher than in spring and summer as there is more drainage partly due to lower evaporation and higher snowmelt. Moreover, the leaching in spring is lower as the increased plant growth demands more nitrate which reduces the nitrate available for leaching. Winter leaching of nitrate tends to be higher after hot, dry summers than after cool, wet summers because in dry summers the denitrification loss and the pasture nitrogen uptake is lower (Di & Cameron, 2002). Di & Cameron (2002) highlight the importance of strategies to mitigate nitrate leaching. The most obvious strategy is to avoid supplying more nitrogen than the plants demand. Knowledge on the plants demand is necessary as it differs between the various seasons. Further fertilizers should be limited before and during autumn and winter when the leaching is stronger. More strategies summarized by Di & Cameron (2002) are “Grow a cover crop in the autumn-winter periods”, “Delay the ploughing of pasture leys until late autumn or spring”, “Balancing input of other nutrients”, “Use of nitrification inhibitors”, “Improved stock management”, “Precision farming”, “The use of buffer zones”, “Whole farm budgeting”, “Regulation” or “Use of computer models to mitigate nitrate leaching”.

Two main problems result from nitrate leaching into surface- and groundwater: 1) Contamination of drinking water and 2) Eutrophication of surface water.

The contamination of food or drinking water can pose health risks to humans (Ward et al., 2018). The nitrate itself is regarded as non-toxic but the reduction of the ingested nitrate leads to the formation of the toxic nitrite (Brender & Brender, 2020). Nitrite is a risk for infant methemoglobinemia (blue-baby syndrome) (Knobeloch et al., 2000). Moreover, there is a risk for cancer or birth defects with nitrate ingestion (Ward et al., 2018). The world health organization (WHO) established the guideline value for nitrate in drinking water on 50 mg/l (for nitrite 3 mg/l) in the fourth edition of “Guidelines for Drinking-water Quality” (WHO, 2022).

Dissemination of nitrate into surface waters or groundwater through seepage can cause **eutrophication** of aquatic systems (Bashir et al., 2013). Eutrophication is a one of the most serious environmental problem for our surface water resources (Smith et al., 2006). Eutrophication comes from the Greek expression *eutrophos* meaning well-nourished (American Heritage Dictionary, 2018). The German Duden describes the eutrophication as unwanted increase of nutrients in a water body and the associated useless and harmful plant growth (Duden-redaktion, 2020). Nutrients responsible for the eutrophication of ecosystems are particularly phosphorus and nitrogen (Carpenter et al., 1998). The eutrophication in lakes is mainly due to the phosphorus (Schindler, 1977) whereas in coastal ecosystems the nitrogen is responsible (Nixon et al., 1996). Eutrophication can lead to excessive algae growth which endangers the aquatic life due to oxygen depletion and reduction of light input (Bashir et al., 2013). The bacterial decomposition of the excess biomass consumes a lot of oxygen leading to anoxia (Carpenter et al., 1998).

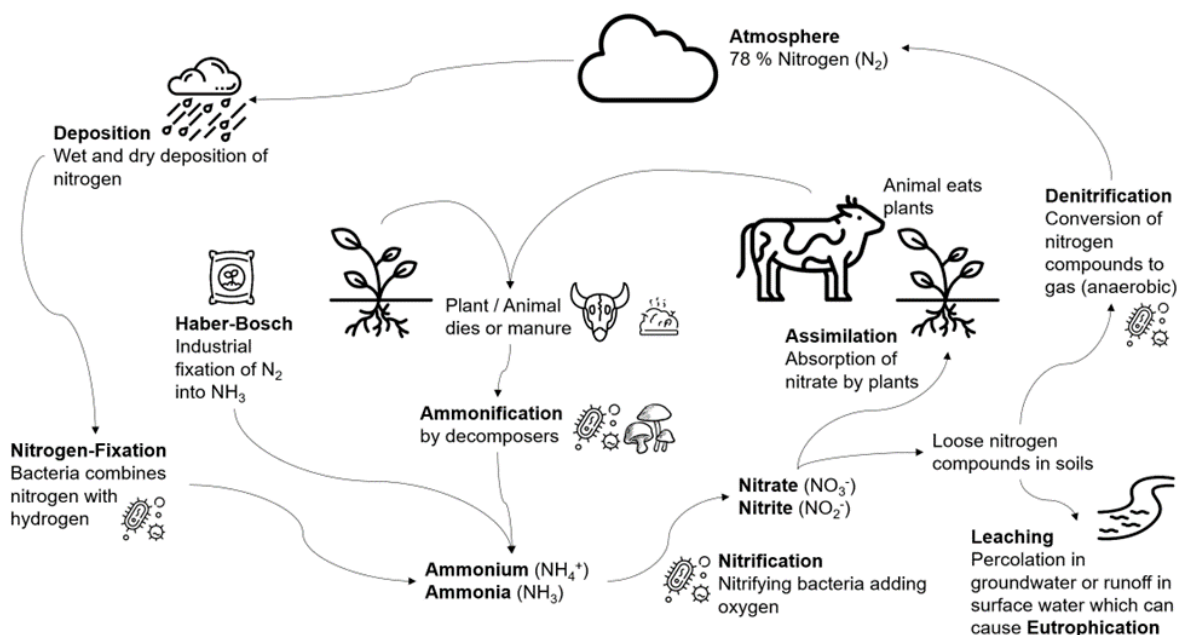


Figure 3: Simplified illustration of the nitrogen cycle. Own illustration with icons from Flaticon (2023).

1.1.2 Dissolved Organic Carbon (DOC)

The average DOC concentration 2011-2020 from the NAWA exceeded the threshold in 18 % of the 95 measuring stations (BAFU (Hrsg.), 2022). Same as for nitrate the DOC concentration in surface water is worst in areas with intense agricultural land use (Figure 4).

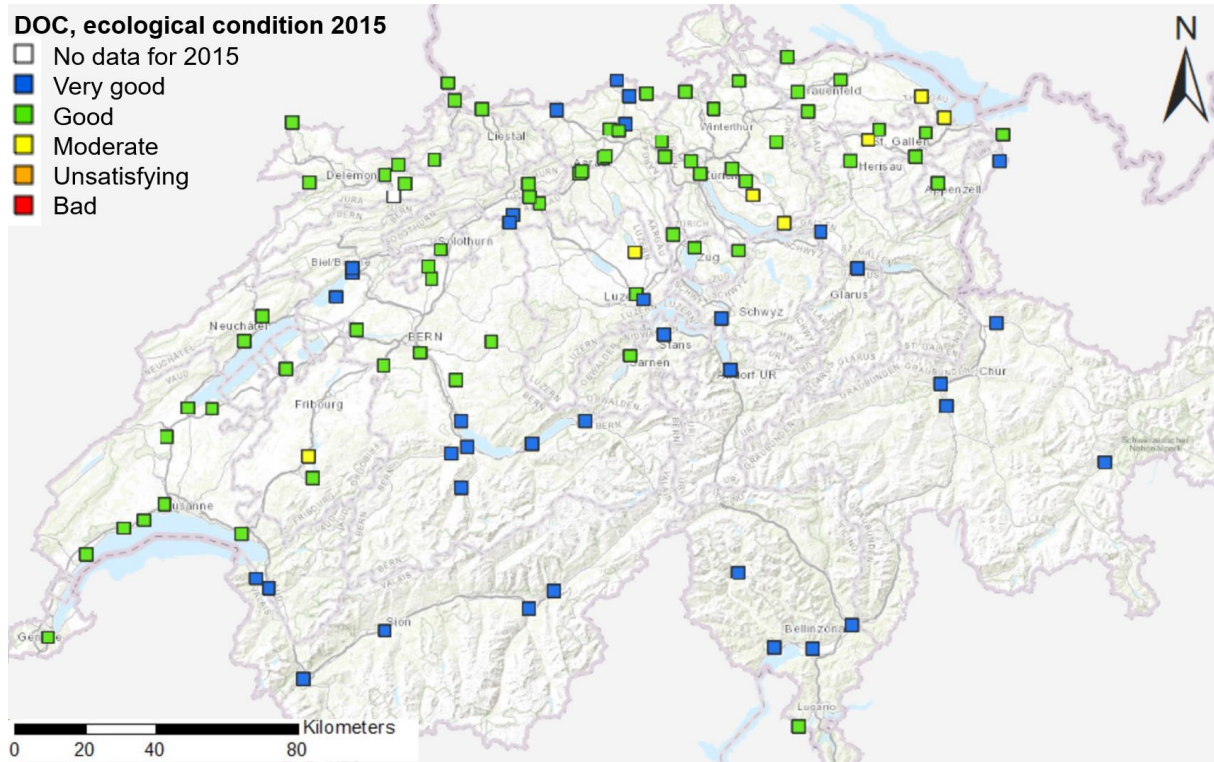


Figure 4: NAWA DOC measurements. Assessment of stream conditions based on NAWA (BAFU (Hrsg.), 2013) DOC results from 2015. The evaluation from “Bad” to “Very good” corresponds to the European water framework directive. Background map: (swisstopo, 2021).

Excursion DOC:

Dissolved organic carbon (DOC) is a part of dissolved organic matter (DOM). Besides DOC, DOM also includes the mass of other elements such as nitrogen, oxygen and hydrogen (Kiss et al., 2002). Globally the amount of DOC in marine and freshwater is equal to the amount of carbon in the earth atmosphere (Hedges, 1992). Organic carbon originates from decomposition of decaying plants or animals (Robertson & Paul, 2000). DOC can originate from algae or other aquatic plants, terrestrial plants or soils (Kritzberg et al., 2004). Winterdahl et al. (2016) investigated the sensitivity of DOC concentrations to changes in temperature and discharge and found a positive correlation. DOC is temperature regulated as biological processes and growth increases with temperature (Ratkowsky et al., 1982). The DOC concentration affects water quality and ecosystems where a high concentration is generally not beneficial to the ecosystems health because it can lead to darker water which reduces the light input and consequently the photosynthesis (Houser et al., 2003). In addition, a high DOC concentration can lead to reduced dissolved oxygen levels which is problematic for fish and other organisms (Murdoch et al., 2021).

1.2 Excursion: The Beaver (in Switzerland)

There are two distinct species of beaver: the Canadian beaver (*Castor canadensis*, Kuhl 1820) and the European beaver (*Castor fiber*, Linnaeus 1758) (Zahner et al., 2021). Beavers are the second-largest living rodents after the capybaras (Heard, 2014), with adults reaching a total length up to 135 cm and weight up to 22-25 kg (Zahner et al., 2021). The average life expectancy of a beaver is 8 years, and they have 2-3 young per litter (maximum five). Beavers are herbivores with a food choice determined by the season. In summer and spring, beavers primarily feed on herbaceous plants, leaves, grasses, herbs und aquatic plants. In autumn and winter they eat woody plants as tree barks. Beavers especially like to eat corn, sugar beets, wheat and canola. The beaver has the ability to build dams, which it does for three primary reasons (Zahner et al., 2021):

1. Prevention of drying / freezing of the water body.
2. Security from enemies due to high water level and securing the entrance of the beaver lodge.
3. Development of food sources and transport routes for food and building materials.

There are various types of beaver-modified landscapes, such as single beaver dams, beaver dam cascades and beaver meadows. These distinct types are summarized in this work as “Beaver reach”, which represents the beaver impacted area between the upstream and downstream water sampling location.

The characteristics of beaver dams and ponds (location, size, permeability, etc.) exhibit significant variability (Figure 5). Depending on the pond expansion opportunities ponds can be spatially extensive and shallow or steeper (Chaubey & Ward, 2006). The floodplain can be inundated permanently or temporarily when the water level in the channel exceeds the floodplain height leading to increased lateral connectivity between channel and floodplain (Larsen et al., 2021).

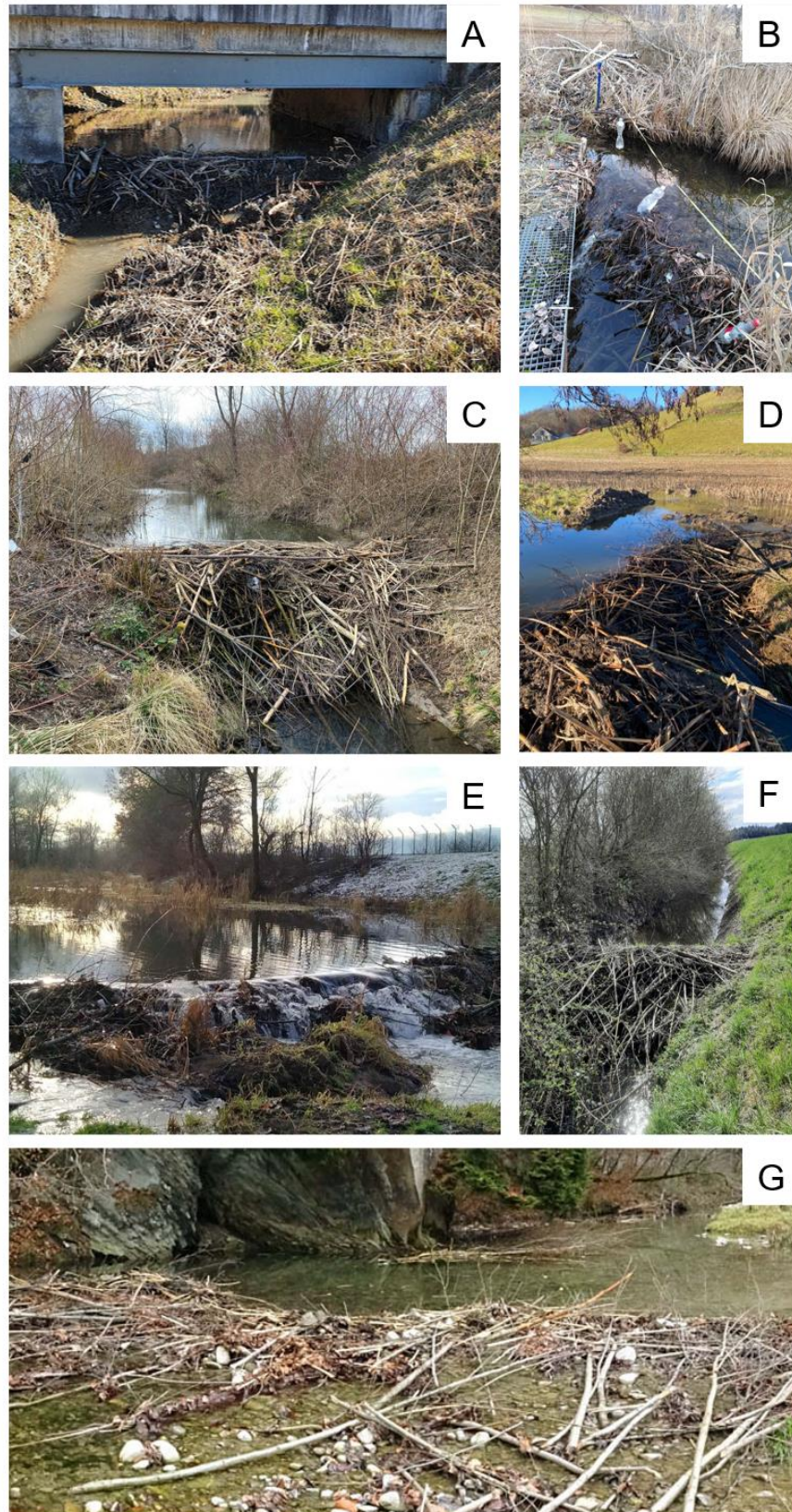


Figure 5: Examples of beaver dam types. Pictures taken by the volunteers during the winter sampling. (A) Beaver dam under a bridge, (B) anthropogenic intervention on dam height with electric fence, (C) high and (almost) impermeable dam, (D) flooding of field by dammed water, (E) dam with large beaver pond, (F) anthropogenic channelization upstream, (G) strongly permeable dam.

Historically, beavers were widely distributed across the northern hemisphere, although their distribution area was limited by the temperature in the north and south (Zahner et al., 2021). The global population before extermination is estimated around 100 million in Eurasia and 60 to 400 million in North America (Djoshkin & Safanov, 1972; Zahner, 1997). During the last centuries, beavers were nearly eradicated by hunting, with only a few thousand individuals remaining (Zahner et al., 2021). In Switzerland, the last autochthonous beavers were exterminated at the beginning of the 19th century (Stocker, 1985).

Conservation and reintroductions in several phases have led to a comeback of beavers in the 20th and 21st centuries in Europe and North America (Zahner et al., 2021). The population of the Eurasian beaver is currently estimated at approximately 1.5 million (Halley et al., 2021). In Switzerland, 141 beavers were released at 30 sites between 1956 and 1977 (Minnig et al., 2016), leading to slow initial population growth, followed by a rapid increase since 2000, resulting in a beaver population of 1'600 across the country in 2008 (Angst, 2010). The beavers in Switzerland are mainly distributed on the Swiss plateau (Figure 6).



Figure 6: Distribution of beavers in Switzerland in 2008. Map is based on the national beaver population survey in the year 2008 when the beaver population was 1'600 (Infofauna, 2008).

Wright et al. (2002) describe the beaver as an *ecosystem engineer*. An *ecosystem engineer* must have the ability to “[...] create a patch with a combination of conditions not present in the landscape [...]” and that “[...] there must be a species that can live in the engineered patches that are not present in patches unmodified by the engineer” (Wright et al., 2002). These two criteria are met by the beaver with its ability to build dams leading to changes in the character of the river, the river habitats and ecosystems (Müller & Watling, 2016).

Ecosystem services are benefits that humans derive from ecosystems (Daily & Matson, 2008). The beaver provides valuable ecosystem services, such as water retention during flood events, water storage during dry periods, groundwater recharge, water purification or sediment retention (Zahner et al., 2021). Moreover, the creation of floodplain wetlands can lead to biodiversity increases (Larsen et al., 2021). These benefits are especially important in the context of the ongoing revitalization of Swiss streams. Since the 18th century, water corrections have been carried out on large scale (BAFU (Hrsg.), 2022), leading to a decline of floodplain areas by ~ 90 % since 1850 (Müller-Wenk, 2003). The amendment to the Waters Protection Act (WPA) in 2011 determines that a quarter of the constructed stretches of Swiss waterways, i. e. 4'000 km, must be revitalized by 50 years from 2011 (BAFU (Hrsg.), 2022).

Despite ecological benefits from the beavers' activities, its creative urge can lead to conflicts with human land use, such as undermining, dam building, tree felling and crop feeding. Therefore, the coexistence of beavers and humans requires beaver management strategies. In Switzerland, the cantons are responsible for the beaver management (Zahner et al., 2021).

1.3 State of the research

Beavers are recognized as keystone species and ecosystem engineers due to their impacts on the environment (Grudzinski et al., 2022). Acknowledgement is growing that beaver systems tend to improve water quality (Burchsted et al., 2010). This chapter gives a brief overview on the state of research of beaver systems impacts on hydrology (chapter: 1.3.1), geomorphology (chapter: 1.3.2) and ecosystems (chapter: 1.3.3). The chapter 1.3.4 on biogeochemical processes is more in detail: 1) Summary of two literature synthesis 2) Impact of beaver systems on nitrogen cycle (focus nitrate) 3) Impact of beaver system on the carbon cycle (focus DOC) 4) Further biogeochemical impacts. A case study outlining the potential for nitrate removal in a beaver system in a meandering river is provided in Appendix A.

1.3.1 Hydrology

Beaver dams reduce the flow velocity of water and increase the water level on the upstream subsequently altering the downstream discharge. The increased water residence time upstream of the beaver dam can have impacts on water temperatures, water storage capacity and evaporation. Furthermore, the potential for ground- and surface water interactions (hyporheic exchange) is enhanced upstream of beaver dams (Figure 7) (Larsen et al., 2021).

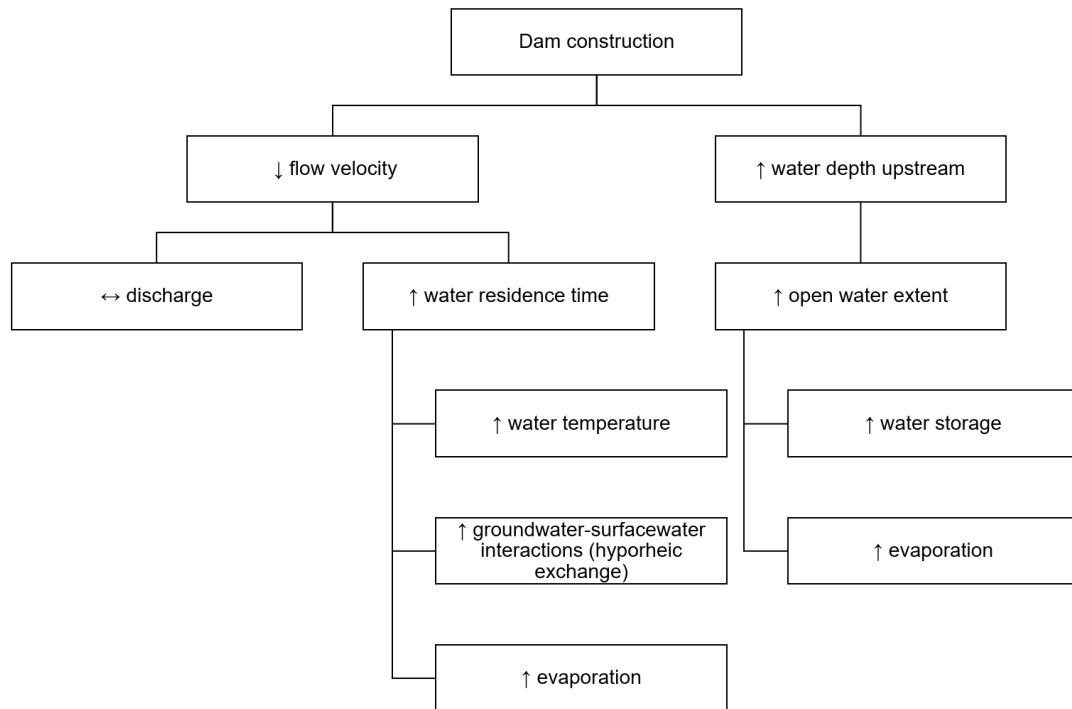


Figure 7: Impacts of beaver systems on hydrology. The illustration is based on the literature review of Larsen et al. (2021) and the arrows indicate: ↔=change, ↓=decrease, ↑=increase.

1.3.2 Geomorphology

Beaver dams and the associated reduced flow velocity limit the longitudinal sediment connectivity, resulting in a delay in downstream sediment transport. Sediment is accumulated upstream of beaver dams, leading to the formation of sediment wedges. During high discharge events, the deposited sediment can be mobilized, and beaver dams may breach, releasing retained water and sediment. Beavers also dig small canals and wider channels, increasing lateral hydrological connectivity. The burrowing activities of beavers can lead to destabilization and erosion of banks. Moreover, the removed material from this building activities is a sediment source not to be neglected (Figure 8) (Larsen et al., 2021).

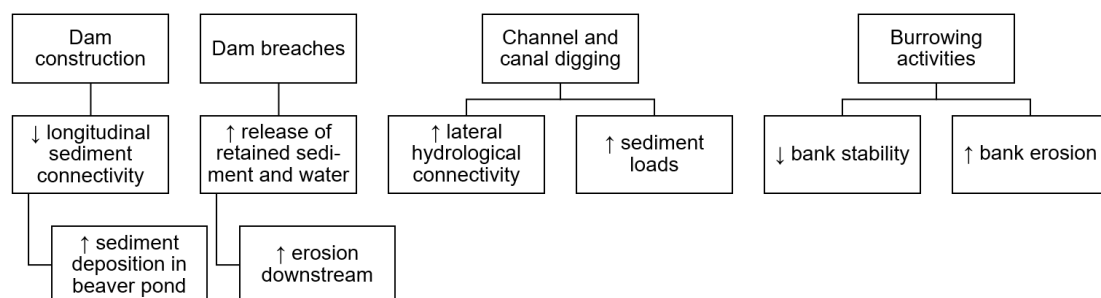


Figure 8: Impacts of beaver systems on geomorphology. The illustration is based on the literature review of Larsen et al. (2021) and the arrows indicate: ↔=change, ↓=decrease, ↑=increase.

1.3.3 Ecosystems

The beavers' activities and systems have a strong impact on aquatic and riparian ecosystems (Figure 9). Beaver dams transform water from lotic (flowing water) conditions to a mix of lotic and lentic (still water) conditions. This shift in conditions, coupled with increased light availability, potentially increases ecosystem productivity (Larsen et al., 2021).

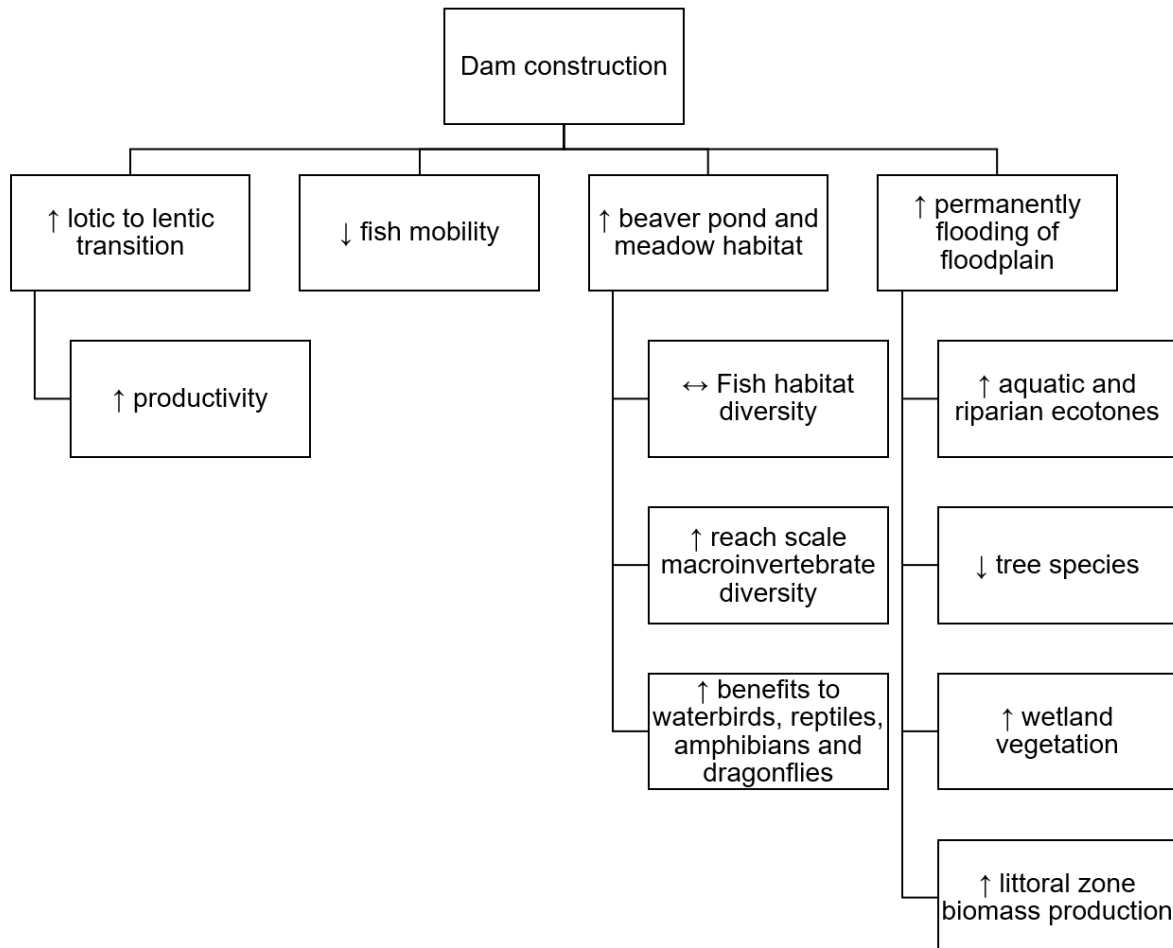


Figure 9: Impacts of beaver systems on ecosystems. The illustration is based on the literature review of Larsen et al. (2021) and the arrows indicate: ↔=change, ↓=decrease, ↑=increase.

1.3.4 Biogeochemistry

1.3.4.1 Summary of two literature synthesis (nitrate and DOC)

Beaver systems are known to have the capacity to impact water quality parameters. Literature syntheses by Grudzinski et al. (2022) and Larsen et al. (2021) indicate a clear trend towards decreased nitrate concentrations and increased DOC concentrations downstream of beaver systems (Figure 10 and Figure 11).

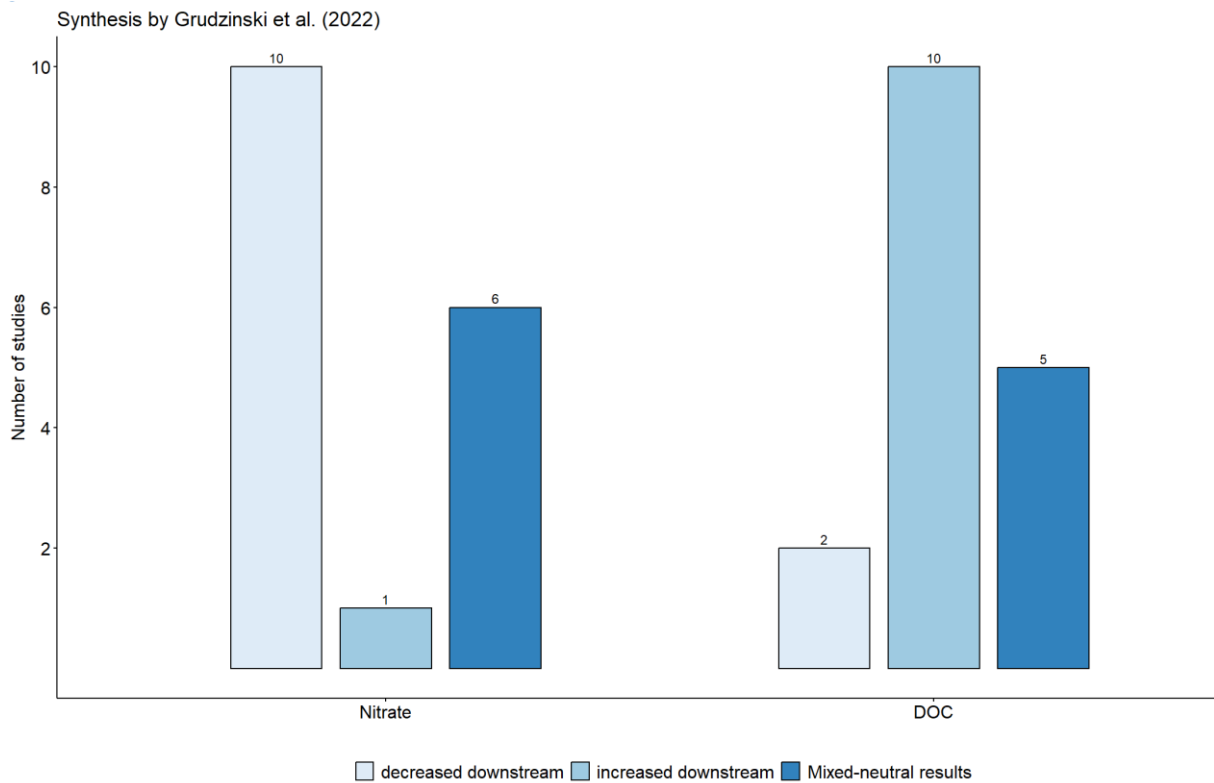


Figure 10: Synthesis by Grudzinski et al. (2022). Beaver impacts on nitrate and DOC concentrations.

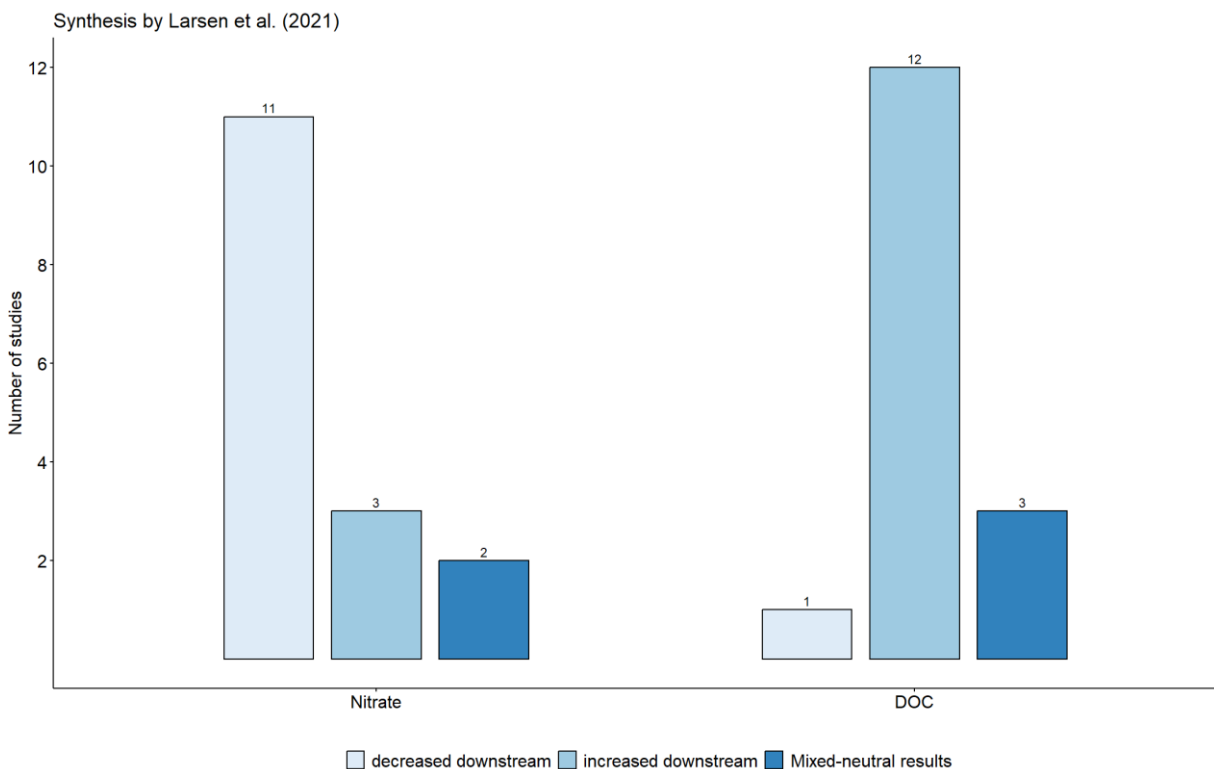


Figure 11: Synthesis by Larsen et al. (2021). Beaver impacts on nitrate and DOC concentrations.

“[...] from a mass balance perspective the development of beaver ponds, wetlands and meadows may create both sources and sinks of e.g. carbon, nitrogen, and phosphorus in the riverine nutrient cycles” (Larsen et al., 2021). A conceptual model of beaver impacts on biogeochemistry and water quality is presented in Figure 12.

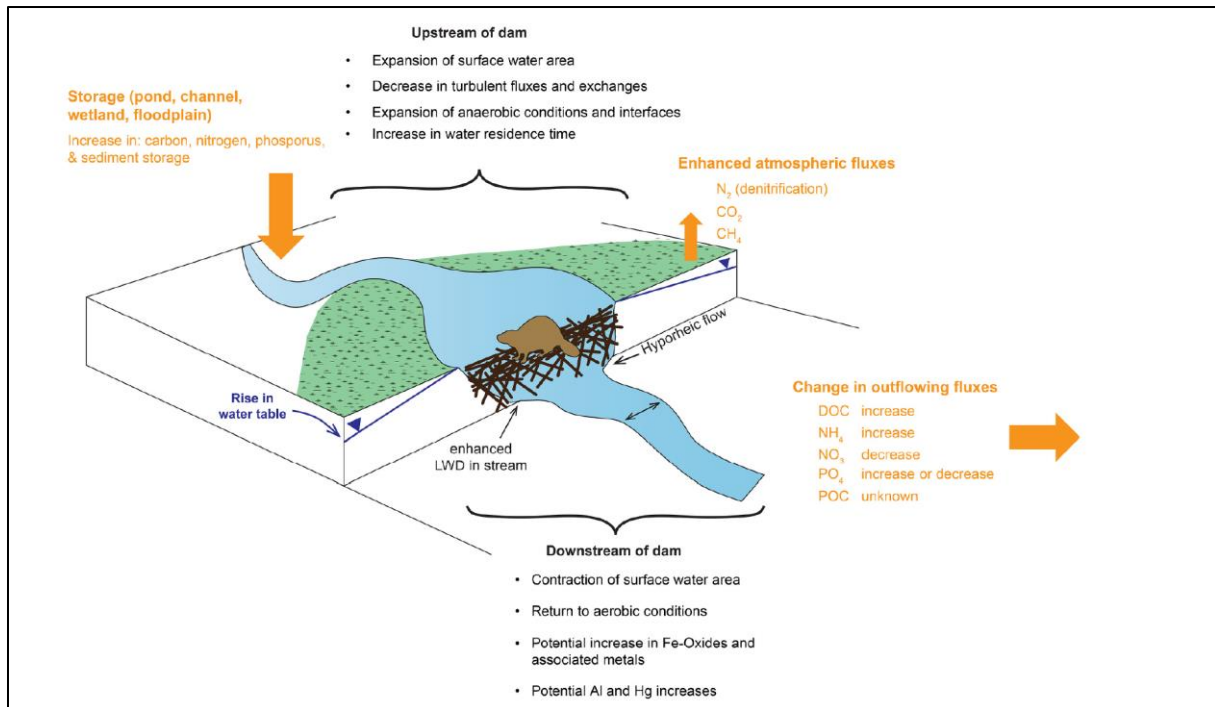


Figure 12: Conceptual model of beaver impacts on biogeochemistry and water quality (Larsen et al., 2021).

1.3.4.2 Impacts of beaver systems on the nitrogen cycle (focus nitrate)

Nitrogen accumulation tends to be increased within beaver impacted systems. A study estimated 9 to 44 times higher total nitrogen accumulation in beaver dammed areas than in the absence of beaver dams (Francis et al., 1985). The increased nitrogen accumulation can be attributed to:

- 1) Spatial increase in biofilm extent across sediments offers more potential for nitrogen fixation and decomposition processes to occur (Francis et al., 1985).
- 2) Increased sequestration of organic matter inputs (Devito & Dillon, 1993).
- 3) Inputs through the beavers' consumption of vegetation and their waste (Naiman & Melillo, 1984).
- 4) Uptake of inflowing nitrogen, especially nitrate and ammonium, by wetland vegetation (seasonal storage) (Devito & Dillon, 1993; Naiman & Melillo, 1984).
- 5) Decay of biomass under anaerobic conditions (ammonification) releasing ammonium within sediment and soil pore waters (Naiman et al., 1994).

Increased surface water extent, temperatures and floodplain water levels as well as decreased turbulences enhance anaerobic conditions upstream of beaver dams (Naiman et al., 1994). The extension of anaerobic conditions is prominent for surface water with permanently limited turbulence such as benthic ponds or wetlands (Battin et al., 2016) or in saturated floodplain or meadow soils (Larsen et al., 2021).

The increased spatial extent of anaerobic conditions and the turn down of organic matter cycling are fundamental for the denitrification process, which reduces nitrate to atmospheric nitrogen, allowing nitrogen to be lost to the atmosphere (see Denitrification 1.1.1) (Larsen et al., 2021). The denitrification process in beaver impacted areas primarily occurs within benthic biofilms and subsurface microbial communities (Lazar et al., 2015). Naiman et al. (1994) established denitrification rates from the beaver ponds and meadows twice as high as from the nearby forest. Highest denitrification rates were measured in summer (Naiman et al., 1994).

Another factor reducing nitrate concentrations within beaver systems is the uptake of biomass, particularly by macrophytes (aquatic plants) and biofilms (Devito and Dillon, 1993). The breakdown of organic matter in beaver ponds results in increased ammonium concentrations (chapter: 1.1.1: ammonification) which can subsequently undergo oxidation to nitrate (chapter: 1.1.1: nitrification) if the water returns to aerobic conditions.

The potential for re-oxidation of ammonium in downstream aerobic conditions is dependent on the rates of ammonification processes occurring upstream. Nitrate reduced through denitrification undergoes conversion into atmospheric nitrogen, leading to its removal from the beaver system. Conversely, when nitrate is reduced through ammonification, it results in the formation of ammonium, which remains within the beaver system and retains the potential for re-oxidation (Larsen et al., 2021).

The findings regarding the impact of beaver systems on the nitrogen cycle align with an analysis conducted by Saunders & Kalff (2001) on river systems flowing through wetlands and lakes without the presence of beaver dams. In those systems, losses in nitrate concentration were primarily due to denitrification, followed by nitrogen sedimentation and uptake by aquatic plants (Saunders & Kalff, 2001). Beaver activities contribute to the creation of wetlands (Lazar et al., 2015), which have potential for nitrogen removal (Cheng et al., 2020). Jordan et al. (2011) estimated that in the wetlands of the United States, a substantial amount of 5'800 kilotons of nitrogen can be removed annually. Lazar et al. (2015) summarized the denitrification rates from various studies conducted in different types of wetlands (Figure 13).

Study	Setting	Denitrification
		mg N m ⁻² d ⁻¹
Naiman et al., 1994	beaver pond	2.0
Naiman et al., 1994	wet meadow	2.6
Batson et al., 2012	constructed wetland	3.4
Song et al., 2012	constructed wetland	0.8–15.8
Bonnett et al., 2013	wetland	17.9
Scott et al., 2008	constructed wetland	16.8
This study	beaver ponds	97–236
Xue et al., 1999	constructed wetland	48–283
Xue et al., 1999	constructed wetland	48–223
Vecherskiy et al., 2011	beaver pond	266
David et al., 2006	reservoir in agricultural landscape	170–616

Figure 13: Denitrification rates in different types of wetlands (Lazar et al., 2015).

1.3.4.3 Impacts of beaver systems on the carbon cycle (focus DOC)

Floodplain inundation and tree felling by beavers contribute to a reduction in carbon stored within standing vegetation (Naiman et al., 1994). Through accumulation of organic matter on the mineral soil surface (littering), carbon is stored at the surface of beaver meadows. Carbon storage is higher in impounded soils compared to unimpounded soils (Johnston, 2014). The rate of carbon accumulation in the soil depends on the net primary production and the decomposition rate of plant litter (Rees et al., 2005). Reduced drainage conditions promote soil organic carbon sequestration (Tan et al., 2004), as the decomposition rates are significantly lower under anaerobic conditions compared to aerobic conditions (Updegraff et al., 1995). It is important to note that the impact of beaver systems on carbon storage is not always substantial. For instance, a study conducted in Minnesota revealed that 70 % of the beaver-occupied sites were already peatlands or wetlands before the appearance of the beaver, which naturally have comparably high levels of carbon storage (Naiman et al., 1994). DOC concentrations can fluctuate strongly in summer and autumn due to intense macrophyte growth and bacterial production (Mann & Wetzel, 1995).

The increased DOC concentrations downstream of beaver systems (chapter: 1.3.4.1, Figure 10 and Figure 11) might be attributed to increased organic carbon production and storage within beaver systems as well as increased water residence time in beaver systems leading to a net increase in DOC concentration (Larsen et al., 2021). X. Wang et al. (2018) attributed the increased DOC concentrations downstream to interactions of the ponded water with soil carbon in flooded riparian areas, caused by raising water levels resulting from beaver damming. The findings for beaver systems align with observations for in-network lakes and wetlands, where the increased DOC concentrations are attributed to enhanced aquatic net ecosystem production in lentic environments (Kalinin et al., 2016). Nummi et al. (2018) associate the increased DOC concentrations with the decomposition of organic matter in beaver systems.

1.3.4.4 Other impact on biogeochemical processes

Beaver ponds and wetlands are expected to increase the retention of total sorbed and particulate phosphorus (Devito & Dillon, 1993). There is a contrast between enhanced phosphorus retention and potential for its release under anaerobic conditions which lead to inconsistent patterns of beaver system impacts on phosphorus concentrations (Larsen et al., 2021).

Increased water, sediment and nutrient storage resulting from beaver damming may potentially affect the cycling of contaminants such as pesticides, pharmaceuticals and microplastics. Moreover, beaver systems may increase the storage and retention capacity of microplastics and other particulate urban or industrial pollution (Larsen et al., 2021).

Beaver dams disrupt the river continuum concept (RCC) by transition of lotic (flowing water) into a mix of lotic and lentic (standing water) conditions (Larsen et al., 2021). The disruption of fluvial continuums creates a system which evolves over time to more open river corridors comprised of wetlands and meadows instead of tall riparian forests (Burchsted et al., 2010). The transition to lentic conditions is attributed to the longitudinal decrease and lateral increase of water connectivity resulting in a rise of the shallow groundwater table (Polvi & Wohl, 2012; Wohl & Beckman, 2014). The shallower groundwater table causes an expansion of benthic

habitats in ponds and backwater channels as well as littoral habitat in riparian areas and flood-plain wetlands (Polvi & Wohl, 2012). Wetland vegetations and littoral zone biomass production in lentic zones are affecting nutrient exchange processes which could explain the increased export of DOC from beaver systems (Larsen et al., 2021).

1.4 Research objectives

Given the increasing extent of beaver dams across Swiss river networks, the capacity for these dams to provide natural benefits to pollution problems, particularly nitrogen loads, is essential information for decision makers and land users in Switzerland.

It is known from the literature that beaver systems tend to decrease the nitrate concentrations and increase the DOC concentrations in surface waters (chapter: 1.3.4.1, Figure 10 and Figure 11). Yet the beaver system characteristics determining the extent of these impacts remains unclear.

The goal of this project is to evaluate how water quality is influenced by beaver systems in their spatial variation across Switzerland, and which beaver dam systems might be most effective in delivering the important ecosystem service of water quality improvement.

In the frame of this master thesis, the following questions will be addressed:

1. What are the spatial and seasonal patterns of riverine nitrate and DOC concentrations upstream and downstream of beaver systems throughout Switzerland?
2. Which characteristics of beaver systems (water residence time, number of dams, slope of the beaver reach, etc.) determine the extent of beaver system impacts on riverine nitrate and DOC concentration?

By answering these questions, the aim is to contribute valuable insights into the role of beaver systems in improving water quality and provide guidance for management strategies.

2. Study setup

This master thesis is a quantitative study that aims to investigate the impact of beaver systems on water quality across Switzerland. Beaver systems were identified and localized during the national beaver monitoring between December 2021 and April 2022, a project launched by the Swiss Federal Office for the Environment (FOEN). Since 2008 no national beaver census has been conducted, but since then a lot has changed in the beaver population dynamics. To obtain a comprehensive understanding of the beaver population, which is crucial for effective beaver dam management, a national beaver census was scheduled for winter 2020/21. Due to the COVID-19 pandemic, the beaver census was postponed by one year. The census was conducted in winter, as the beaver activity is particularly prominent at this time of the year, which makes the mapping easier than in summer (Zahner et al., 2021). From December 2021 to April 2022, 313 volunteers surveyed 7'000 km of the Swiss river network to identify signs indicative of beaver presence. As part of this survey, water samples were collected upstream and downstream of beaver systems. In order to examine seasonal variability, the same sites were resampled in summer 2022 by two civil servants for infauna (Owen and Mael) and two master students (Raphael and Kaspar).

The location of the beaver reaches, along with the laboratory results from the water samples build the data basis for this master thesis. 1044 beaver dams were documented during the beaver monitoring in winter 2021/2022. 165 beaver reaches were sampled in summer and winter, while 83 beaver reaches were sampled either in winter or summer (Figure 14). The focus of this master thesis lies on the 165 beaver reaches sampled in both seasons, allowing a comprehensive analysis of seasonal variations.

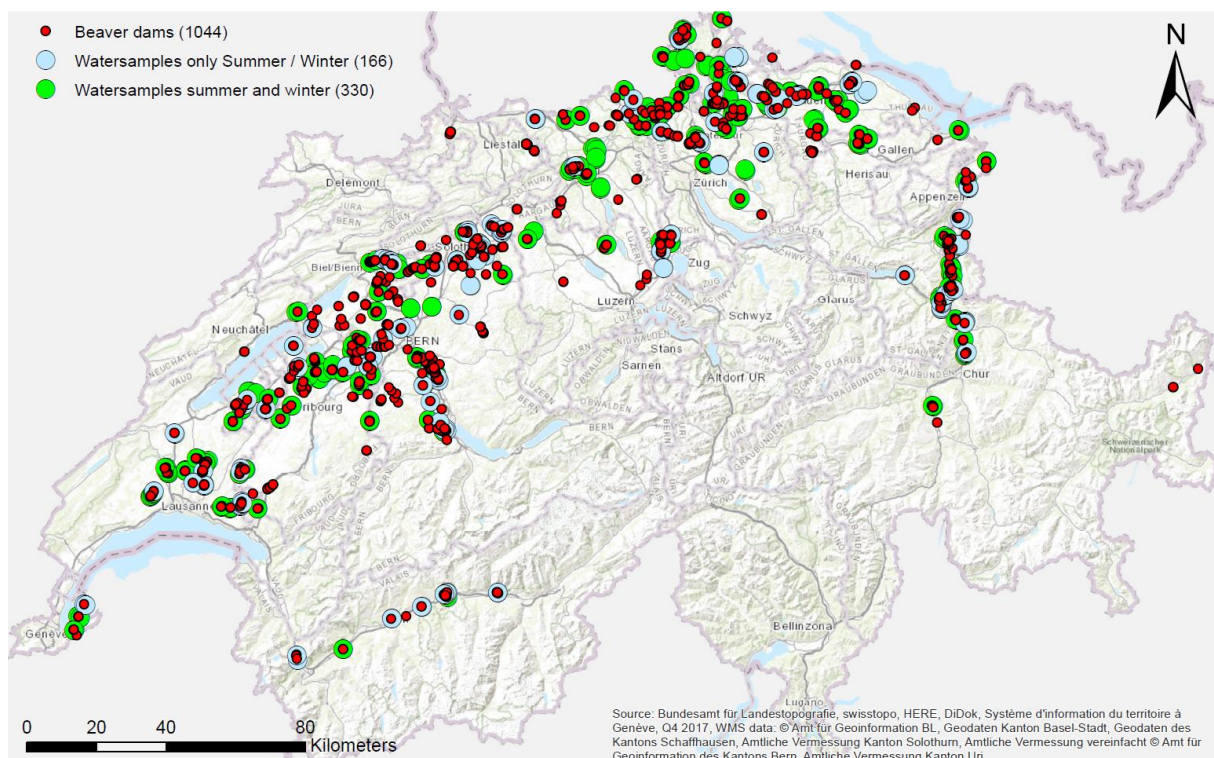


Figure 14: Beaver dams and the sampling locations. Background map: (swisstopo, 2021).

The documented beaver dams are predominantly located on the Swiss plateau (Figure 14). The Swiss plateau belongs to the temperate climate zone according to Köppens climate classification (Blumer, 2015). In an average year, the region receives a precipitation range of 800 to 1400 mm, predominantly as rain. During the winter months, frost (min. temperature 2 m above ground $< 0^{\circ}\text{C}$) is common. In contrast, the summer months experience a few dozen summer days (max. temperature 2 m above ground $> 25^{\circ}\text{C}$) (MeteoSchweiz, 2014).

According to the climate bulletin, the winter 2021/22 exhibited moderate conditions across the country, regionally sunny and notably dry in the south. In February, temperatures across Switzerland were approximately 2°C higher than the average recorded between 1991-2020. January and February were both exceptionally sunny throughout Switzerland (MeteoSchweiz, 2022b).

Summer 2022 was the second warmest since records began in 1864. The summer temperatures were 2.3°C higher than the 1991-2020 average. The heat began unusually early in June and persisted throughout July and August. The heat was accompanied by a prolonged period of insufficient rainfall. Across many regions, the precipitation levels from June to August reached between 60 % and 80 % of the average precipitation recorded between 1991 and 2020. Particularly in July, when a majority of the samples were collected, some regions of Switzerland received less than 30 % and locally less than 10 % of the normal precipitation (MeteoSchweiz, 2022a).

3. Data

An overview of the data generation and collection process is presented in a flowchart (Figure 15). The complete dataset is digitally available.

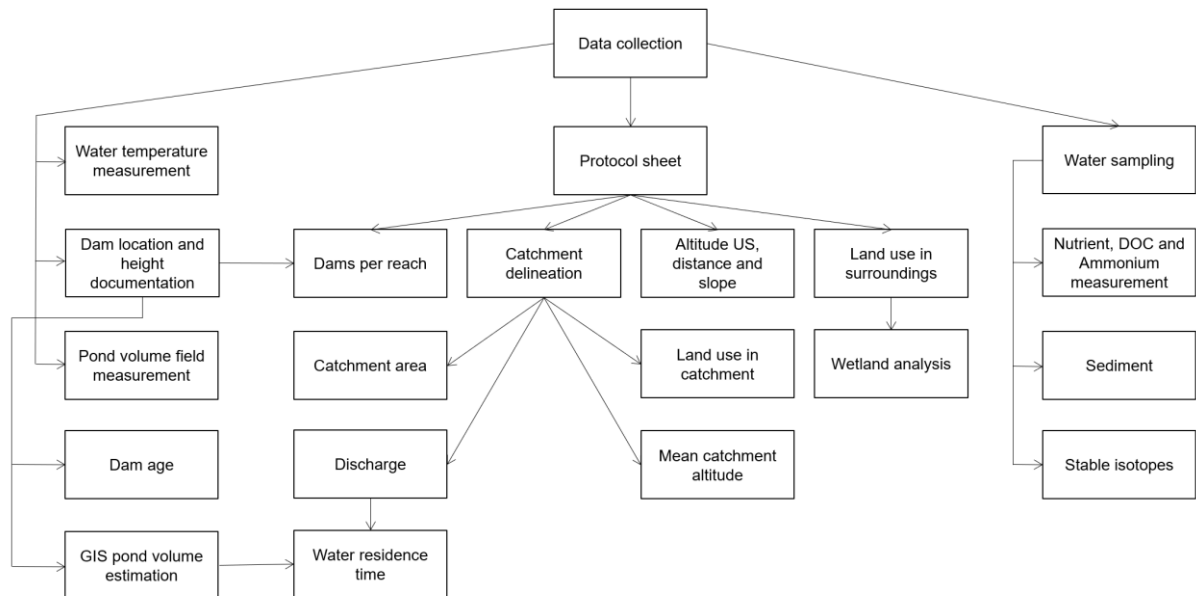


Figure 15: Flow chart of the data generation process. Planning and analysis steps are not depicted in this flowchart.

4. Methods

In this chapter, I present the methodological framework developed to address the research questions (chapter: 1.4). A different selection of methods, mainly quantitative, is applied in this framework. The main work packages involve water sampling, measurement of water samples, data cleaning, determination of beaver system characteristics and data analysis.

4.1 Beaver survey and water sampling by volunteers

During the winter of 2021/22, the national survey of beaver populations was conducted by 313 volunteers. The survey enabled to locate beaver reaches (survey) and water samples were taken upstream (US) and downstream (DS) of beaver systems (water sampling). Regional coordinators instructed the volunteers prior the survey and water sampling. Further the volunteers got written instructions as well as tutorial videos in order to fulfil their task successfully.

4.1.1 Beaver survey

The second Switzerland-wide beaver survey has been organized by the Biberfachstelle (Infofauna, CSCF). In a first step the volunteers had to map signs of beaver occurrences on 1:10'000 maps in A4-format. The volunteers surveyed 7'000 km of the Swiss river network and used a protocol sheet to gather additional information. The volunteers were advised to conduct the mappings between December and April as beaver signs are best recognizable at this time of the year. The beaver signs as burrows, feeding grounds, winter stocks and dams were directly documented on the map using the provided signature legend (Figure 16).

 Spuren & Zeichen des Bibers			
	Fällplatz		Bau
	Frassplatz		Kunstabau
	einzelne Nagespur, Strecken > 10 m		Mittelbau
	Ausstieg, Schlipfe, Wechsel		Burg am Ufer
	Damm		freistehende Burg
	Bibergeil, Castoreum		verlassener Bau (Dach kann auch eingestürzt sein)
	Kanal		Fluchtröhre (unter- oder oberhalb Wasseroberfläche)
	Trittsiegel		Wintervorrat

Figure 16: Signature legend for the mapping of the beaver occurrences (Infofauna, 2021b).

To determine the current distribution of beavers, the volunteers were instructed to differentiate between beaver tracks from the winter season 2021/22 and abandoned territories, which can be distinguished visually (Figure 17).



Figure 17: Differentiation of new gnawing tracks (left) and old gnawing tracks (right) (Infofauna, 2021b).

In addition, the volunteers were instructed to take photographs of all beaver dams and burrows and upload them, along with their locations, to the Webfauna app. Further information on the national beaver survey 2021/22, as well as the survey instructions (Infofauna, 2021b), are available on the Infofauna webpage.

4.1.2 Water sampling

The volunteers were required to sample water US and DS of the identified beaver reaches. The US sample was taken at the *backwater effect*, where the water was still flowing before being dammed. The DS sample was taken beyond the (last) beaver dam (Figure 18, Figure 19 and Figure 20).

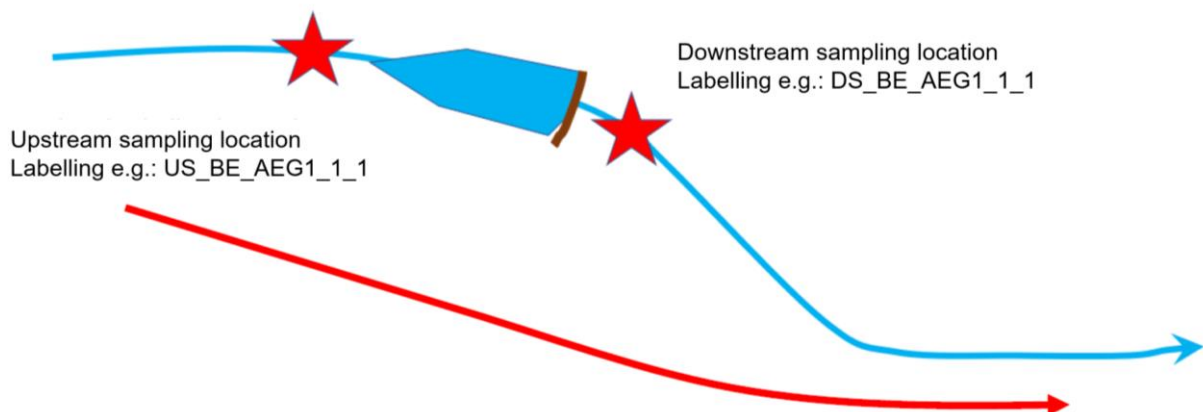


Figure 18: Sampling locations for a single beaver dam (Infofauna, 2021a).

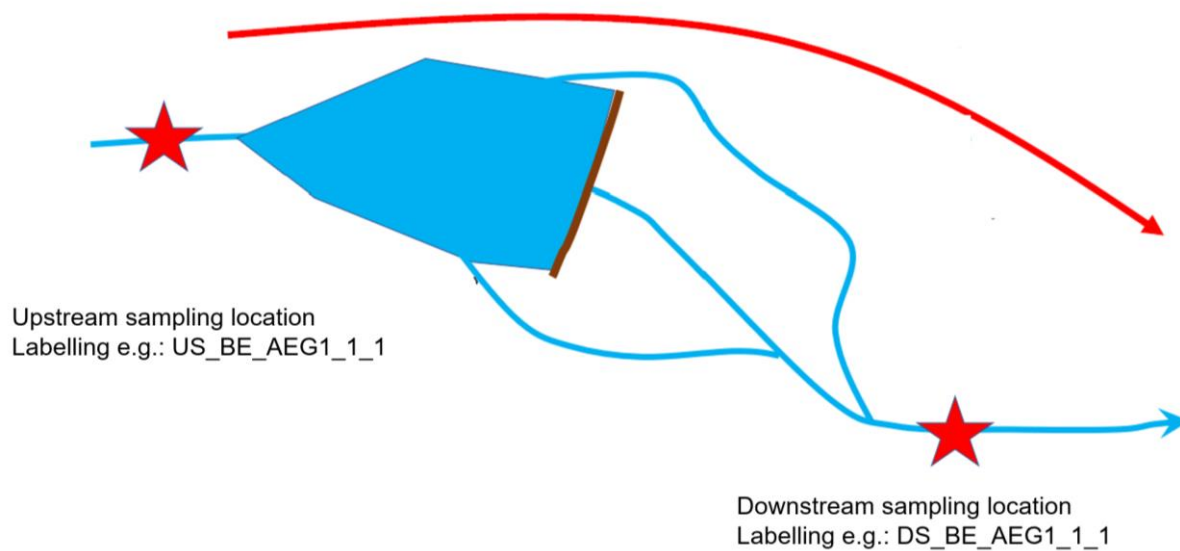


Figure 19: Sampling locations for river sections with bypass channel (Infofauna, 2021a).

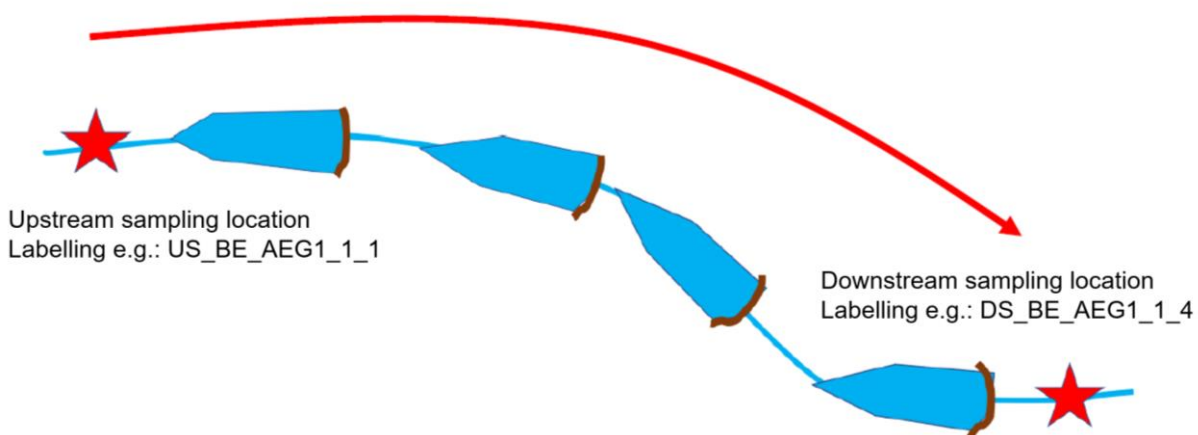


Figure 20: Sampling locations for beaver dam cascades (Infofauna, 2021a).

Five different samples were taken US and DS of the beaver impacted area (Table 2). During winter, nutrient and DOC samples were collected separately, whereas in summer, they were combined as the laboratories informed us that one falcon tube of 50 ml water was sufficient for the analysis (Figure 21). The instructions on sampling, storage and transport can be found in Appendix B.

Table 2: Sample types, storage conditions and analysis laboratory.

Sample type	Storage	Analysis
Sediment transport	without sunlight, cool (e.g. cellar)	cLab Berne
Stable isotope	Fridge, 4 °C	cLab Berne
Ammonium	Freezer, -20 °C	EAWAG
Nutrients	Fridge, 4 °C, max. 1 week	EAWAG (and cLab Berne in summer)
Dissolved Organic Carbon	Fridge, 4 °C, max. 1 week	EAWAG (and cLab Berne in summer)



Figure 21: Four types of water samples. In winter DOC and nutrients were in separate falcon tubes. Ammonium and DOC + Nutrients samples were filtered with a 0.22 μm filter.

Once the samples were collected, I stored the sediment samples in the cellar of the Institute of Geography and the stable isotopes samples in the fridge at cLab Berne. The ammonium samples were stored in the freezer at cLab Berne. Prior transportation to EAWAG, the ammonium samples were sorted and packed in a polystyrene box to ensure their frozen state throughout the delivery process.

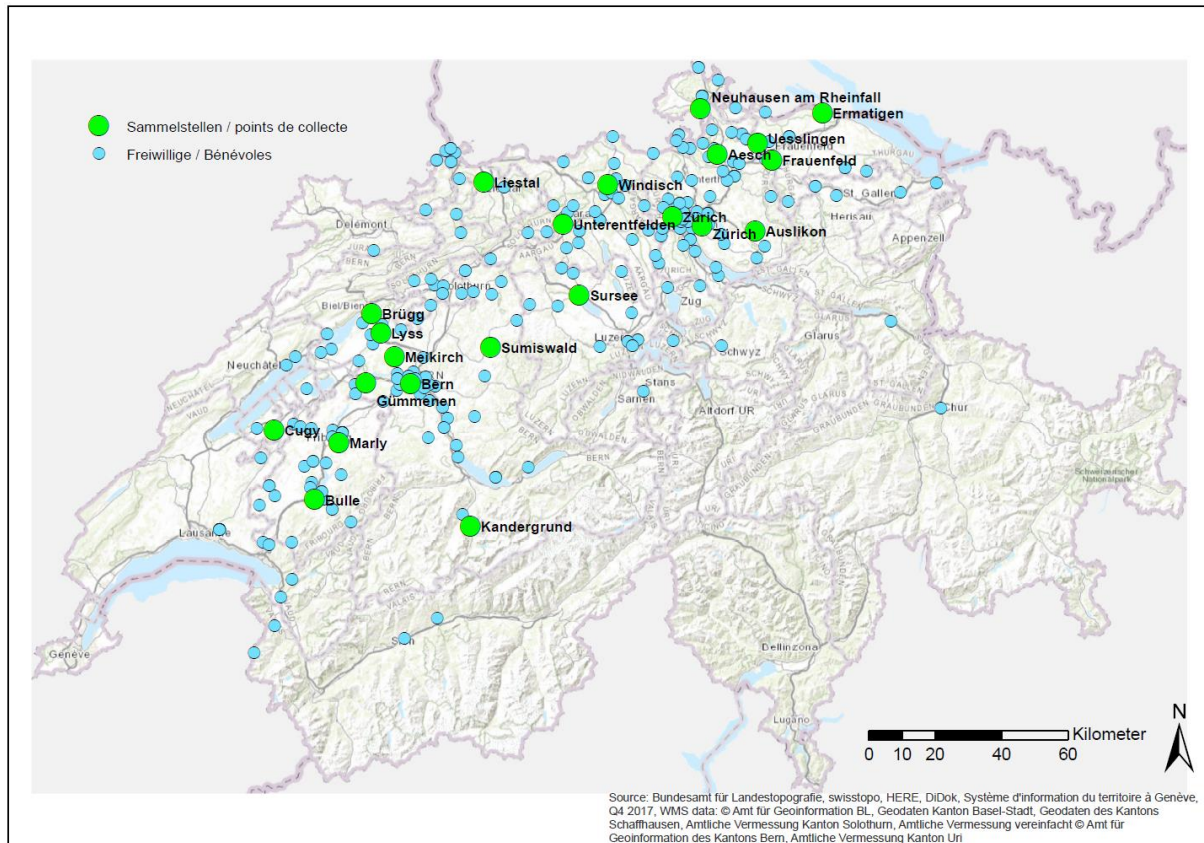


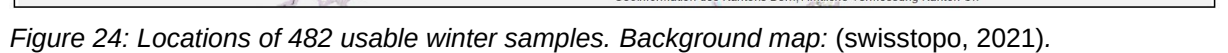
Figure 23: Collecting points for ammonium samples. The smaller dots reflect the residences of the 313 volunteers. Background map: (swisstopo, 2021).

In order to rectify errors that occurred during the sampling, labelling and storage process, an elaborate data cleaning procedure was conducted. Table 3 presents a list of errors that occurred. In certain cases, despite these errors, the corresponding samples were still usable (Table 3).

Table 3: Examples of sampling errors.

Error	Description	Data cleaning
Sampling	Not enough water sampled	Sample could, in most cases, still be measured, but barely enough water. Most samples usable .
Sampling	Falcon tubes for ammonium sample completely filled (instead of $\frac{3}{4}$).	Tube exploded when stored at - 20 °C → sample unusable .
Labelling	US and DS reversed	If the correct coordinates were on the protocol sheet this error could be fixed → sample usable . Otherwise sample unusable .
Labelling	No date and/or time on the tubes	If the information was on the protocol sheet → sample usable . Otherwise sample unusable .
Labelling	Completely incorrect labelling e.g., "US Damm 3"	Sample not assignable → unusable .
Labelling	Wrong coordinates on protocol sheet	If sampling locations were marked on the map → sample usable . Otherwise sample unusable .
Storage	Nutrients and DOC samples sent to EAWAG without cooling elements	Sample unusable .
Storage	Wrong timing of sending the nutrients and DOC samples resulting in samples in the package over the week-end	Sample unusable .
Storage	All samples stored in the freezer	Only ammonium sample usable and other sample unusable .
Storage	All samples stored in the fridge	Ammonium sample unusable . Other samples usable .

Following the data cleaning process, 156 out of the 638 winter samples had to be removed from the dataset. However, there are still usable winter samples from 482 sites (Figure 24).



4.2.1 Teams and sampling locations

The goal of the summer 2022 sampling campaign was to revisit the 482 locations previously

Due to resource limitations, the EAWAG did not have the capacity to measure all nutrient and

It was not possible to resample all the 482 locations due to various reasons (Table 4). The

Table 4: Reasons for the incomplete summer sampling.

Reasons	Issue	Affected locations
Dam destroyed or strongly permeable	Backwater effect not recognizable	60
No authorization	Not allowed to go into the area	26
Dryness in summer 2022	No water upstream and/or downstream of beaver reach	26
Doublette	(Almost) same locations were sampled more than once in winter	20
Poor coordinate notation by volunteers	No beaver dams in the area	14
Accessibility	No possibility to take water samples	6

4.2.2 Beaver dam height documentation

The estimation of beaver pond volume (chapter: 4.7.2) requires information on the heights of the beaver dams. During the summer sampling campaign we documented all beaver dams, along with their corresponding heights, using the Webfauna application. The accuracy of the dam locations is within ± 10 m, although it may be less accurate in certain areas due to poor signal. The measurement of dam heights was conducted using a meterstick.



Figure 25: Measurement of dam height. Raphael filtering the water samples, Owen registering the dam location and Mael measuring the beaver dam height with a meterstick (from left to right).

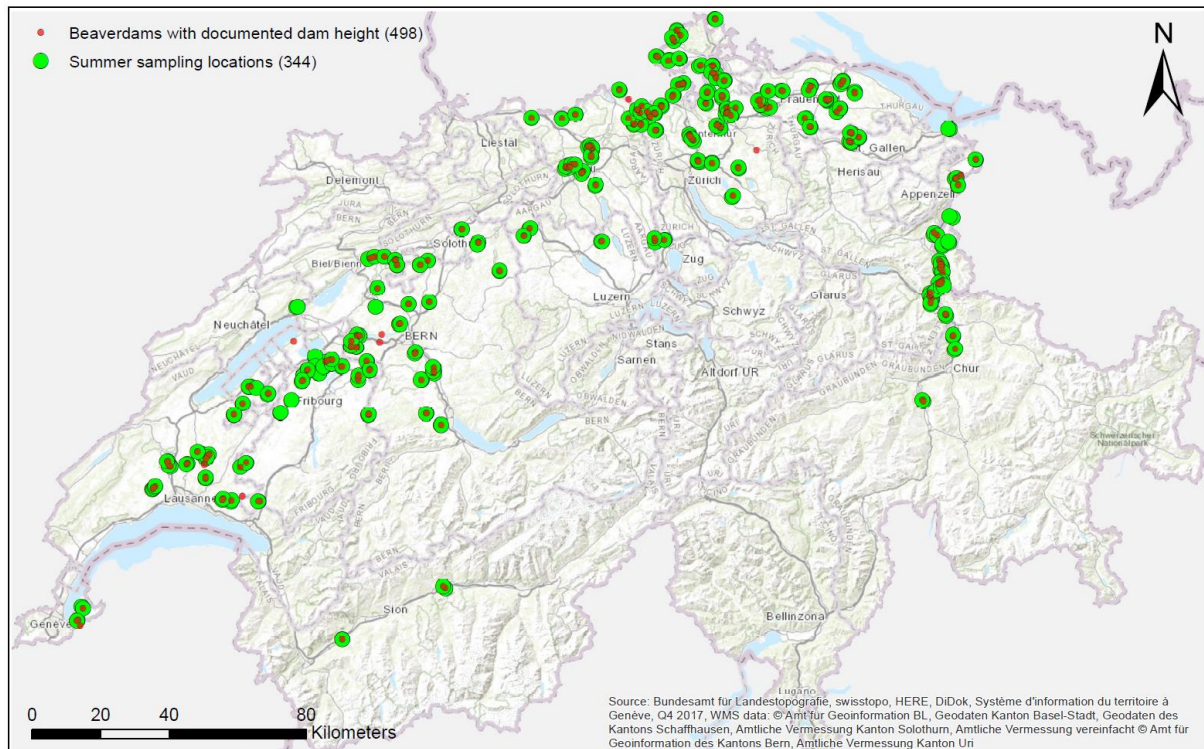


Figure 26: Summer sampling locations and beaver dams with documented dam height. Background map: (swisstopo, 2021).

4.2.3 Water temperature measurement

In order to assess the degree of water cooling or heating within beaver systems, we conducted water temperature measurements US and DS using a WTW 3500 Multimeter. To avoid any potential interference from direct sunlight, water temperature measurements were taken in the shade. Water temperature was only measured during the summer campaign.

4.3 External lab measurements (EAWAG & GIUB)

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. The ammonium samples were measured at EAWAG.

4.3.1 Nutrient measurements

The nutrient analysis addresses: Sodium (Na^+), Magnesium (Mg^{2+}), Calcium (Ca^{2+}), Potassium (K^+), Fluoride (F^-), Chloride (Cl^-), Bromide (Br^-), Nitrate (NO_3^-) and Sulfate (SO_4^{2-}). The laboratory techniques employed by the EAWAG are summarized in Table 5, while Table 7 provides an overview of the laboratory techniques utilized by the cLab Berne.

Table 5: Laboratory techniques for nutrient analysis by EAWAG (EAWAG 2021).

Parameter	Gerät / Seriennummer	Methode	Literatur	Einheit	BG / LOQ	Messbereich	Messfehler ±	Kommastellen
Fluorid	F ⁻	Metrohm 930 Compact IC Flex mit chem. Suppression / Seriennr.: 1.930.2560	Säule: Metrohm Metrosep A Supp 5 100/4 mm DIN EN ISO 10304-1, 2009	mg/L	0.05	Hoch: 0.05 - 1.00	0.02	2
					0.05	Tief: 0.01 - 0.5		2
Chlorid	Cl ⁻	Metrohm 930 Compact IC Flex mit chem. Suppression / Seriennr.: 1.930.2560	Säule: Metrohm Metrosep A Supp 5 100/4 mm DIN EN ISO 10304-1, 2009	mg/L	0.5	Hoch: 0.5 - 50.0	0.2	1
					0.10	Tief: 0.10 - 5.00		2
Bromid	Br ⁻	Metrohm 930 Compact IC Flex mit chem. Suppression / Seriennr.: 1.930.2560	Säule: Metrohm Metrosep A Supp 5 100/4 mm DIN EN ISO 10304-1, 2009	mg/L	0.05	Hoch: 0.05 - 1.00	0.02	2
					0.05	Tief: 0.01 - 0.50		2
Nitrat	NO ₃ ⁻ -N	Metrohm 930 Compact IC Flex mit chem. Suppression / Seriennr.: 1.930.2560	Säule: Metrohm Metrosep A Supp 5 100/4 mm DIN EN ISO 10304-1, 2009	mg/L	0.1	Hoch: 0.1 - 6.0	0.1	1
					0.1	Tief: 0.05 - 2.00		2
Sulfat	SO ₄ ²⁻	Metrohm 930 Compact IC Flex mit chem. Suppression / Seriennr.: 1.930.2560	Säule: Metrohm Metrosep A Supp 5 100/4 mm DIN EN ISO 10304-1, 2009	mg/L	1	Hoch: 1 - 100	2	0
					0.25	Tief: 0.25 - 5.00		2
Natrium	Na ⁺	Metrohm 930 Compact IC Flex / Seriennr.: 1.930.1160	Säule: Metrohm Metrosep C 6 250/4 mm DIN EN ISO 14911, 1999	mg/L	1.0	1.0 - 50.0	0.2	1
Kalium	K ⁺	Metrohm 930 Compact IC Flex / Seriennr.: 1.930.1160	Säule: Metrohm Metrosep C 6 250/4 mm DIN EN ISO 14911, 1999	mg/L	0.5	0.5 - 8.0	0.1	1
Calcium	Ca ²⁺	Metrohm 930 Compact IC Flex / Seriennr.: 1.930.1160	Säule: Metrohm Metrosep C 6 250/4 mm DIN EN ISO 14911, 1999	mg/L	5.0	5.0 - 100.0	1.0	1
Magnesium	Mg ²⁺	Metrohm 930 Compact IC Flex / Seriennr.: 1.930.1160	Säule: Metrohm Metrosep C 6 250/4 mm DIN EN ISO 14911, 1999	mg/L	1.0	1.0 - 50.0	0.2	1

The NO₃⁻ - N values are converted to NO₃⁻ by multiplying them with a factor 4.4268 (Table 6).

Table 6: Conversion from NO₃⁻-N to NO₃.

Atomic mass nitrogen	14.007 g/mol
Atomic mass oxygen	15.999 g/mol
Ion mass nitrate	62.004 g/mol
Conversion from NO ₃ ⁻ - N to NO ₃ ⁻ :	62.004 g/mol: 14.007 g/mol = 4.4268
Ion mass Nitrate / Atomic mass Nitrogen	

The nutrient samples were measured with a Metrohm 930 Compact IC Flex (Figure 27).



Figure 27: Metrohm 930 Compact IC Flex. Measuring device at EAWAG for the nutrient samples.

Table 7: Laboratory techniques for nutrient analysis by cLab Berne.

Parameter		Device	Columns and suppressors	Method	Measuring range [mg/l]
Fluoride	F ⁻	Autosampler AS-AP, Ser.-No.: 19050389 IC Anion, Dionex Aquion, Ser.-No.: 190440020 Thermo Fisher	Anion Suppressor AERS carbonat 4mm, Prod.-No.: 085029 Anion Column, Prod.-No.: 046034 Thermo Fisher	Eluent (2.7 mmol/L Na ₂ CO ₂ + 0.3 mmol/L NaHCO ₃); 1.5 mL/min; isocratic	0.05 - 5
Chloride	Cl ⁻				0.5 - 50
Bromide	Br ⁻				0.05 - 5
Nitrate	NO ₃ ⁻				0.5 - 50
Sulfate	SO ₄ ²⁻				0.5 - 50
Sodium	Na ⁺	Autosampler AS-AP, Ser.-No.: 19050389 IC Cation, Dionex Aquion, Ser.-No.: 190340039 Thermo Fisher	Cation Suppressor CERS 4mm, Prod.-No.: 088668 Cation Column, Prod.-No.: 046073 Thermo Fisher	Eluent (20 mmol/L Methanesulfonic acid); 1mL/min; isocratic	0.2 - 20
Potassium	K ⁺				0.1 - 10
Magnesium	Mg ²⁺				0.2 - 20
Calcium	Ca ²⁺				0.6 - 60

4.3.2 DOC measurements

The EAWAG measured DOC by catalytic combustion (Table 8) with a Shimadzu TOC-L CSH (Figure 28).

Table 8: Laboratory technique EAWAG for DOC (EAWAG 2021)

Parameter	Gerät / Seriennummer	Methode	Literatur	Einheit	BG / LOQ	Messbereich	Messfehler ±	Kommastellen
DOC	Shimadzu TOC-L CSH / Artikelnr.: 638-91105-23 Seriennr.: H54205000493	katalytische Verbrennung 720°C --> Messung von CO ₂ mittels IR	DIN EN 1484, August 1997	mg/L	0.5	0.5 - 10.0	0.2	1

The method employed by cLab Berne for measuring DOC differed slightly from the EAWAG method. Rather than utilizing the DOC method, which measures filtered samples directly, cLab Berne opted for the NPOC (non-purgable organic carbon) method. In this method, samples are acidified, causing carbonates to convert into CO₂, which is subsequently removed through airflow. However, a drawback of this approach is the potential loss of volatile organic compounds, such as formic acid.

The cLab Berne utilized the Dimatoc 2100 device, which employs thermal-catalytic combustion to convert samples to CO₂ at a temperature of 850 °C, which is then detected by a NDIR detector. The detection limit of this setup is 0.53 mg/l, and the standard deviation for measurements conducted by the cLab Berne was 0.13 mg/l, resulting in a measuring error of 0.26 mg/l.



Figure 28: Shimadzu TOC-L CSH. Measuring device at EAWAG for DOC.

4.3.3 Ammonium measurements

The ammonium samples were measured by EAWAG using colorimetric determination (Table 9) with a Skalar San++ Autoanalyzer (Figure 29).

Table 9: Method EAWAG to measure the ammonium concentration.

Device	Skalar San++ Autoanalyzer
Method	Colorimetric determination of ammonium nitrogen after reaction to a blue color complex (Berthelot's reagent)
Measurement range	0.02 – 0.1 mg/l



Figure 29: Skalar San++ Autoanalyzer. Measuring device used at EAWAG for ammonium analysis.

4.3.4 Comparison of EAWAG and cLab Berne measurements

For the comparison of nutrient and DOC concentrations measurements between EAWAG and cLab Berne, five beaver reaches (US and DS) were sampled twice and measured in both laboratories. The nutrient concentration discrepancies between the two laboratories were within the measuring error and did not require any adjustment.

However, the measured DOC values at EAWAG were approximately 1.4 times higher than those at cLab Bern (Figure 30), possibly due to slightly different measuring techniques (chapter: 4.3.2). Therefore, it is crucial to directly compare DOC concentrations measured at EAWAG and cLab Berne. Our primary focus lies in comparing the US and DS DOC concentrations from the individual beaver reaches. This comparison remains viable as the US and DS DOC concentrations were consistently measured in the same laboratory.

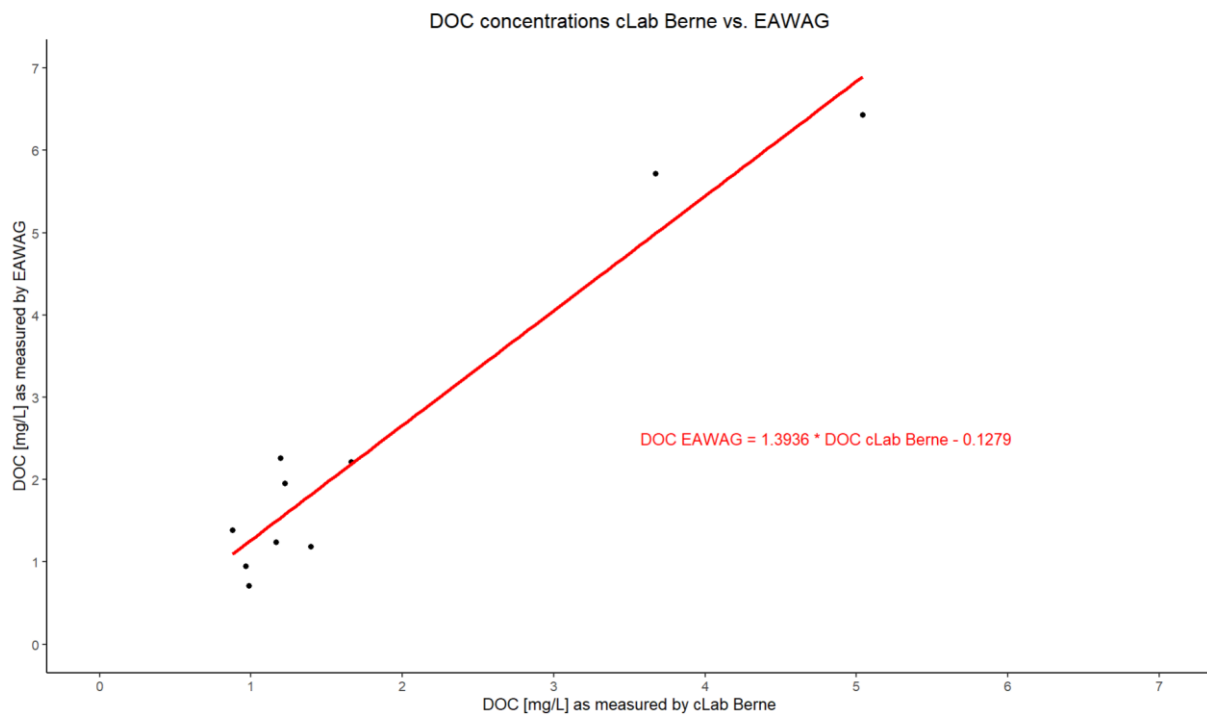


Figure 30: DOC concentrations measured by EAWAG and cLab Berne.

To enable a comparison of DOC samples between EAWAG and cLab Berne, the cLab Berne DOC concentrations were adjusted to the EAWAG DOC concentrations with the linear regression equation (Figure 30). After the adjustment, the results from EAWAG and cLab Berne exhibit improved agreement (Figure 31).

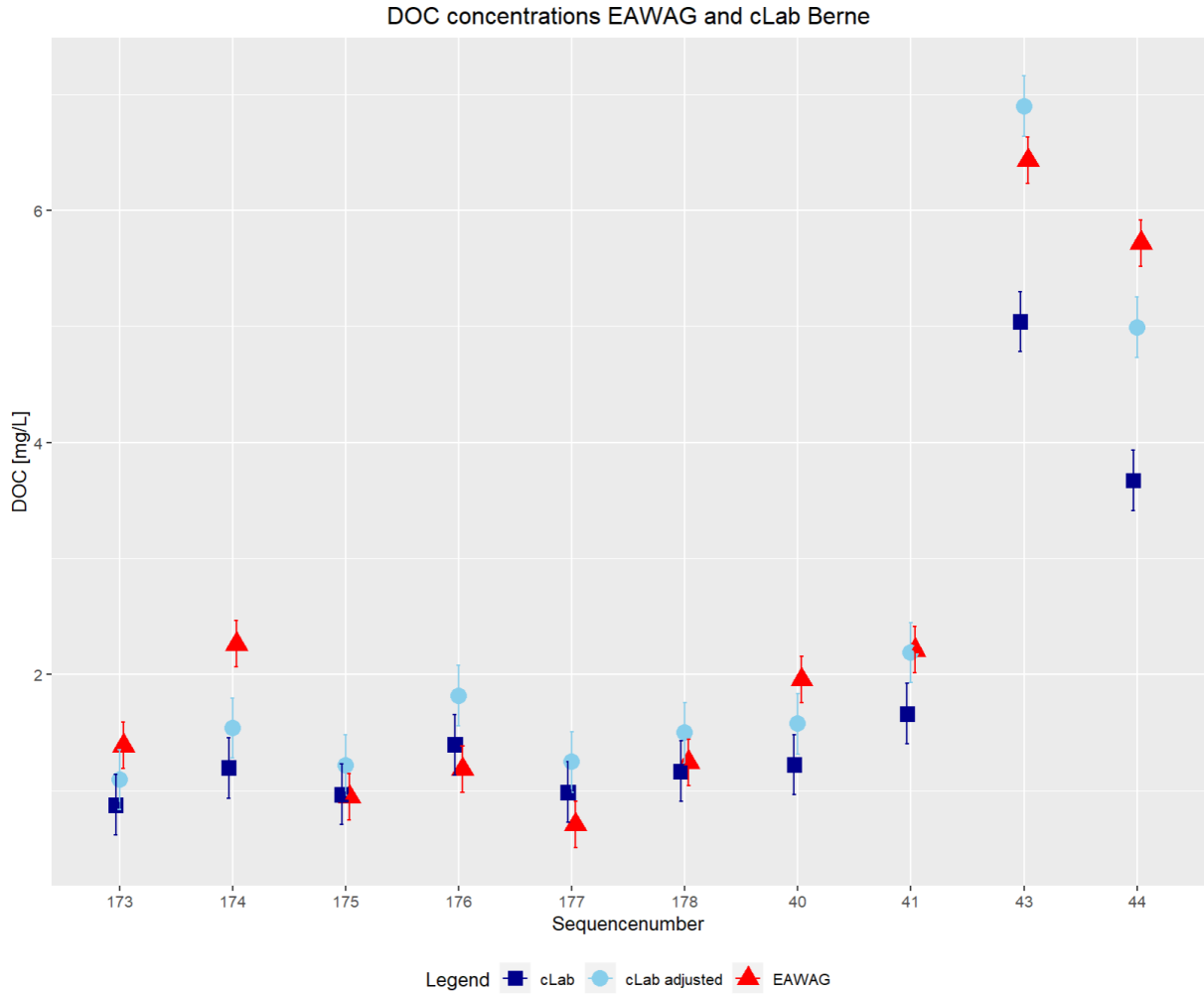


Figure 31: Adjustment of the cLab Berne DOC concentrations. Comparison of the measured EAWAG, measured cLab and adjusted cLab DOC concentration for five beaver reaches with error bars. The measuring error for EAWAG is 0.2 mg/l, while cLab and cLab adjusted, it is 0.26 mg/l.

4.4 Stable isotope analysis

To estimate water residence time and evaporation in the beaver system, I conducted measurements of $\delta^{18}\text{O}$ (‰), $\delta^2\text{H}$ (‰), $\delta^{17}\text{O}$ (‰) and ^{17}O -excess composition for US and DS samples. I utilized a Cavity Ringdown Spectrometer (CRDS) at cLab Berne.

The δ -values of the isotopes, expressed in permille, were calculated in relation to the Vienna Standard Mean Ocean Water (Equation 1) ((Craig, 1961):

Equation 1: Calculation of the δ -value.

$$\delta_{\text{sample}} = \frac{R_{\text{sample}} - R_{\text{V-SMOW}}}{R_{\text{V-SMOW}}} * 1000$$

where R represents the ratio of $^{18}\text{O}/^{16}\text{O}$, $^{17}\text{O}/^{16}\text{O}$ or $^2\text{H}/^1\text{H}$ of the sample and the V-SMOW.

Skrzypek et al. (2015) developed a hydro calculator based on the Craig-Gordon model (Craig & Gordon, 1965). This model allows an estimation of evaporation based on the hydrogen and oxygen stable isotope composition of inflowing and outflowing water in a pond. The method was validated for an arid area in northwest Australia.

4.4.1 Cavity Ringdown Spectroscopy (CRDS)

In Cavity Ringdown Spectroscopy (CRDS) light with a specific wavelength is injected with a laser into a cavity with three mirrors (“build-up phase”). A photodetector generates a signal that is proportional to the light intensity in the cavity. Once the detector voltage exceeds a threshold, the laser is turned off, leading to a decrease in intensity due to the mirrors reflecting slightly less than 100 % of the light. This decline in intensity is known as the “ring-down phase” and its duration is measured. The presence of gas in the cavity causes a shorter “ring-down” time compared to an empty cavity (Figure 32). Different molecules exhibit unique absorbance peaks at specific wavelengths. Using this information, the absorption intensity is converted into concentration (Picarro, 2015).

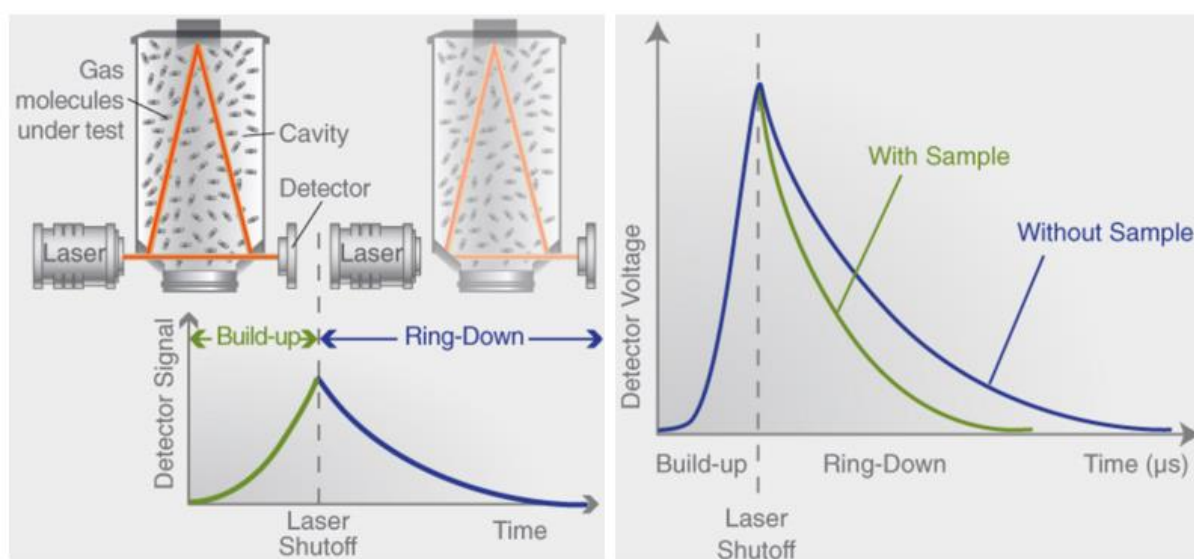


Figure 32: Cavity Ringdown Spectroscopy (CRDS). Schematic of a Picarro CRDS analyzer (left) and light intensity as a function of time (right) (Picarro, 2015).

4.4.2 Measuring techniques for stable isotopes

The analyzer utilized in the cLab Berne is the Picarro Cavity Ringdown Spectrometer L2140-I coupled with a high-precision A0211 vaporizer (Figure 33). Detailed information regarding the analysis setup can be found in Table 10.

Table 10: Analysis setup for CRDS.

Sample storage before analysis	Winter samples: Fridge, 4 °C Summer samples: Cellar, protected from sunlight	
Vials	1.75 ml (pipette)	
Vials per run	Maximum 150 vials per run	
Labeling	Winter: W + Sequence number, e.g. W331 Summer: S + Sequence number, e.g. S331	
Standards for calibration	3 standards at the beginning of the run (heaviest to lightest) and 3 standards at the end of the run (lightest to heaviest). KLEMAT (light), BERNMQ (intermediate), VENICE (heavy) The data were calibrated using the linear equation obtained by plotting the concentration measured by the analyzer against the concentration indicated on the calibration standard.	Example of the run architecture in Figure 33
Deionized water (DI) water for drift correction	2 DI at beginning and end of the run, next to the standards 1 DI after eleven water samples	
Injections	8 for standards and 6 for water samples and DIs Total injections: 6x8 + 99x6 = 642 For the postprocessing the first three injections from each vial were discarded.	
Duration (run 105 vials)	9 minutes per injection 9x642 = 5'778 (~ 4 days)	
Syringe cleaning	Syringe is cleaned at the beginning and at the halftime of each run with Aceton and N-Methyl-2-pyrrolidone (NMP)	
Septum change	At the same time as the syringe is cleaned	
Carrier gas	N ₂ with a pressure of 2.5 ± 0.5 PSI	
Analysis mode	O ¹⁷ High precision	
Instrument precision provided by the manufacturer	± 0.025 ‰ for δ ¹⁷ O and δ ¹⁸ O ± 0.1 ‰ for δ ² H (Vallet-Coulomb et al., 2021)	
Isotope ratio in ‰	Relative to the Vienna Standard Mean Ocean Water V-SMOW	

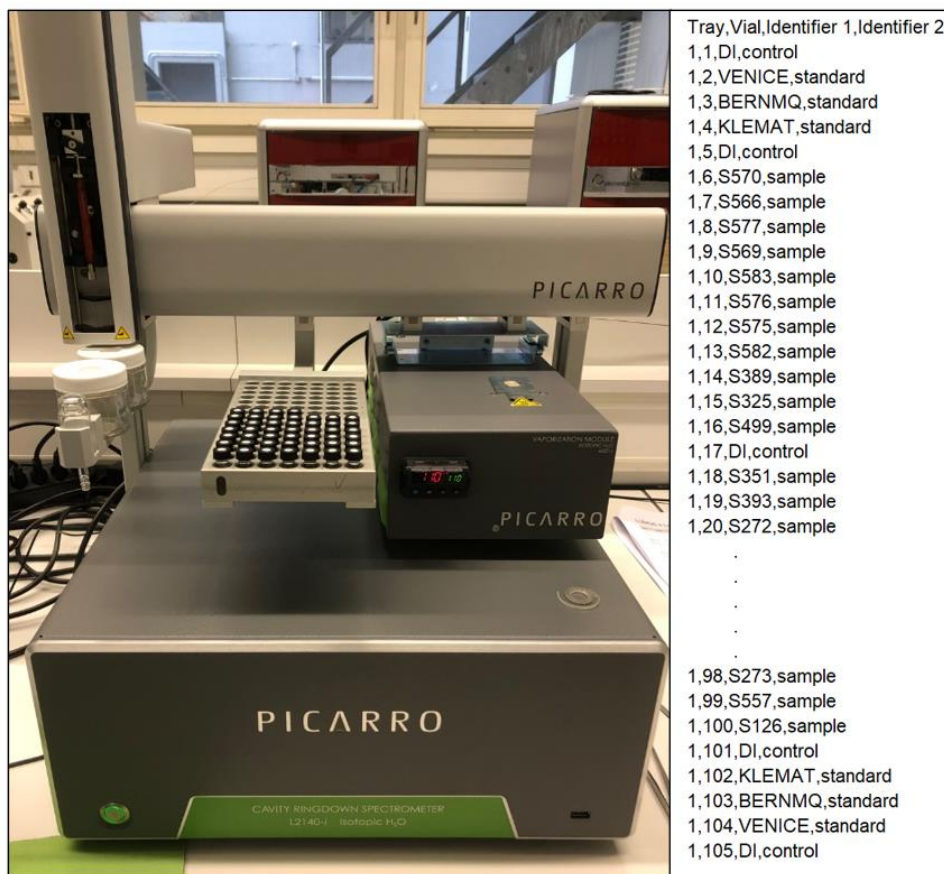


Figure 33: Cavity Ringdown Spectrometer L2140-I (left) and run architecture (right).

4.5 Sediment load analysis

Livia Vogel and Linus Fässler have been hired to measure the sediment load of the water samples.

Prior to analysis, the 0.22 μm filter was weighed using a high-precision Mettler Toledo balance with an accuracy of ± 0.1 mg. In a next step the bottle containing the water was weighed. The sample was shaken before being transferred into the container. The sediment filter was installed beneath the container, with the smooth side facing upward and the rough side downward. A vacuum pump accelerates the filtering process, while an intermediate vessel prevents any water from entering the vacuum pump.

Once the water had passed through the filter, the sediment residues in the container were rinsed using Milli-Q water. The filter was then removed and dried in an oven at 30 °C for 6 hours. After drying, the filter, along with the sediment particles, was reweighed using the high-precision balance. Finally, the weight of the empty water bottle was measured.

The sediment load in mg/l was calculated using the approximation that 1 kg (1'000 g) of water sample equals 1 L (Equation 2).

Equation 2: Calculation of the sediment load.

$$\text{Sediment load } \left[\frac{g}{l} \right] = \frac{W_{\text{Filter+Sediment (dried)}} - W_{\text{Filter (empty)}}}{W_{\text{Bottle+Watersample}} - W_{\text{Bottle (empty)}}} * 1'000 \text{ g} = \frac{W_{\text{Sediment}}}{W_{\text{Watersample}}} * 1'000 \text{ g}$$

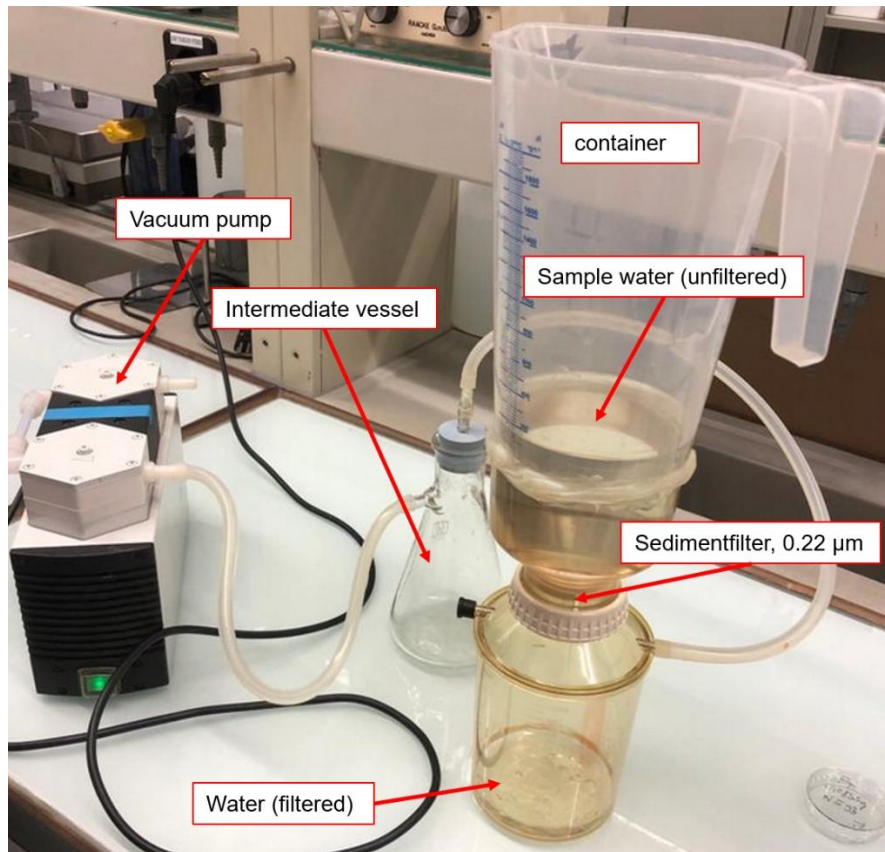


Figure 34: Setup for the sediment analysis.

4.6 Catchment delineation

Dr. Massimiliano Zappa, Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), has developed a discharge model that has the capability to simulate discharge for specific locations and timeframes. The model relies on catchment polygons for the DS coordinate, which I calculated using QGIS and ArcMap. Digital Elevation Models (DEM) with a pixel size of 2 m and 0.5 m were obtained from swisstopo (swisstopo, 2022a). The high data volume posed a challenge for the calculation processes in GIS, leading to reduced processing speed and computer crashes. In order to address this issue, four different methods utilizing varying DEM resolutions and GIS programs (Appendix C, Table 22) were tested on ten locations.

The results showed that catchment delineations without preprocessing of the DEM resulted in unrealistic and low-quality catchment polygons, particularly in areas with high anthropogenic impact (Figure 35). In order to obtain accurate catchment polygons, preprocessing of the DEM was necessary. Therefore, I incorporated the river network (“Fließgewässer” polyline from swissTLM3D (swisstopo, 2022b)) into the original DEM (swisstopo, 2022a) through a process known as “burning” (Appendix C, Table 23). As a result, the river paths were consistently represented by the lowest altitude within their surroundings, causing altitudes deviating from the actual altitude (Appendix C, Figure 96).

Upon visual examination, I observed that the polygons generated by the three methods with DEM preprocessing are almost identical (Figure 35). Considering the calculation time and data volume, I opted to calculate the 165 polygons using the ArcMap method and a preprocessed 2 m x 2 m DTM. The further steps for the catchment delineation can be found in Appendix C, Table 24. However, in 13 catchments situated in urban areas and/or regions with subterranean water, the chosen method resulted in inaccurate catchment polygons. To address this issue, I drew those 13 polygons manually considering the DEM and the Swiss river network (swisstopo, 2022b).

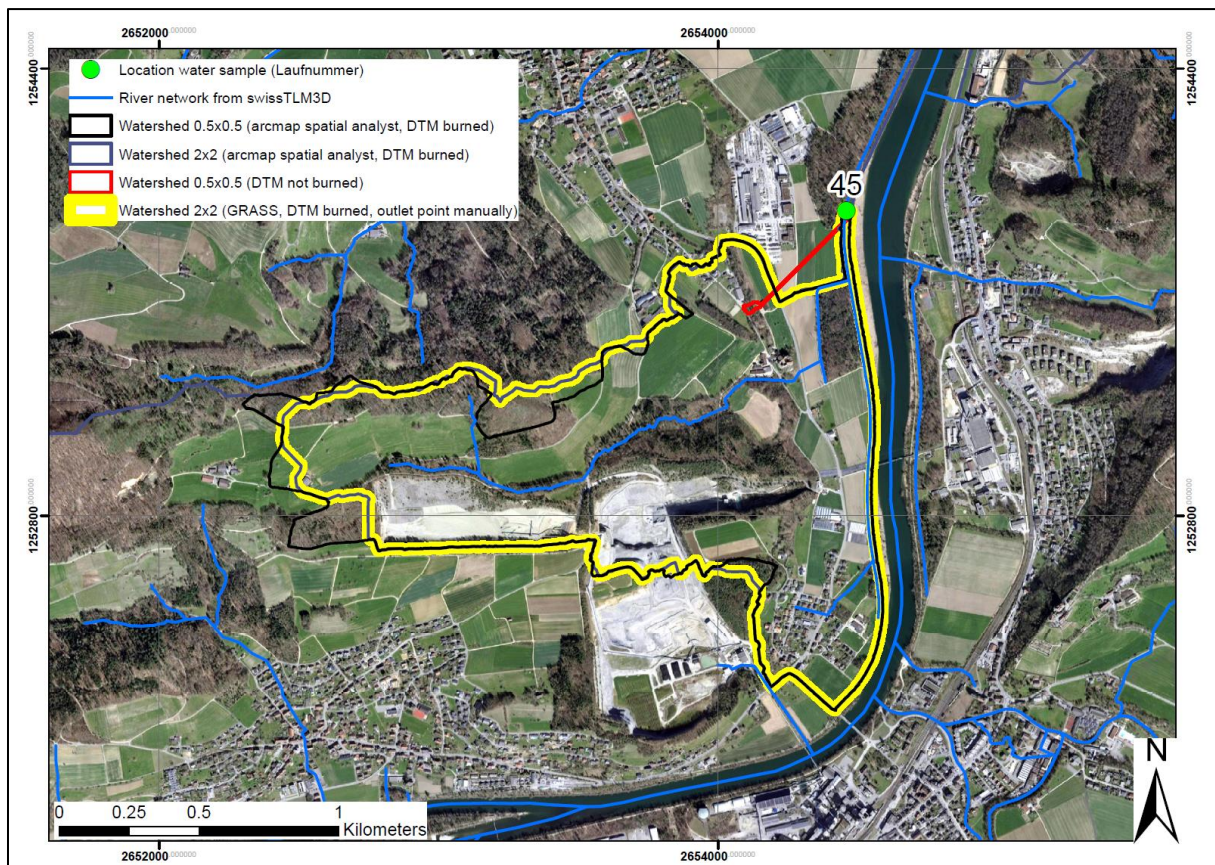


Figure 35: Different catchment delineation and preprocessing methods. Background map: (swisstopo, 2018, 2022b).

4.7 Water residence time estimation by volume and discharge

The nominal residence time (τ_n) of the water in the beaver reaches can be estimated by dividing the volume of the beaver ponds (V_n) by the volumetric flow rate (Q) (Equation 3) (Larsen et al., 2021):

Equation 3: Calculation of the nominal residence time.

$$\tau_n = \frac{V_n}{Q}$$

It should be noted that the equation provides an estimation rather than an exact calculation, as both the volume and discharge are also estimated (chapter: 4.7.1 and 4.7.2). Furthermore, not the entire volume is engaged in the active flow (Larsen et al., 2021).

4.7.1 Discharge estimations

The discharge estimations are made in collaboration with Dr. Massimiliano Zappa, WSL. Catchment polygons (chapter: 4.6) as well as the time and date of the water sampling were provided as input data for the discharge model.

4.7.2 Water volume estimation

Due to time limitations, I adopted a quantitative GIS approach to estimate the water volume of the beaver reaches instead of manually measuring the water volume of each beaver reach. To validate the quantitative approach, we manually measured the water volume of six beaver reaches.

4.7.2.1 Field measurement for validation

The selection of the beaver reaches for water volume field measurement based on different criteria (Table 11).

Table 11: Criteria for manual water volume measurement.

Criteria	Description
Accessibility	Since the manual measurements were made during the summer campaign, the vegetation cover could hinder the access to the water.
Diversity (number of dams)	Single beaver dams as well as beaver dam cascades needed to be manually measured.
Diversity (channel type)	Beaver impacted areas with various channel types (slope, anthropogenic influence, etc.) needed to be considered.
Water level	The beaver ponds had to be completely filled with water.

We divided the river path between the US and DS sampling location in n-sections of approximately 10 m length. From each section we measured the length, the width and the depth (in the middle of the stream) (Figure 37). The lengths and widths were measured with a meterstick and the depth with an avalanche probe which was fixed to a telescopic rod (Figure 36).

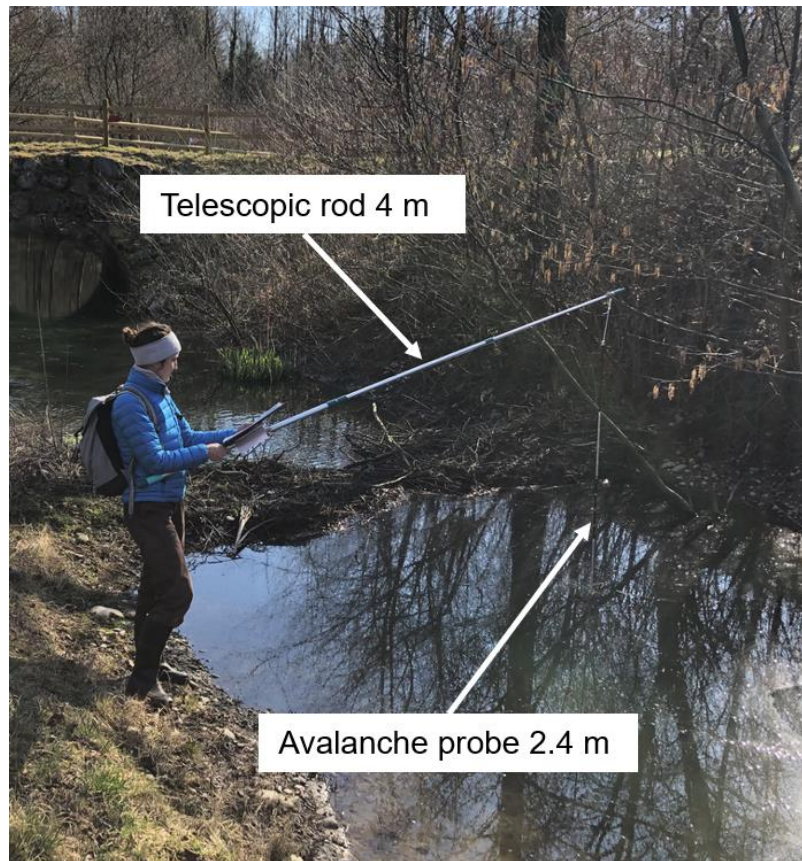


Figure 36: Cécile Auberson (Infofauna) measuring pond depth.

In addition, the angle of incidence of the channel bank was estimated through visual assessment. Although the bathymetric morphology varied across different river sections, an average angle of incidence of 45° was considered to be a reasonable approximation.

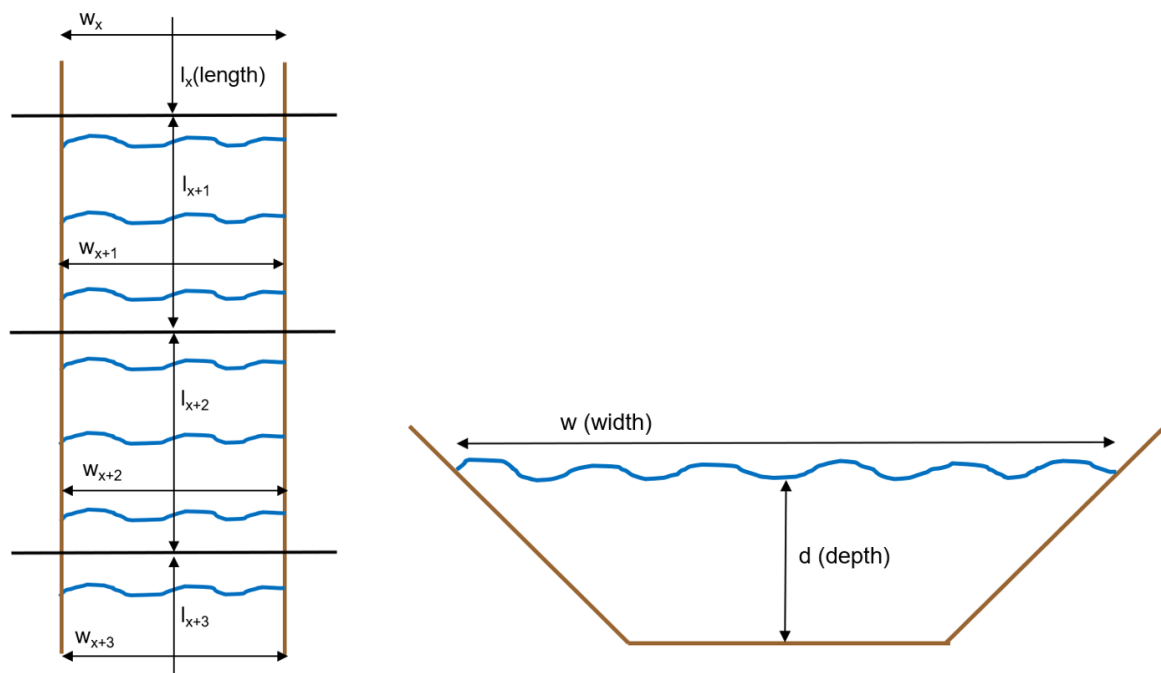


Figure 37: Ortho view (left) and cross profile (right) illustrating length, width and depth.

The n-sections are summed up (Equation 4) to get the total volume for each beaver reach as e.g., in beaver reach number 93 with two beaver dams (Table 12).

Equation 4: Calculation of the volume from the field measurement.

$$Volume \text{ field measurement} = \sum_{x=1}^n (l_x w_x d_x - \frac{d_x^2}{l_x})$$

Table 12: Water volume calculation. Beaver reach number 93 which was manually measured during the summer campaign.

Beaver reach: 93 (LAN02)			Date: 25.07.2022			Remark: Beaver Reach, two beaver dams, measured from DS to US, the angle of the rivershore is 45 °									
Sector	Dam 1	1	2	3	4	Dam 2	5	6	7	8	9	10	Backwater	Total	
Length (flow direction) [m]	0	25	45	35	25	0	20	15	20	10	20	55	0	270	
Width [m]	0	7	5.5	5	4	0	8	8	6	4	2	1.5	0		
Surface water area [m²]	0	175	247.5	175	100	0	160	120	120	40	40	82.5	0	1260	
Depth [m]	0	0.9	0.9	0.85	0.7	0	1.3	1.1	0.7	0.9	0.7	0.3	0		
Volume [m³] (without angle)	0	157.5	222.75	148.75	70	0	208	132	84	36	28	24.75	0	1111.75	
Crosssection angle both riversides [m²]	0	0.81	0.81	0.7225	0.49	0	1.69	1.21	0.49	0.81	0.49	0.09	0		
Volume angle [m³]	0	20.25	36.45	25.2875	12.25	0	33.8	18.15	9.8	8.1	9.8	4.95	0	178.8375	
Netvolume [m³]	0	137.25	186.3	123.4625	57.75	0	174.2	113.85	74.2	27.9	18.2	19.8	0	932.9125	

4.7.2.2 Quantitative approaches

Three different quantitative methods were tested on their capability in representing the field measurements.

The first approach utilizes the Equation 5 as proposed by Brooks & Hayashi (2002).

Equation 5: Calculation of the volume, first approach.

$$V_{max} = \frac{A_{max} * h_{max}}{1 + \frac{2}{p}}$$

Karran et al. (2017) applied this equation in beaver ponds with diverse morphologies. They found a median coefficient of $p = 0.91$. To evaluate the equation, I applied it using $p = 0.91$, where A_{max} represents the surface water area as detected from aerial photos and h_{max} represents the dam height as measured in the summer campaign. I did this calculation for each pond in the beaver reach and summed up the values. However, a challenge of this method is the difficulty of accurately identifying the surface water area beyond the vegetation cover. It became apparent that this approach often resulted in values lower than those obtained from the field measurement (Figure 42).

The ArcMap and QGIS methods are similar to each other. In both methods, the volume is calculated based on the beaver dam height and the LiDAR data from the digital elevation model (DEM). The volume between a designated plane height and the surface derived from the DEM is computed (Figure 38).

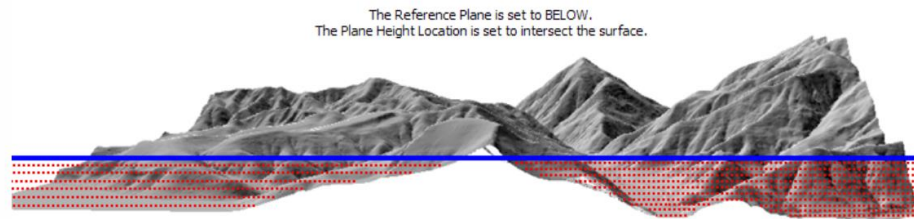


Figure 38: ArcMap surface volume tool (esri, 2016).

Working with LiDAR (Light detection and ranging) derived DEMs close to surface water areas presents certain challenges. LiDAR can provide only a monochromatic map of bottom reflectance (C. K. Wang & Philpot, 2007). Moreover, the continuous changes in watercourses and vegetation cover can result in inaccurate DEMs in surface water areas (swisstopo, 2022a). Despite those challenges, James et al. (2007) demonstrate that LiDAR can locate headwater channels even if they lie beneath dense canopy, where channels cannot be identified on aerial photos. Cavalli et al. (2008) assessed the efficacy of airborne LiDAR data in the recognition of channel-bed morphology and found that it was possible to survey the channel bed in shallow water depths without the need for a bathymetric LiDAR sensor. Cavalli et al. (2008) figured that “Depending on the accuracy required and on local conditions (e.g. the presence of vegetation on the channel banks), LiDAR data can be considered as a substitute of traditional field survey techniques or as a tool for a preliminary recognition of channel morphology”. This finding aligns with the information provided by swisstopo (Gandor Florian, swisstopo, personal communication, October 18, 2022, Appendix D), which states that for shallow watercourses, the channel morphology is captured well in the LiDAR data. For further validation, I generated some cross sections based on the DEM for three beaver reaches. The cross sections tend to exhibit the shape of the channel morphology, indicating that the LiDAR likely penetrated through the shallow water. If the LiDAR had not penetrated through the shallow water, the cross sections across the rivers would appear more flattened (Figure 39).

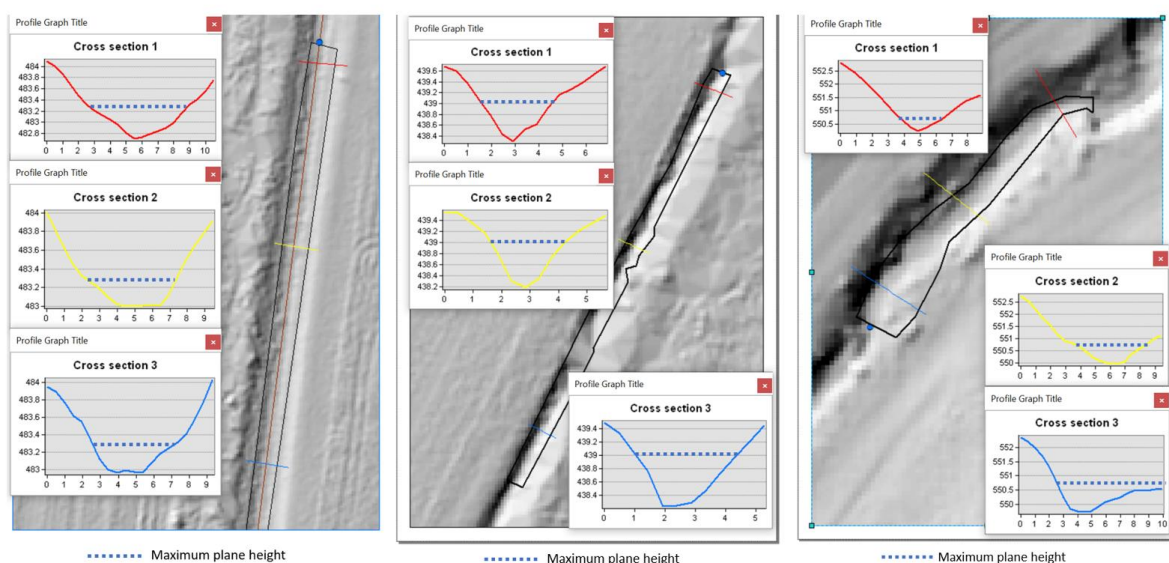


Figure 39: LiDAR and shallow water. Cross sections in the beaver reaches 85 (SAR03), 70 (WBK01) and 41 (ZW01) (from left to right) indicating that the LiDAR penetrated through the water. The maximum plane height is the altitude from the top of the beaver dams.

In the ArcMap method, the volume is calculated using the *Surface Volume* tool, whereas in the QGIS method the almost similar *Volume Calculation Tool* is employed (Appendix E). The altitude of the beaver dam locations is determined by using the *Extract values to point* tool, which extracts the altitude from the DEM layer. Subsequently, the dam height is added to the altitude of each beaver dam location, resulting in the altitude of the top of the beaver dam, which is utilized as the plane height in the ArcMap tool and base level in the QGIS tool (Figure 40).

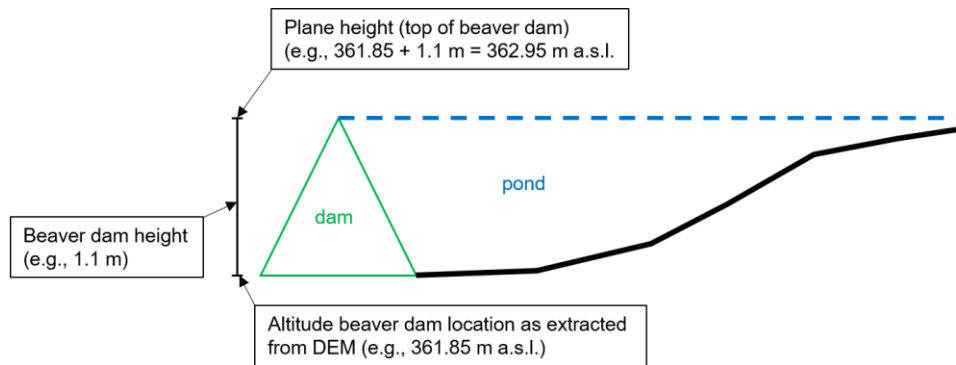


Figure 40: Illustration on plane height determination.

A difference between the two methods is the size of the polygon for the input surface (ArcMap) and the area polygon layer and DEM height layer (QGIS), respectively (Figure 41). In the ArcMap method, a polygon is created by reclassifying the DEM into two classes: One class includes altitude values between the bottom and top altitude of the beaver dam, while the second class includes altitude values outside these boundaries. Then I drew the polygon based on this reclassification process. Whereas in the QGIS method I drew the polygon based on the aerial photo.



Figure 41: Polygons for volume calculation. Reclassification of the DEM for the ArcMap method (left) and polygon for the QGIS method (right). Background map: (swisstopo, 2018).

For the volume calculation the DEM with a resolution of 0.5 m was chosen as 2 m is too wide for small streams with a width lower than 2 m.

4.7.2.3 Comparison and validation

To assess the accuracy of the three quantitative methods, I compared their results with the manually measured water volume from six test sites (Figure 42). The QGIS method exhibited the closest representation of the field measurements. Consequently, I utilized the QGIS method for determining the water volume of the 468 beaver ponds in the 165 beaver reaches.

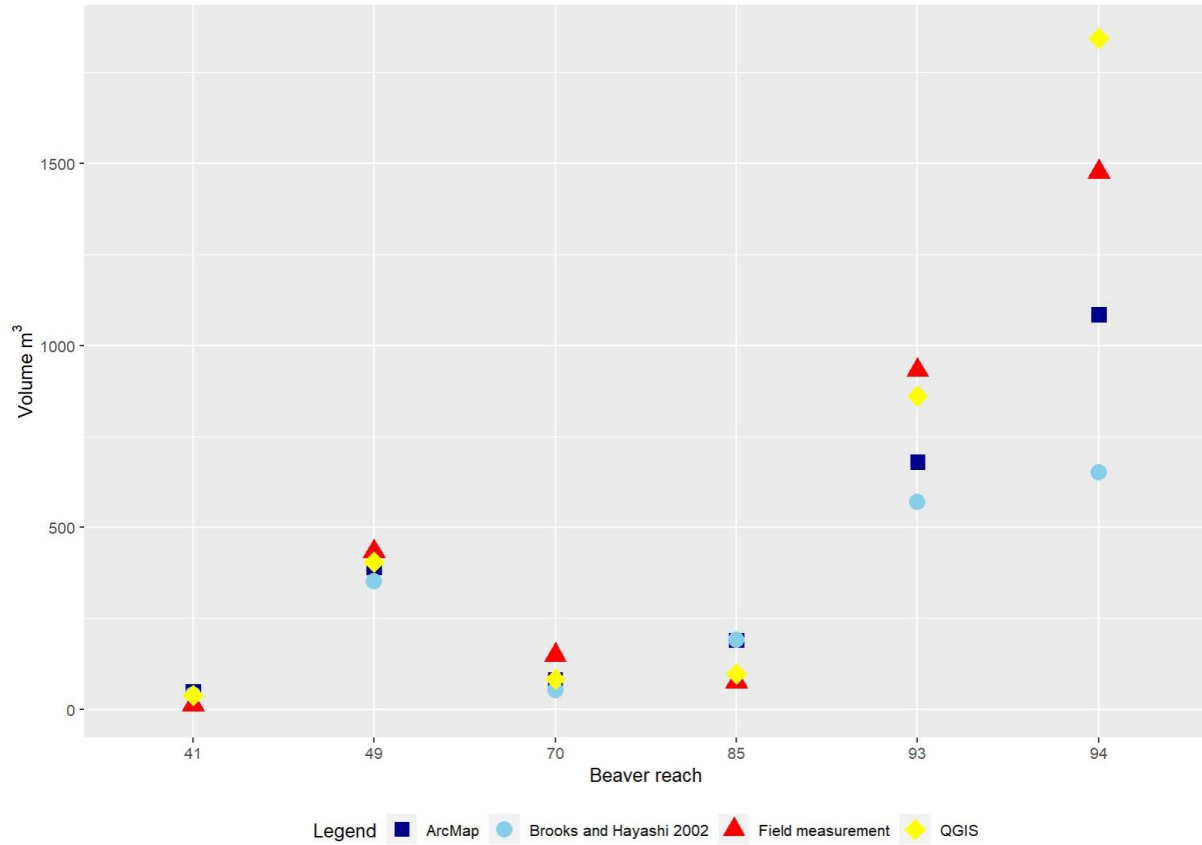


Figure 42: Volume estimations from six test sites with different methods.

4.8 Determination of river slope and distance

In order to examine the potential impacts of the beaver system characteristics river slope and length, I conducted an analysis to determine the distance and slope of the river between the US and DS sampling location.

In a first step I imported the sampling locations, the DEM and the Swiss river network swissTLM3D (swisstopo, 2022b) to QGIS. The altitudes of the sampling locations were determined with the *Extract values to point* tool (chapter: 4.7.2.2). Subsequently, I created polylines from the US to the DS along the swissTLM3D line feature. The distance between the US and DS was determined by calculating the length of the polyline using the *\$length* tool available in the QGIS field calculator. Then, I calculated the slope of the river segment between the US and DS location (Equation 6).

Equation 6: Calculation of the slope between US and DS.

$$\text{Slope [\%]} = \frac{(US_{alti} - DS_{alti}) * 100}{\text{length polyline US to DS}}$$

4.9 Land use in catchments

To assess the impact of different land use types within the catchment areas, I conducted an analysis on the ratio between agricultural land, settlements, forests, and non-productive areas. For this analysis, I utilized the *Arealstatistik Schweiz* data, provided by the Federal Statistical Office (BFS, Bundesamt für Statistik) (BFS, 2021). This dataset assigns each hectare in Switzerland to four main categories (settlement areas, agricultural areas, forest areas and non-productive areas) and 72 sub-categories (BFS, 2006). An overview of the different categories can be found in Appendix F. I imported the area statistics dataset into QGIS and clipped it to the extent of the catchment areas. Subsequently, I separated the shapefile into four different shapefiles, each representing one of the four main categories. Using the vector analysis tool *Count Points in Polygon* the number of points (equal to number of hectares) for each basic category per catchment area was calculated. Additionally, I calculated the ratio of wetland within the catchment area using the *swissTLM3D* dataset (swisstopo, 2022b).

4.10 Land use in the direct surroundings

To assess the potential impact of different land use in the direct surroundings (within 50 m) of the river, I conducted a land cover analysis. I created a buffer zone of 50 m on both sides of the river network polyline (swisstopo, 2022b).

The *Arealstatistik* (BFS, 2006) used for the land use analysis in the catchments (chapter: 4.9) has a resolution of one hectare, which is insufficient to analyze the land use within the 50 m buffer area. The land use information is extracted from the *swissTLM3D* (swisstopo, 2022b) dataset, which describes almost 20 million landscape features and separates them in different subcategories (Figure 43).

Roads and tracks	Road and path networks
Public transport	Railway lines and other rail systems, shipping routes and public transport stops
Buildings	Buildings, walls, dams, constructions relating to transport, communication, energy, sport and leisure
Areas	Plots with special land usage (transport, nature, habitat, leisure, etc.)
Land cover	Ground coverage independent from land usage
Hydrography	Watercourses and lake contours
Single point objects	Selection of prominent landscape features which aid orientation (crossings, sources, caves)
Names	Various names (mountains, areas, towns, etc.)

Figure 43: Subcategories of the *swissTLM3D* dataset (swisstopo, 2022b).

I merged the features from these subcategories within the *swissTLM3D* (swisstopo, 2022b) dataset in layers representing five distinct categories (Table 13).

Table 13: Categories for the land use analysis.

Category	Subcategories from swissTLM3D	Priority
Stagnant water bodies	- Stagnant water bodies	1.
Forest	- Forest - Woody area	2.
Wetlands	- Wetlands	3.
Anthropogenic	- Streets - Railways - Buildings	4.
Agriculture	Areas not included in the other four categories	5.

The layers representing different land use categories may overlap, such as wetlands and standing waters (Figure 44). In situations where layers overlap, priorities were established to handle the overlapping areas (Table 13). For instance, when stagnant water bodies and wetlands overlap, the area corresponding to the overlap was extracted from the wetlands category to ensure that the total area of each category within the buffer polygon does not exceed the total buffer area.

The swissTLM3D does not provide specific features for agricultural land. Through comparisons with orthophotos, it was observed that the areas not falling within the categories of stagnant water bodies, forest, wetlands and anthropogenic, corresponded to areas with agricultural land use (Figure 45). Consequently, all the remaining areas were classified as agricultural land use.

		1 Fels	2 Fels locker	3 Felsbloecke	4 Felsbloecke locker	5 Fliessgewässer	6 Gebüschwald	7 Lockergestein	8 Lockergestein locker	9 Gletscher	10 Stehende Gewässer	11 Feuchtgebiet	12 Wald	13 Wald offen	14 Gehölzfläcche	15 Schneefeld Totels
1	Fels															
2	Fels locker															
3	Felsbloecke															
4	Felsbloecke locker															
5	Fliessgewässer															
6	Gebüschwald															
7	Lockergestein															
8	Lockergestein locker															
9	Gletscher															
10	Stehende Gewässer															
11	Feuchtgebiet															
12	Wald															
13	Wald offen															
14	Gehölzfläcche															
15	Schneefeld Totels															

Figure 44: Categories from the swissTLM3D. Green = allowed to overlap. 10 is stagnant water, 11 wetland and 12-14 forest (swisstopo, 2022b).

According to the product information of the swissTLM3D dataset (swisstopo, 2022b), wetlands (Feuchtgebiet) 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 (Bärtschi Hans, swisstopo, personal communication, March 28, 2023, Appendix G) the wetlands were mapped in swissTLM3D by conducting the following four steps:

1. Adaptation of wetland data from old analog maps to align with the terrain in swissTLM3D.
2. Inclusion of data from the peatland inventory of the BAFU.
3. Incorporation of data from cadastral surveys.
4. Addition of wetted areas that are visible in the aerial photographs.

In the swissTLM3D dataset (swisstopo, 2022b), the representation of streets and railways is in the form of polylines. In order to obtain polygonal areas from these polyline features, a buffer area is created around the polylines (Table 14).

Table 14: Buffer around polylines from the swissTLM3D (swisstopo, 2022b).

Polyline	Streets 1 m	Streets 2 m	Streets 3 m	Streets 4 m	Streets 6 m	Streets 8 m	High- way	Rail- way
Buffer (each side)	0.5 m	1 m	1.5 m	2 m	3 m	4 m	5 m	1 m

In order to investigate the effect of different land use with various distances to the river I created buffer polygons of 5 m, 10 m, 25 m and 50 m around the Swiss river network (swisstopo, 2022b) using the *Buffer* tool in QGIS.

The proportion of the five land use categories within the buffer areas were determined using ArcMap and QGIS (Table 15).

Table 15: GIS land use analysis in direct surroundings. GIS steps to determine the proportion of the five land use categories in the buffer polygons.

Description	Tool	Program
Clip the layers to the 50 m buffer polygons from the 165 beaver reaches	Clip	QGIS
Merge the multiple features of each category to one polygon feature per category	Dissolve	QGIS
Converting the five polygon features to 1x1 m raster	Polygon to Raster	ArcMap
Converting the raster to point features resulting in one point per m ²	Raster to Point	ArcMap
Calculating how many points from each of the five categories are in the buffer polygons (50 m, 25 m, 10 m and 5 m) of the 165 beaver reaches	Count Points in Polygon	QGIS



Figure 45: Land use and buffer polygons. Buffer polygons of 5 m, 10 m, 25 m and 50 m (left). Same location with the land cover point features from five different categories (swisstopo, 2022b) (right). Background map: (swisstopo, 2018).

For each category, the absolute number of land use is counted in m². Additionally, the ratio of the buffer area occupied by each category is calculated.

4.11 Dam Age

In order to estimate how long the beavers have been occupying the current territories, I compared the locations of the beaver dams recorded in the current survey to those from previous surveys. It is important to note that comprehensive recent surveys covering the entirety of Switzerland are lacking. Some cantons, such as Vaud, mapped the beaver occurrences frequently, while others have done so rarely respectively last at the national beaver monitoring in 2008. Infofauna provided a dataset with 1'317 beaver dams from 24 beaver mapping projects (Table 16) (Figure 46).

Table 16: Cantonal and national beaver surveys from previous years.

Canton	Year	Number of dams
National	2007-2008	185
Vaud	2009-2010	39
	2010-2011	38
	2013-2014	52
	2014-2015	22
	2016-2017	132
	2017-2018	29
	2018	78
	2018-2019	47
	2020	43
	2020-2021	79
Liechtenstein	2017	19
	2018	9
Aargau	2012-2013	12
	2016-2017	12
	2018-2019	31
Berne	2014-2015	95
Freiburg	2017	13
Lucerne	2018	24
Thurgau	2017-2018	46
Zug	2017-2018	2
Zürich	2013-2014	33
	2016-2017	109
	2019-2020	168

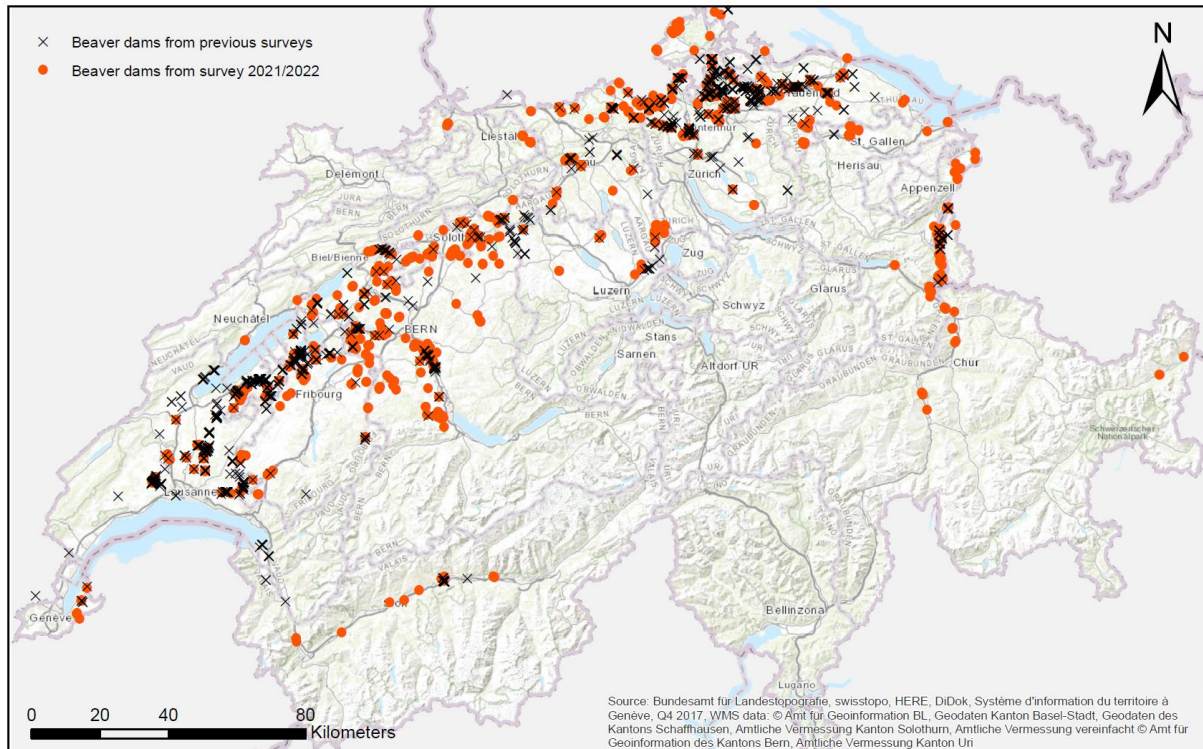


Figure 46: Beaver dam locations from previous and current surveys. Background map: (swisstopo, 2021).

Using the information from previous surveys, it is not possible to determine the exact age of beaver dams. However, it is possible to determine whether the beaver reach was already occupied by beavers in previous surveys (Figure 47).

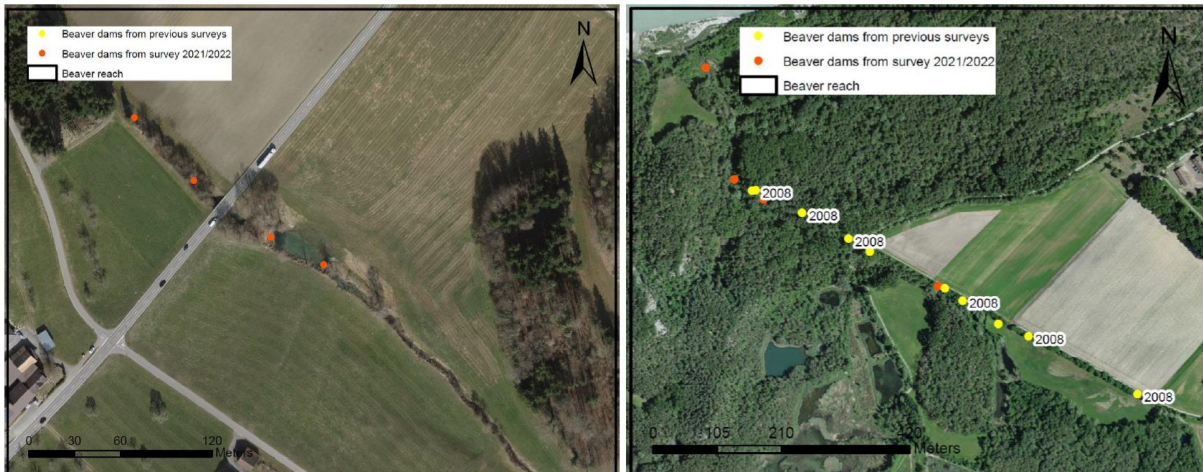


Figure 47: Comparison with previous surveys. Beaver reach with no beaver dams mapped in previous surveys (left) and beaver reach with beaver dams since (at least) 2008. Background map: (swisstopo, 2018).

4.12 Water quality analysis

Various analysis methods are applied aiming to answer the research questions (chapter: 1.4).

4.12.1 General summary water chemistry

For nitrate and DOC, the following analytical steps are completed in order to present a general overview on the concentrations:

1. Comparison between the boxplots from the winter and summer US concentrations.
2. Comparison of the number of beaver reaches with increasing or decreasing concentrations winter and summer.
3. Comparison of the magnitude of increases and decreases in winter and summer.
4. Analysis of spatial patterns by plotting the US concentrations and the magnitude of increase or decrease on a Swiss map.

The general summary of ammonium, bromide, calcium, chloride, fluoride, magnesium, potassium, sodium and sulfate consists of comparing the median concentration across all beaver reaches for US winter, DS winter, US summer and DS summer.

4.12.2 Comparing areas of interest

I subdivided the beaver reaches into seven distinct *Areas of Interest* (Table 17). This division facilitated the comparison of various factors, such as distance, slope, volume, number of dams, and dam age, through boxplots within each Area of Interest. The aim was to form categories with high contrasts such as “nitrate and DOC decreases in both seasons” and “nitrate and DOC increases in both seasons”. Furthermore, the category “nitrate > 25 mg/l” was chosen in order to examine the characteristics of beaver systems with high nitrate concentrations. The category “All” was created to allow a comparison with the entire dataset.

Table 17: Seven areas of interest.

Area of interest	Explanation	Number of beaver reaches
All	All beaver reaches with a complete dataset in summer and winter	153
NO ₃ : --	Beaver reaches with decreasing nitrate concentrations in summer and winter	65
NO ₃ : ++	Beaver reaches with increasing nitrate concentrations in summer and winter	32
NO ₃ (S, US) > 25 mg/l	Beaver reaches with US summer nitrate concentration > 25 mg/l (limit for Swiss rivers)	17
NO ₃ : -- DOC: ++	Beaver reaches with decreasing nitrate and increasing DOC concentrations in summer and winter	24
DOC: ++	Beaver reaches with increasing DOC concentrations in summer and winter	47
DOC: --	Beaver reaches with decreasing nitrate concentrations in summer and winter	31

4.12.3 Correlations between characteristics and (change in) nitrate and DOC concentrations

In a next step I divided the dataset of beaver system characteristics into three distinct categories in order to estimate the relationship to the US concentrations of nitrate/DOC (Category 1), the increase/ decrease of nitrate/DOC concentrations between the US and DS sampling location (Category 2) and the land use in the buffer area of the river between US and DS (Category 3) (Figure 48). To determine the significance of the Pearson correlations I first calculated the t-test (Equation 7). To calculate the p-value I applied the Excel function T.DIST.2T (Equation 8).

Equation 7: t-test calculation (Turney, 2022).

$$t = r \frac{\sqrt{n-2}}{\sqrt{1-r^2}}$$

Where r represents the Pearson correlation and n the number of samples.

Equation 8: Syntax equation (Microsoft 365 Support, n.d.).

$$p = T.DIST.2T(t, n - 2)$$

By convention, a significance level of 0.05 is considered. If the resulting p-value is lower than 0.05, the correlation is deemed significant (Turney, 2022).

Category 1 Characteristics of the catchment or the US sampling location which (may) control the US concentrations of nitrate or DOC:

- Altitude of the US water sampling location
- Mean catchment altitude
- Discharge
- Catchment size
- Water temperature US
- Land use in catchment
- Stable isotope composition
- Ammonium, sodium, magnesium, calcium, potassium, fluoride, chloride, bromide and sulfate concentrations US

Category 2 Beaver system characteristics which (may) cause an increase or decrease in nitrate and DOC concentration within the beaver system:

- 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

Category 3 Land use in the direct surrounding of the river between US and DS (chapter: 4.10).

- 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

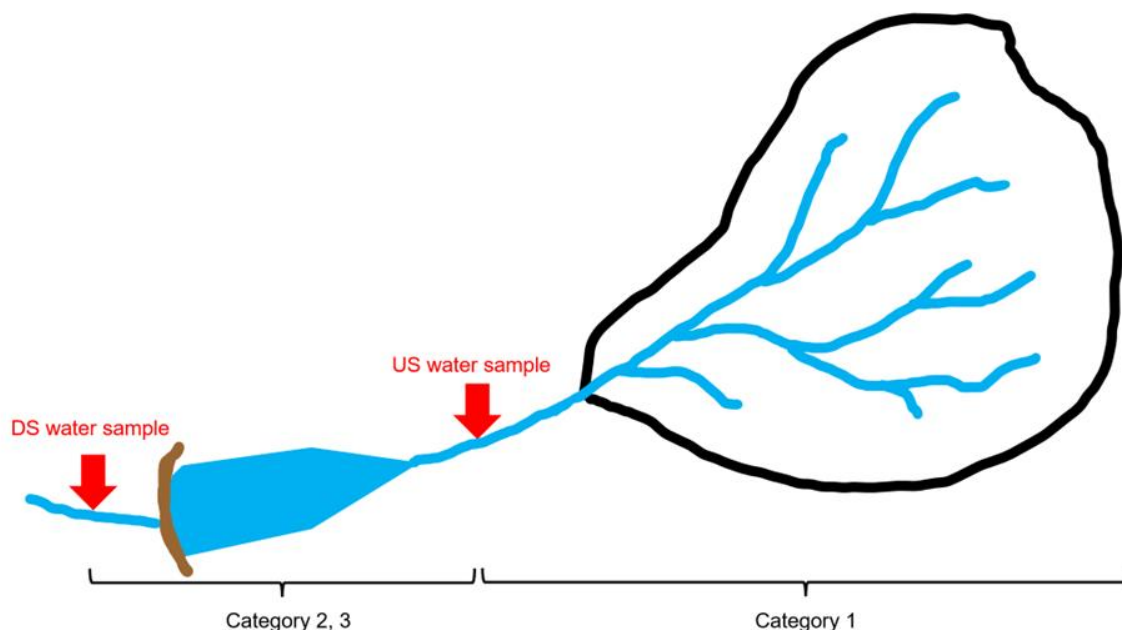


Figure 48: Categories for correlation analysis. Illustration of a catchment and the US and DS water sampling locations. Category 1 represented by general characteristics controlling the US concentrations and Category 2 and 3 represented by characteristics potentially causing changes in nitrate and DOC concentrations.

4.12.4 Wetlands

Based on the initial findings, it became evident that wetlands within the buffer polygons of the beaver reaches have a significant impact on reducing nitrate concentrations and increasing DOC concentrations (chapter: 5.4.3). Consequently, further analysis methods were developed to examine the effects of wetlands in more detail.

25 beaver reaches were identified as having a certain proportion of wetland area within the 50 m buffer polygon. These beaver reaches were categorized into two groups in order to investigate potential impacts of the connectivity between the wetland and river (Figure 49):

1. Wetland directly connected to the water of the river.
2. Wetland and river not directly connected, but with roads, trails, trees, etc. in between.

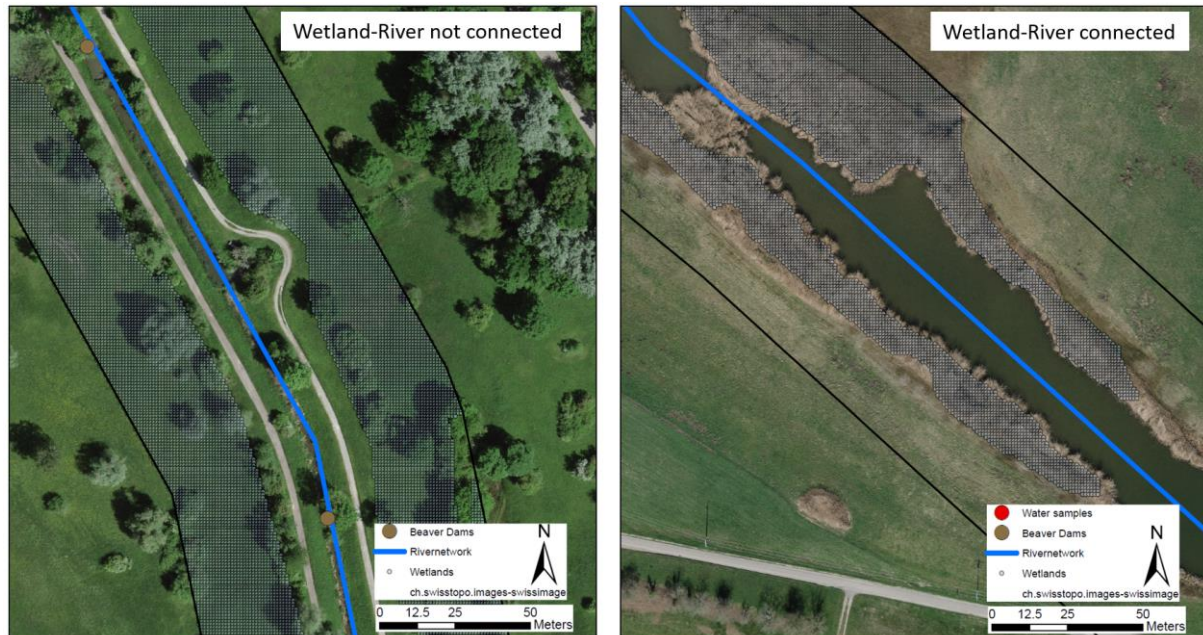


Figure 49: Wetland-River connectivity. Classification of beaver reaches with wetlands in the 50 m buffer area into two categories. Background map: (swisstopo, 2018).

In order to investigate the influence of the wetland size directly connected to the river, the size of the wetland was determined by selecting all the wetland point features, where each point represented an area of one square meter (m^2) (Figure 50).

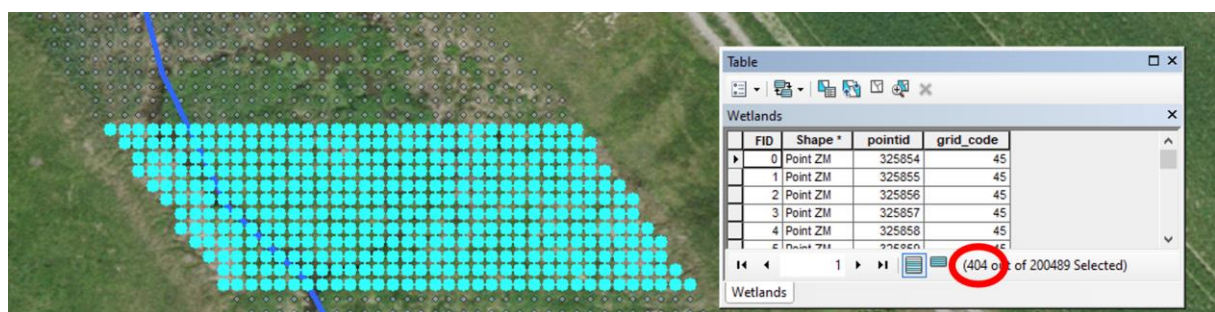


Figure 50: Size of wetland area. In this example, 404 features are selected, which represents 404 m^2 of wetland connected to the river. This figure only demonstrates the counting by selection. When applying the method, the features above and beyond this area would be selected as well. Background map: (swisstopo, 2018).

To gain further insights, expert opinion by Christof Angst, Biberfachstelle, was sought regarding the identification of wetlands created through beaver activities.

5. Results

This chapter begins with a description of the study sites and their characteristics, followed by a general overview of the water chemistry results. Next, the results for different areas of interest are presented. Then correlations between river and catchment characteristics and US nitrate and DOC concentrations as well as changes in nitrate levels are presented. The chapter also includes the results of the wetland analysis and the results from reaches sampled in only one season.

5.1 Characterizations of study sites

5.1.1 Locations

The investigated beaver reaches are mainly on the Swiss plateau. There are also beaver dams in the St. Gallen Rhine Valley and in the Valais (Figure 51).

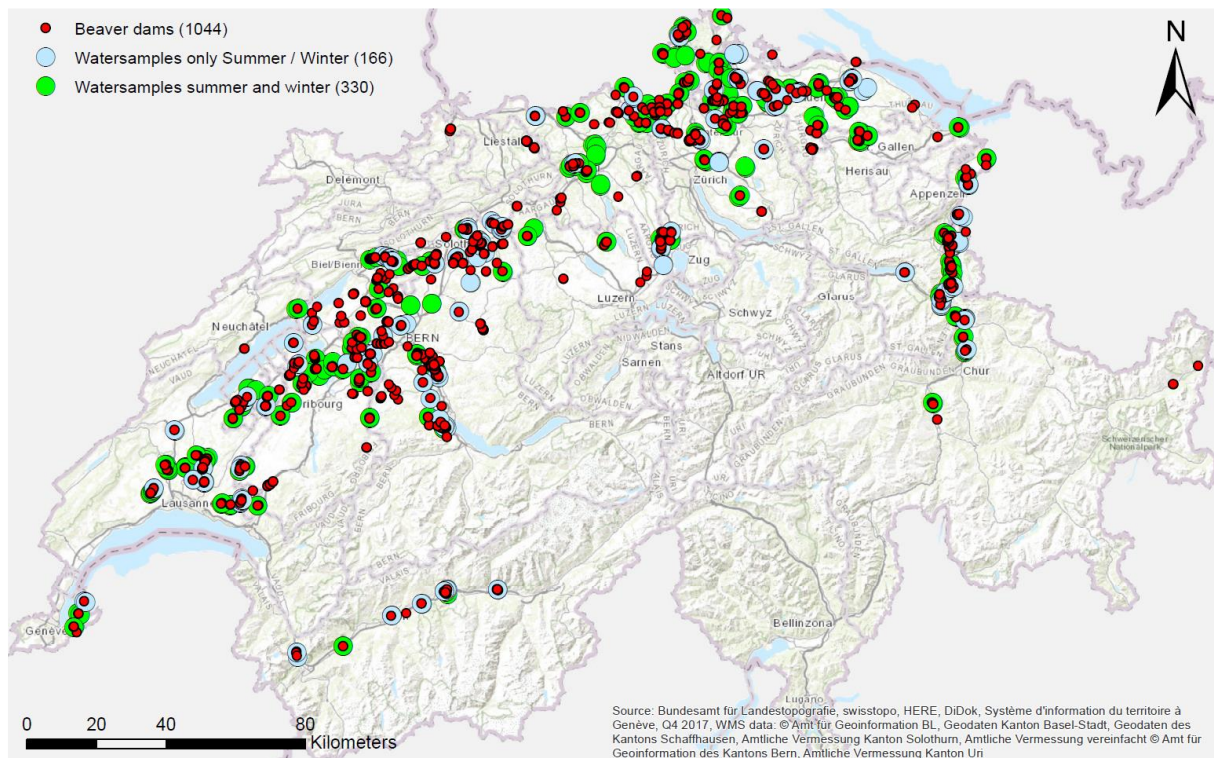


Figure 51: Overview map. Water sampling locations from the winter and summer sampling campaign as well as the beaver dams as they were mapped by the volunteers during the survey in winter 2021/2022. Background map: (swisstopo, 2021).

5.1.2 Altitudes of mapped beaver dams

Most (> 50 %) of the beaver dams mapped during the monitoring in winter 2021/2022 as well as during the summer sampling campaign are located on an altitude between 400 to 500 m a.s.l. (Figure 52).

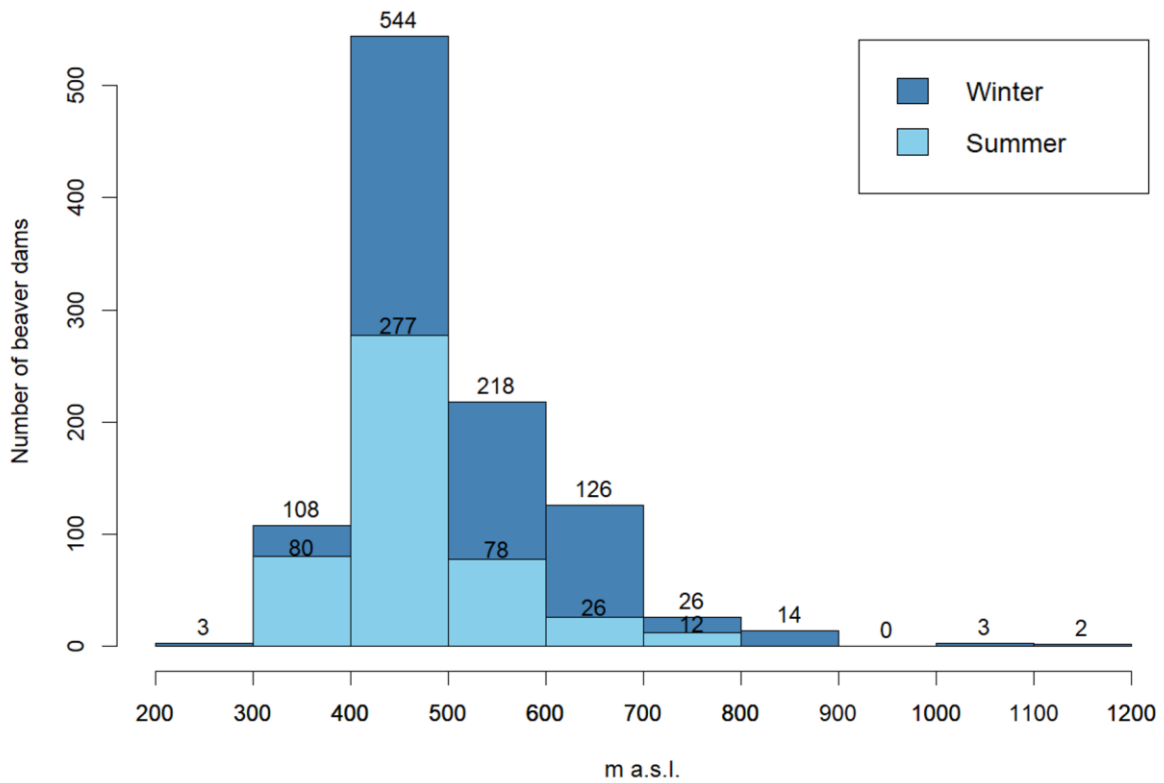


Figure 52: Beaver dam altitudes. Altitudes extracted from (swisstopo 2022a).

5.1.3 Dam heights (summer)

The majority (270) of the beaver dam heights documented during the summer campaign are lower 0.5 m. The highest dams reach 2.5 m (Figure 53).

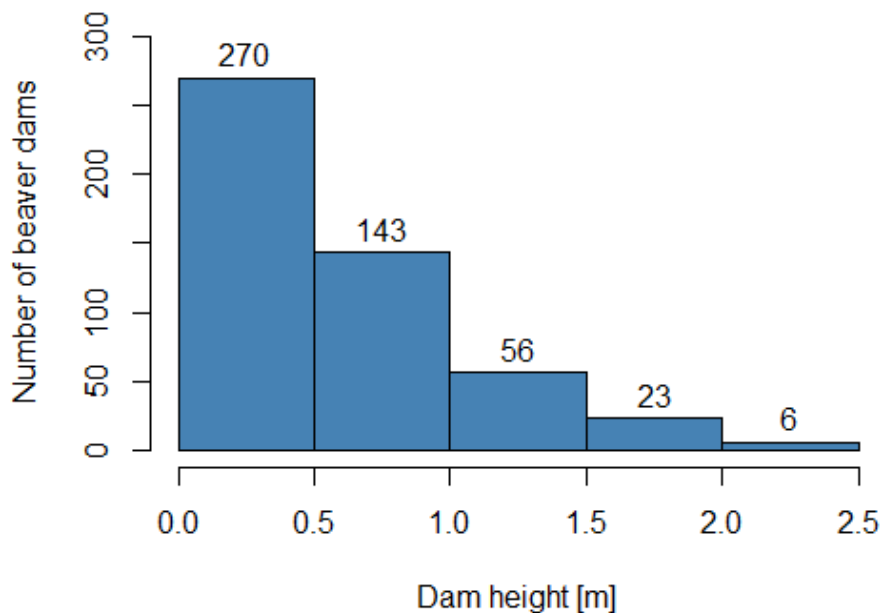


Figure 53: Height of the beaver dams documented in summer. Information on the beaver dam heights is only available in summer.

5.1.4 Water temperature (summer)

The mean DS water temperature (17.70 °C) is 0.24 °C warmer than the mean US water temperature (17.46 °C). The water temperatures were only measured in summer.

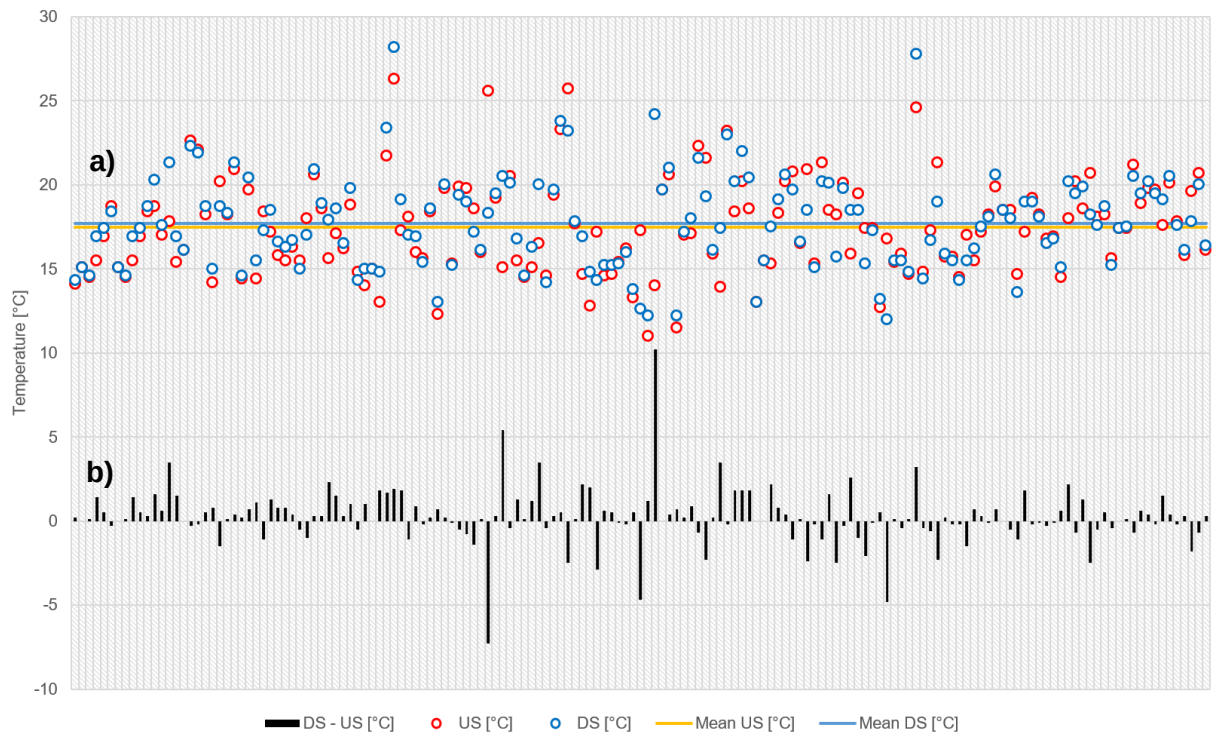


Figure 54: Water temperature measurements. a) US and DS water temperature in summer 2022. b) The black bars demonstrate the difference DS-US meaning that positive numbers represent a warming of the surface water through the beaver system, and negative numbers represent a cooling.

5.1.5 Catchment characterization

5.1.5.1 Catchment size

Most (124 out of 165) of the beaver dammed catchments are below 10 km² (Figure 55). The average size of the 165 catchments is 7.5 km².

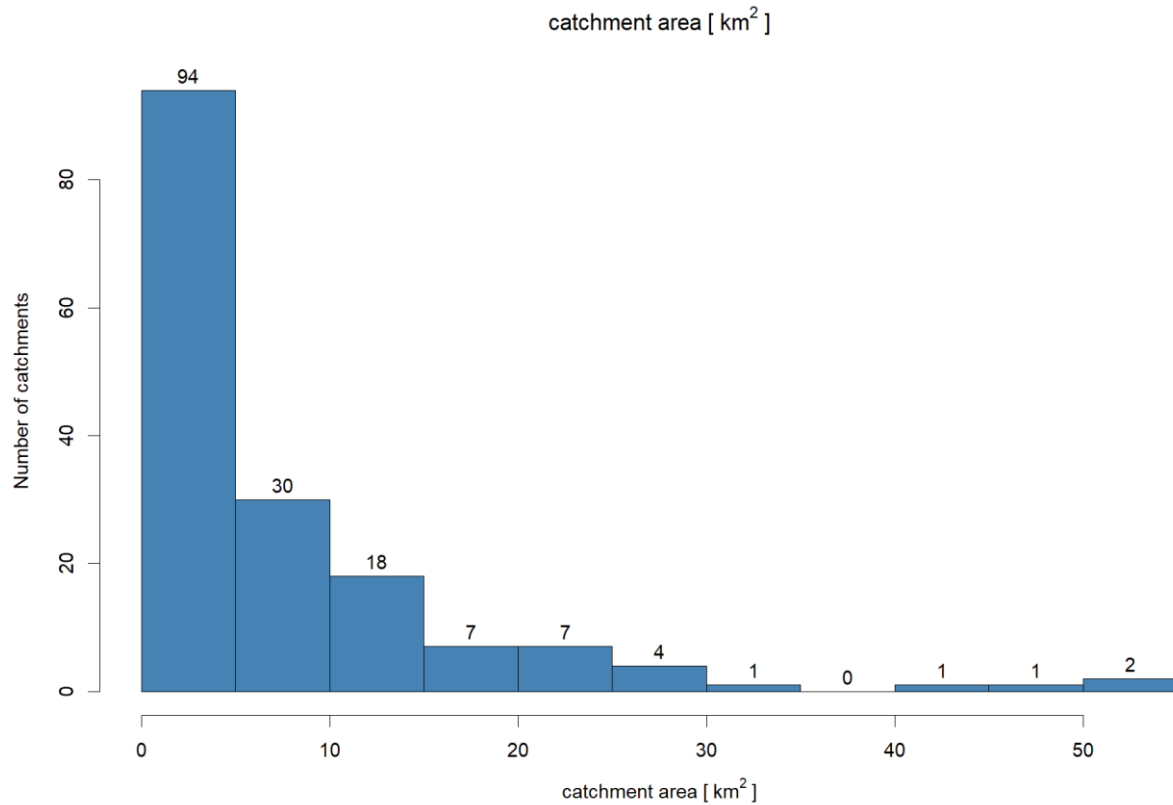


Figure 55: Distribution of the catchment areas.

5.1.5.2 Land use in catchments

The majority of the land use in the catchments is agriculture (56 %, 73'332 hectares), 28 % is forest, 15 % settlement areas and 1 % non-productive areas as e.g. rivers and lakes (Figure 56).

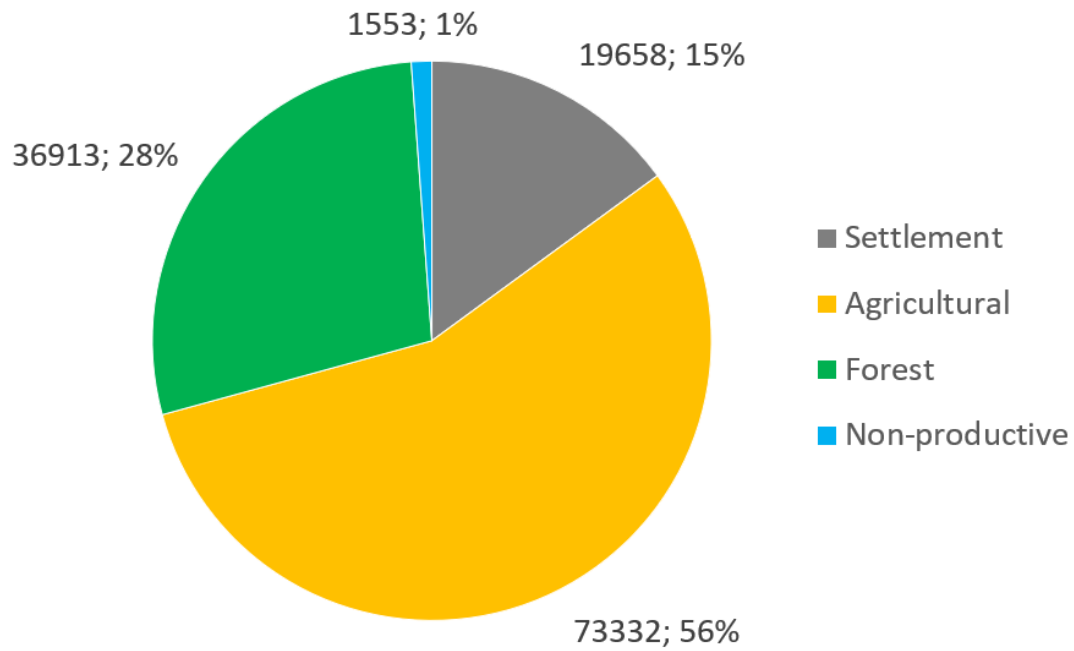


Figure 56: Land use in catchments. Distribution of the land use in the $\sim 1'300 \text{ km}^2$ upstream catchment areas from 165 beaver reaches. The first numbers are the numbers of counted points in the catchment polygons. Each point represents one hectare.

5.1.6 Discharge

Modeled discharge data are available for 153 beaver reaches in winter and 157 beaver reaches in summer. In winter 2021/22 the discharge was clearly higher than in summer 2022 (Figure 57). The average discharge in winter is 72.5 l/s and in summer 21.3 l/s.

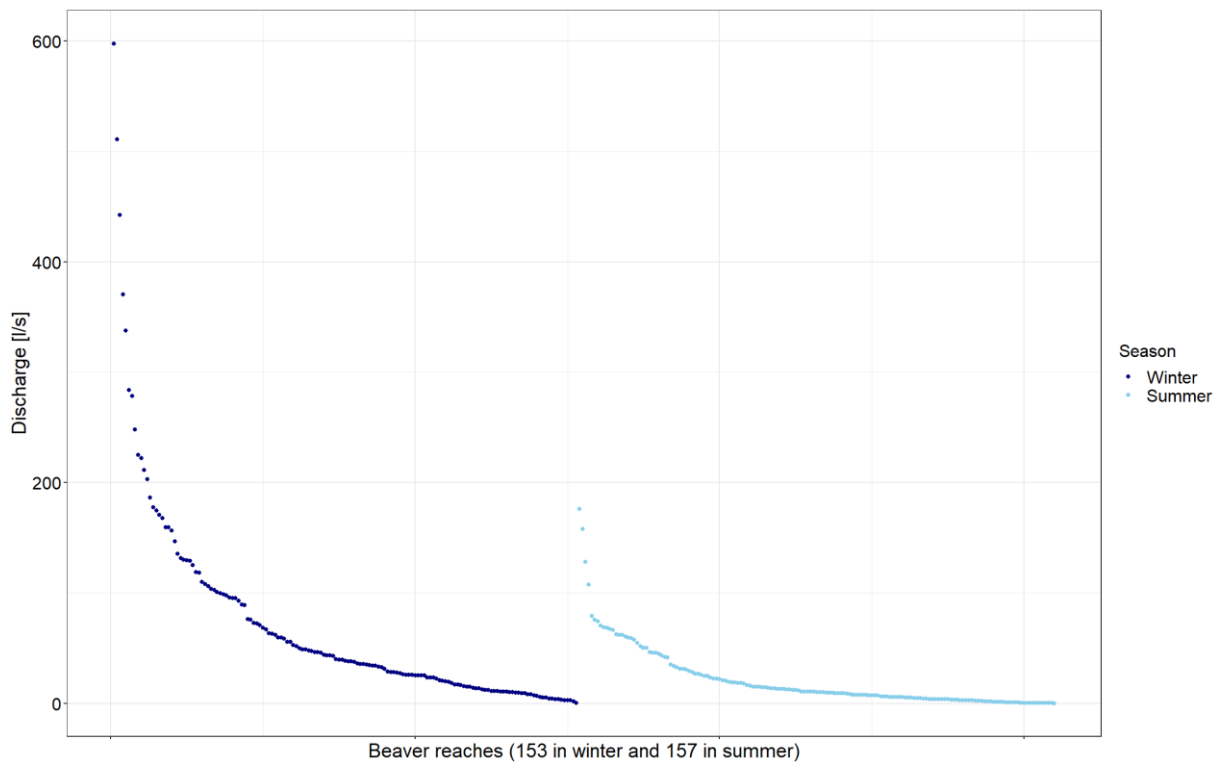


Figure 57: Discharge in winter and summer. Discharge values sorted from high to low for 153 catchments in winter and 157 catchments in summer.

5.1.7 Water volume estimation

The water volume is estimated using the QGIS method (chapter: 4.7.2.2). Most (107) of the 165 beaver reaches have a water volume lower than 500 m³. The largest beaver reaches have a water volume between 3'000 and 3'500 m³ (Figure 58).

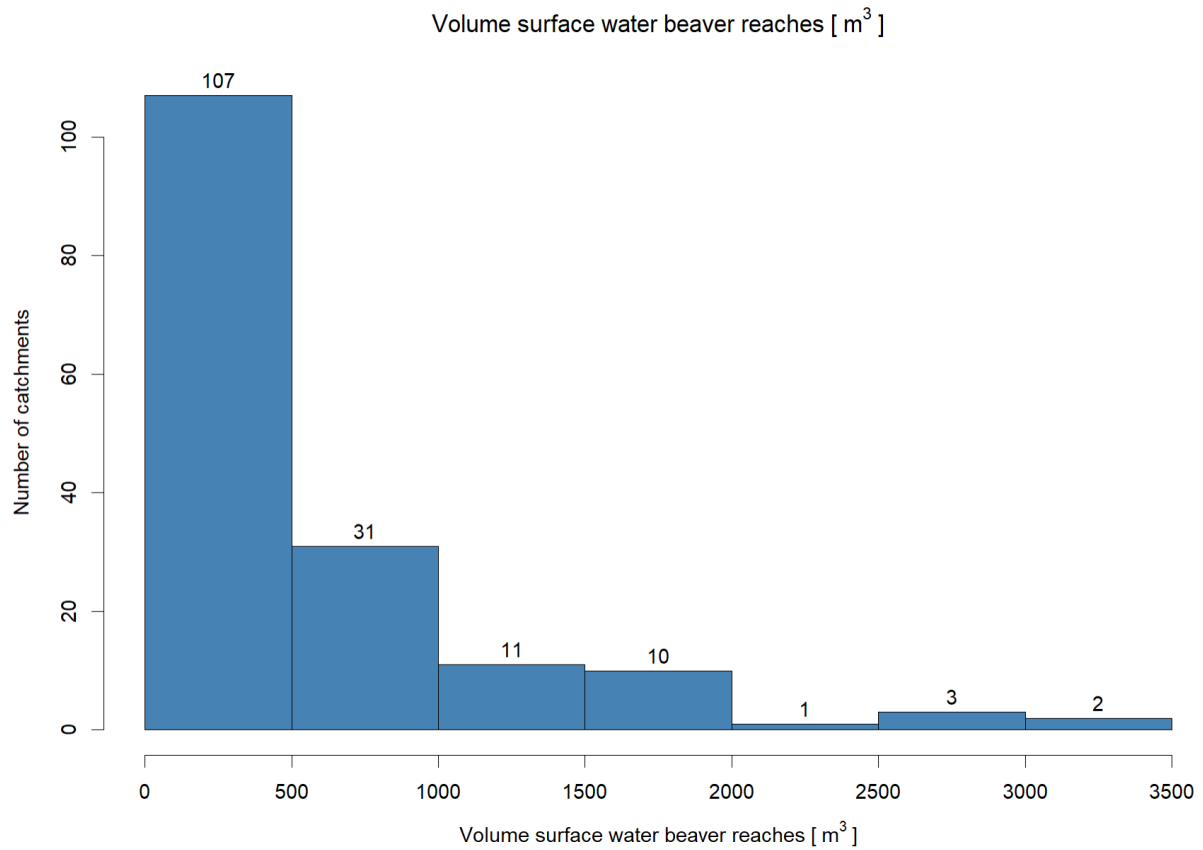


Figure 58: Water volume in the beaver reaches.

5.1.8 River sector between US and DS water sample

In this chapter the characterization of the river sector between the US and DS water sampling location is presented (chapter: 4.8). Figure 59 represents a comparison between the river slope, the number of dams per beaver reach and the beaver reach length.

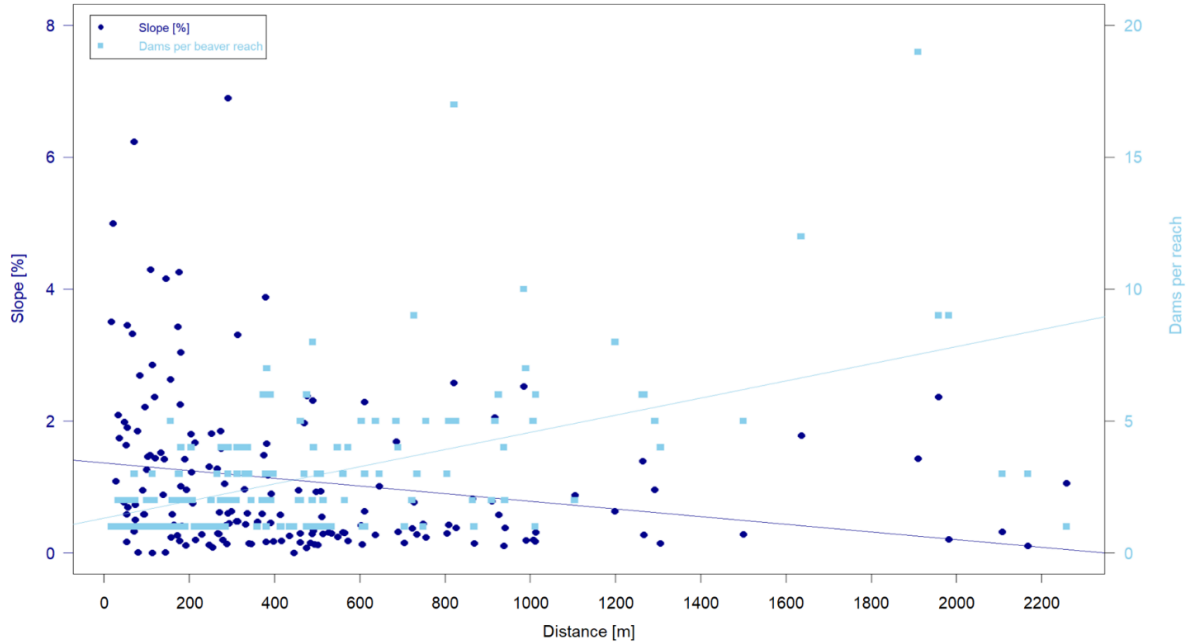


Figure 59: Slope, length and beaver dams per beaver reach.

5.1.8.1 Distance

The distances between the US and DS sampling location reach from 17 m to 2'258 m with a median distance of 336 m.

5.1.8.2 Slope

The minimum slope between US and DS is slightly above 0 % and the maximum is 6.9 %. The median slope is 0.6 %. Analysis using linear regression indicates that there is a tendency for the slope to decrease as the distance between the US and DS sampling location increases (Figure 59).

5.1.8.3 Dams per reach

There are two beaver dams per beaver reach on average. The highest recorded number of beaver dams per reach is 19. There is a tendency for longer reaches to have more beaver dams than shorter reaches (Figure 59).

5.1.8.4 Land use in the direct surroundings

The land use within the buffer polygons, expressed as a percentage of the total buffer polygon area, is predominantly composed of forest and agriculture. The proportion of forest tends to increase as the buffer polygons become smaller, while the ratios of agriculture decrease with smaller polygons. In the case of stagnant water and wetland areas, the outliers with the highest ratio are observed with the 5 m and 10 m buffer zones (Figure 60).

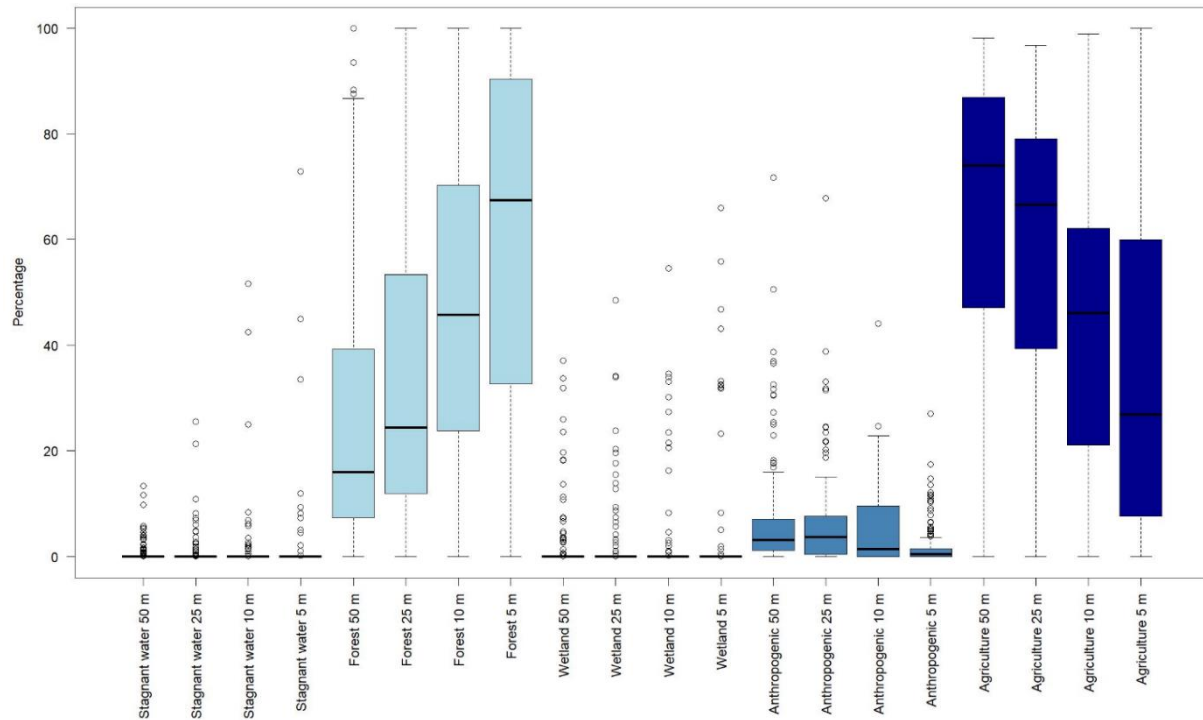


Figure 60: Ratio of land use categories for different buffer width.

5.1.9 Dam age

From the 165 examined beaver reaches, 100 did not have any recorded presence of beaver dams in any previous surveys. 15 reaches were already occupied by beavers during the national beaver census in 2007-2008. In 50 beaver reaches dams were mapped for the first time during cantonal surveys in the years from 2011 to 2020 (Figure 61).

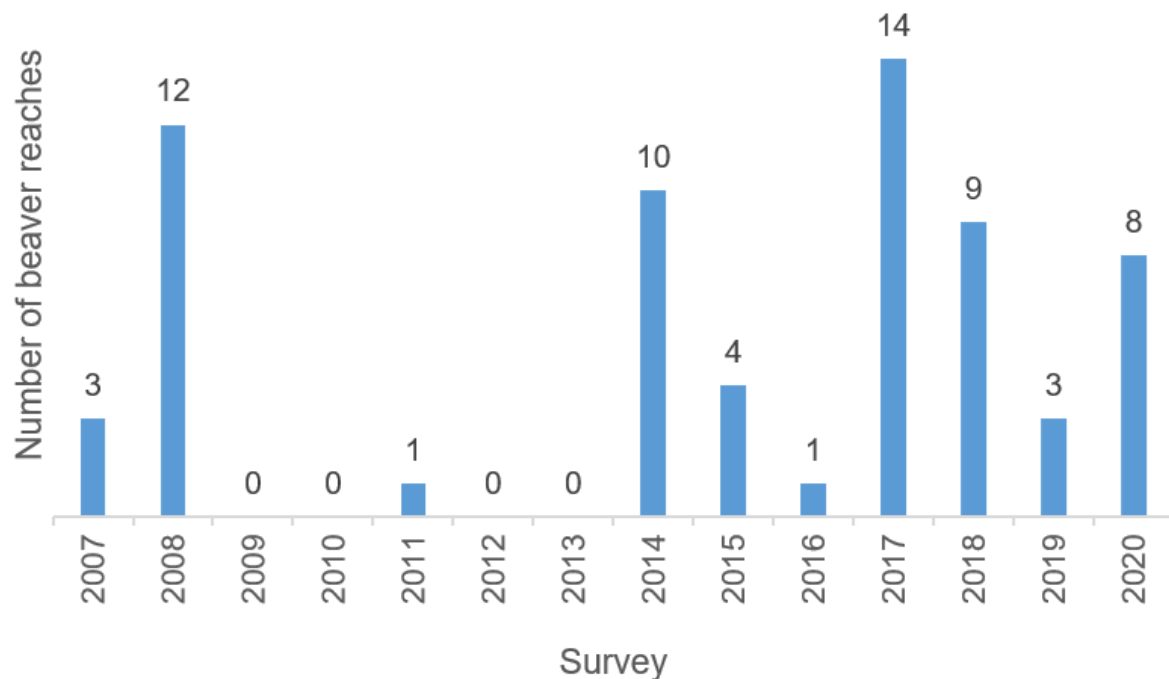


Figure 61: Number of beaver reaches occupied by beavers in previous surveys.

5.2 General summary water chemistry

In this chapter the results for nitrate and DOC concentrations, total suspended sediment and stable isotope composition of the 165 beaver reaches sampled in winter 2021/22 and summer 2022 are presented. Variations in the total number of beaver reaches shown in the figures may occur due to data gaps resulting from the data cleaning process (chapter: 4.1.2, Table 3).

Appendix L provides the results of the ammonium analysis, while Appendix O contains data on additional water chemistry parameters (sodium, magnesium, calcium, potassium, fluoride, chloride, bromide and sulfate). Furthermore, Appendix M presents the analysis conducted using data from beaver reaches that were sampled in only one season.

5.2.1 Nitrate

The median nitrate concentration of 158 beaver reaches is higher in winter (median: 16.34 mg/l) compared to summer (median: 12.76 mg/l). However, it should be noted that the outliers with the highest concentrations reaching up to 100 mg/l, occur specifically during the summer season (Figure 62).

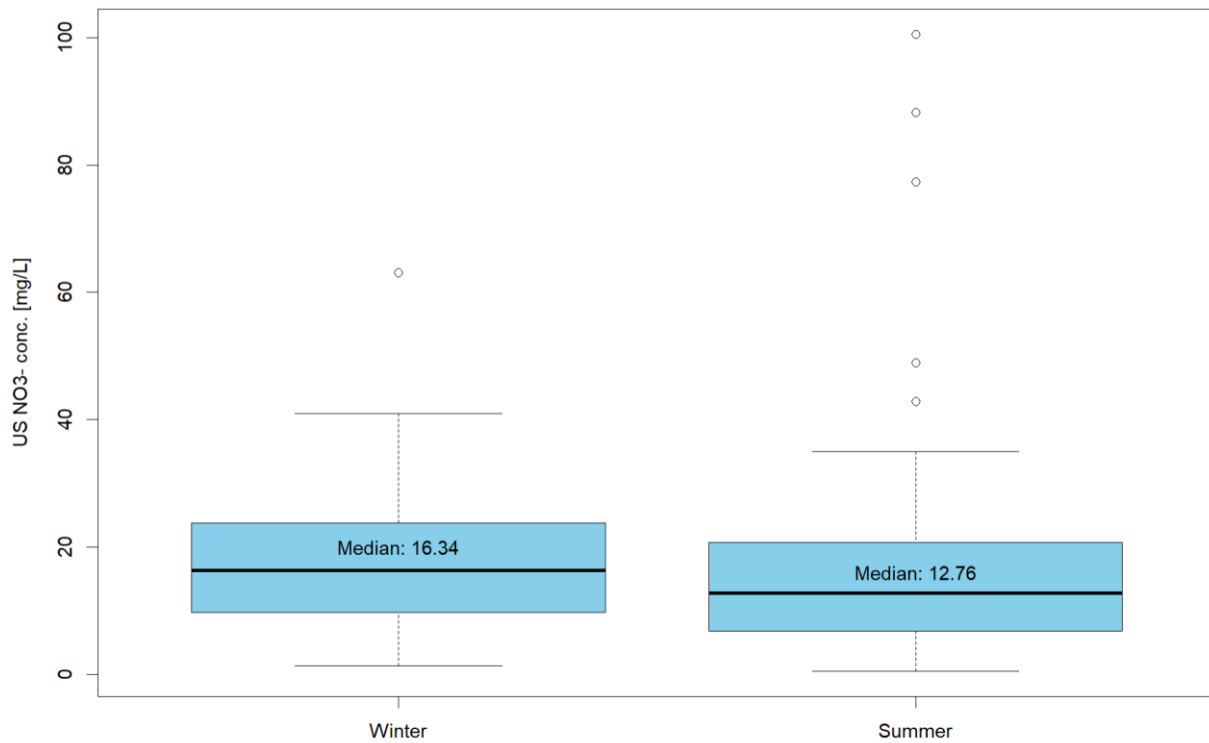


Figure 62: Boxplots US nitrate concentrations in winter and summer.

The comparison between nitrate concentrations US and DS reveals a higher frequency of decreases rather than increases. This effect is more pronounced during the summer season, where out of 158 measurements, 104 showed a decrease, while in winter, 89 out of 158 measurements indicated a decrease (Figure 63).

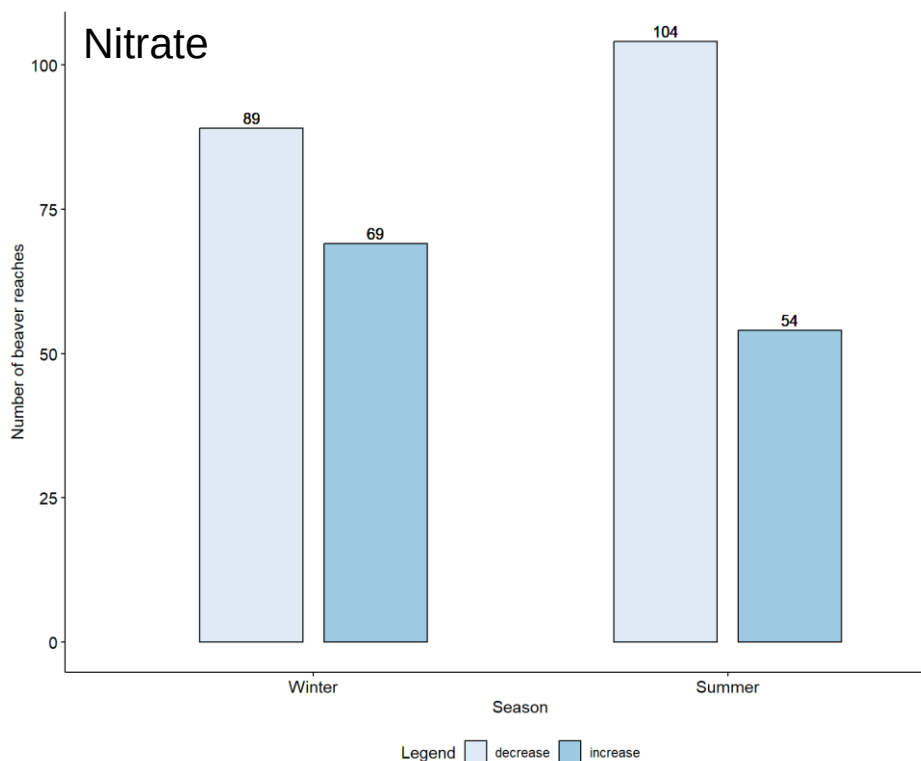


Figure 63: Nitrate increases and decreases. Comparison of nitrate concentrations US and DS of beaver reaches. Decrease means that the DS nitrate concentration is lower.

The differences between US and DS nitrate concentrations are predominantly less than 5 mg/l. The results from winter and summer are divided into four categories. Among these categories, the most common one, comprising 68 beaver reaches, is characterized by decreased concentrations in winter and summer (Figure 64).

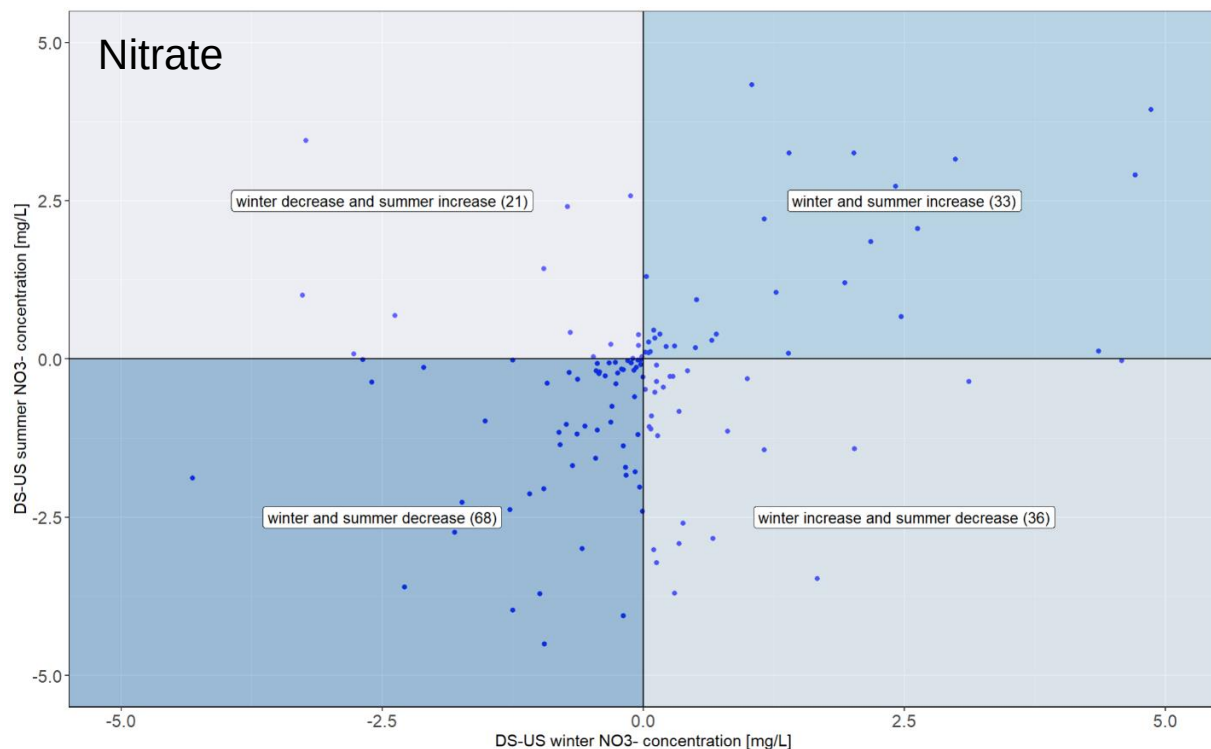


Figure 64: DS – US nitrate concentrations in winter and summer. For the sake of clarity, only differences lower than ± 5 mg/l are depicted in this graph. The complete graph, including outliers (> 5 mg/l), can be found in Appendix H.

The nitrate concentrations appear to be generally higher on the Swiss plateau compared to the St. Gallen Rhine Valley or the Valais. Moreover, locations exhibiting high or low nitrate concentrations during winter also tend to maintain similar patterns during summer. Regarding the differences in nitrate concentrations within beaver reaches across Switzerland, no spatial pattern can be identified. Figure 65 and Figure 66 illustrate the absolute values of concentration changes, while Appendix I presents the changes in relative numbers.

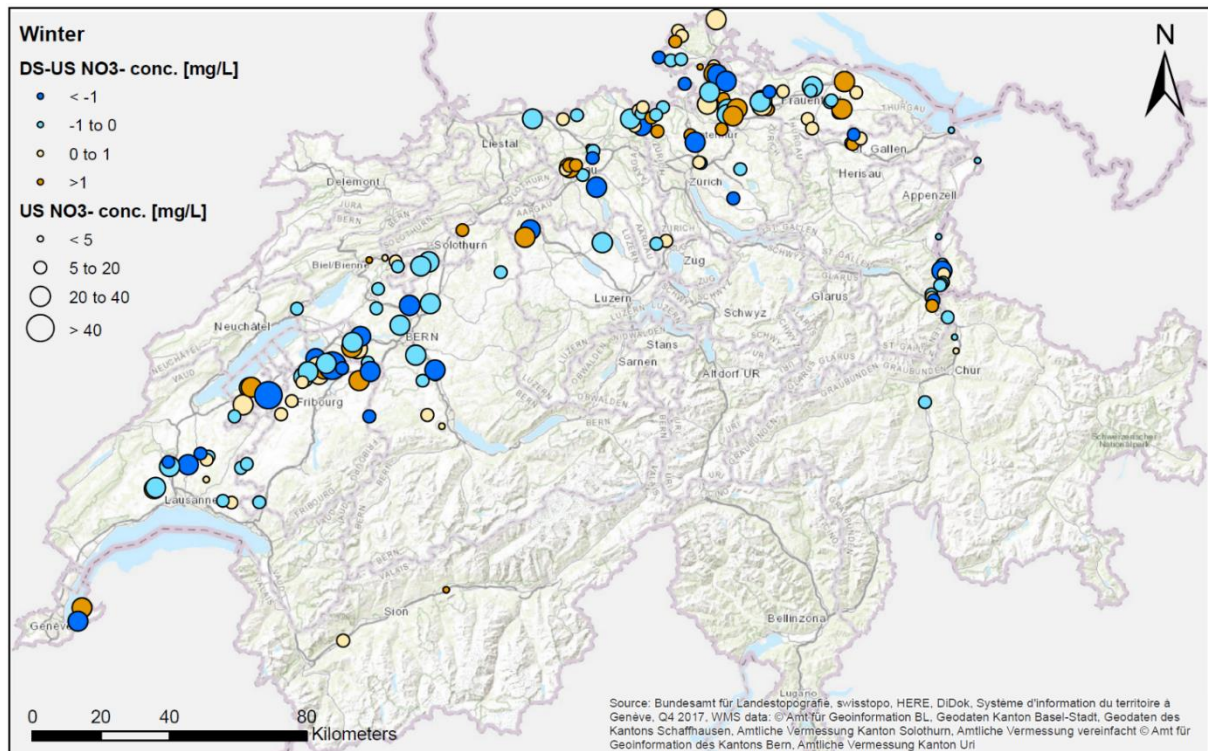


Figure 65: Nitrate concentrations and changes in winter. Map visualizing the winter US nitrate concentrations and the differences between US and DS (DS minus US). Negative values indicate lower DS concentrations. Background map: (swisstopo, 2021).

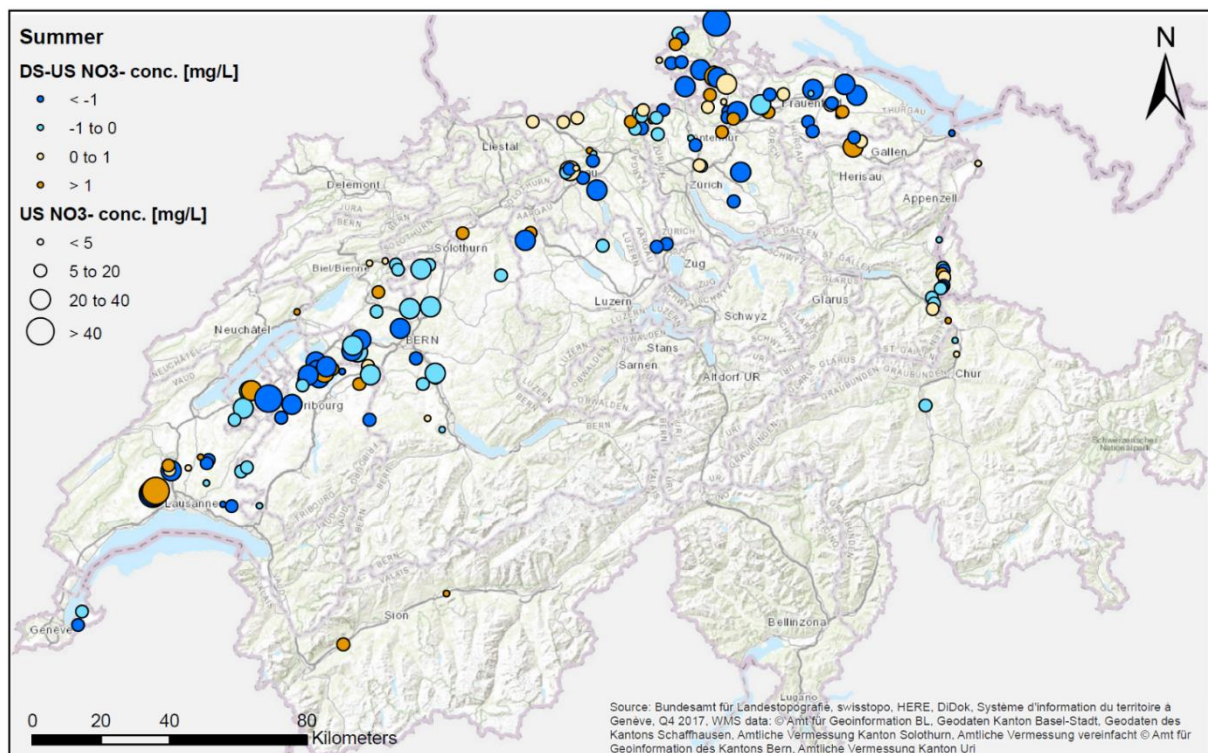


Figure 66: Nitrate concentrations and changes in summer. Map visualizing the summer US nitrate concentrations and the differences between US and DS (DS minus US). Negative values indicate lower DS concentrations. Background map: (swisstopo, 2021).

5.2.2 Dissolved Organic Carbon DOC

In contrast to the nitrate concentration, the median US DOC concentration is higher in summer (2.78 mg/l) than in winter (1.98 mg/l) (Figure 67).

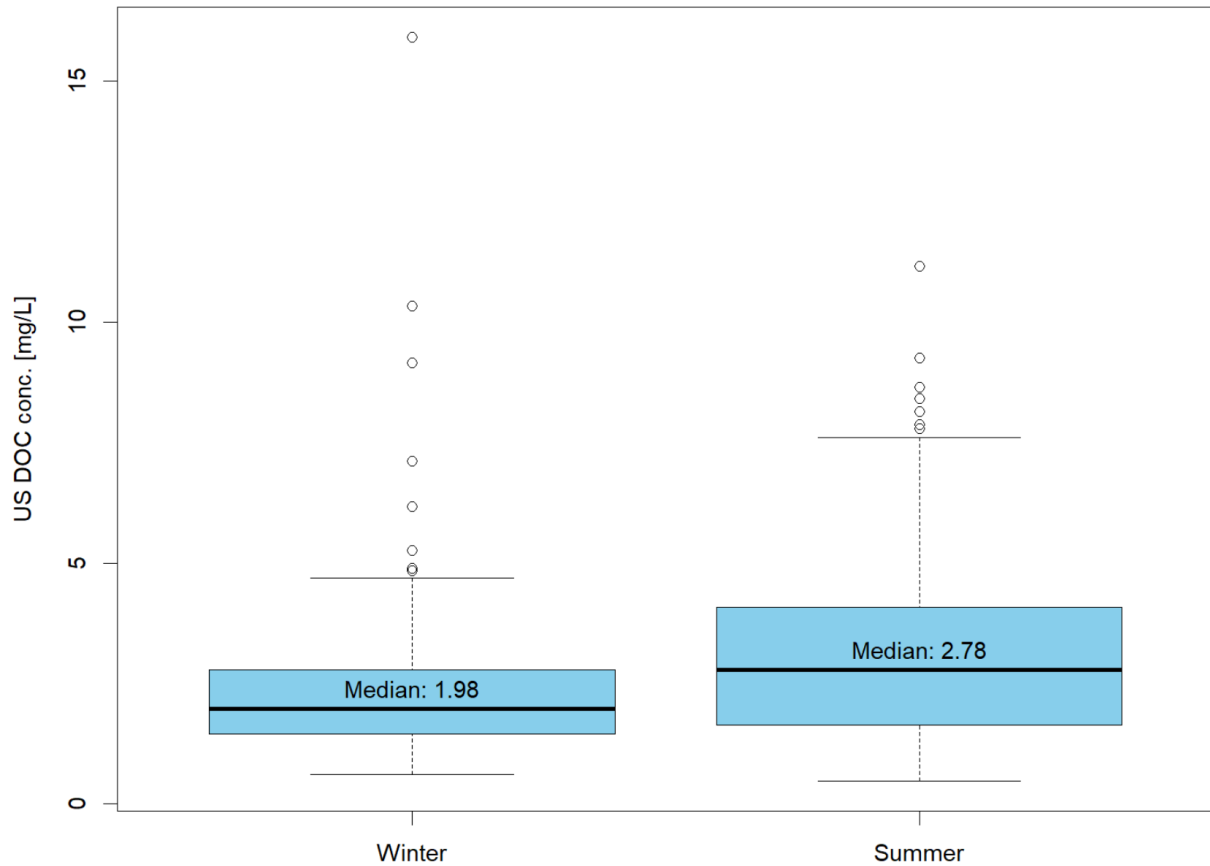


Figure 67: Boxplots US DOC concentrations in winter and summer.

During winter, the ratio of beaver reaches with decreasing DOC concentrations (80) is nearly equal to those with increasing DOC concentrations (77). However, in summer, there is a clear tendency for beaver reaches to exhibit an increase in DOC concentration (97). A decrease in DOC concentrations was observed in only 60 beaver reaches during the summer season. (Figure 68).

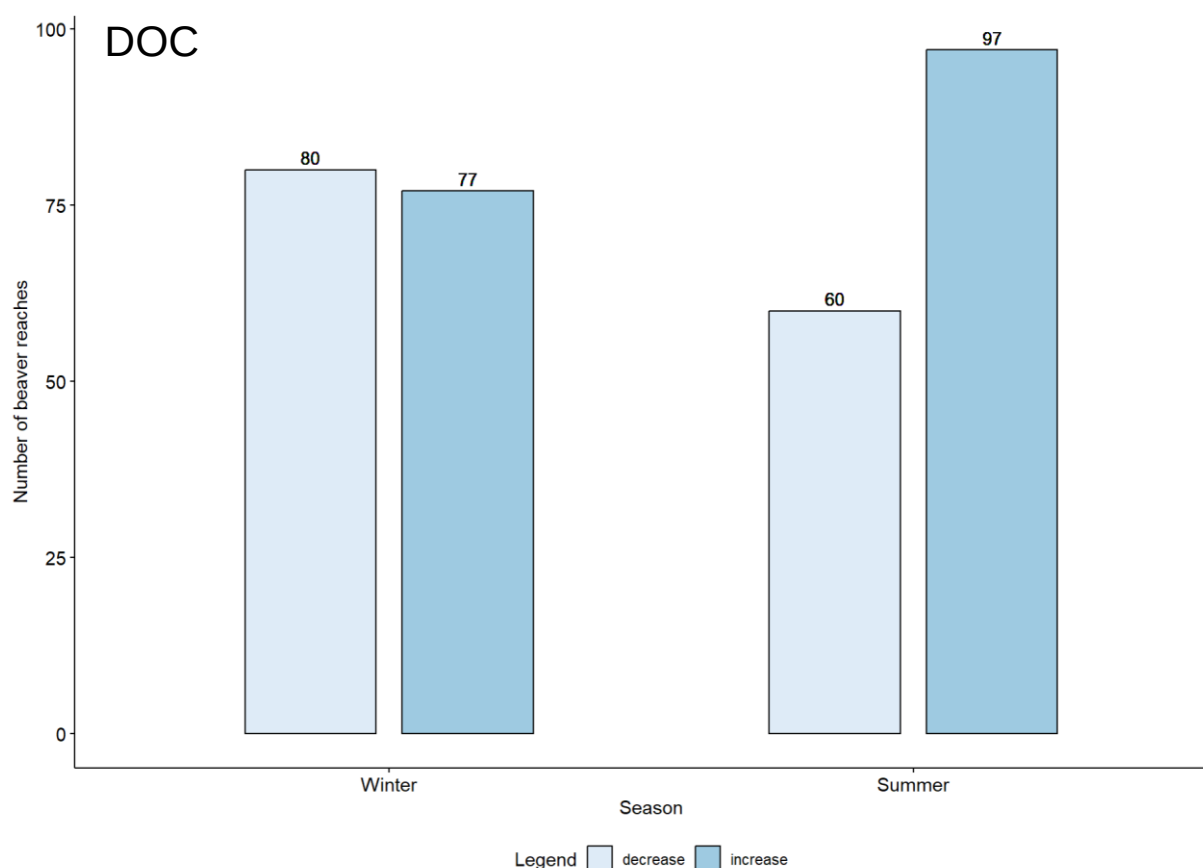


Figure 68: Comparison of DOC concentrations US and DS of beaver reaches. Decrease means that the DS DOC concentration is lower.

The differences between the US and DS DOC concentrations are generally smaller compared to the differences in nitrate concentrations. Especially in winter, the differences are mainly below 0.5 mg/l. The results from winter and summer are classified into four categories. Among these categories, the most common ones are beaver reaches exhibiting increasing DOC concentrations in summer (Figure 69). Beaver reaches with differences > 2 mg/l are summarized in Appendix J.

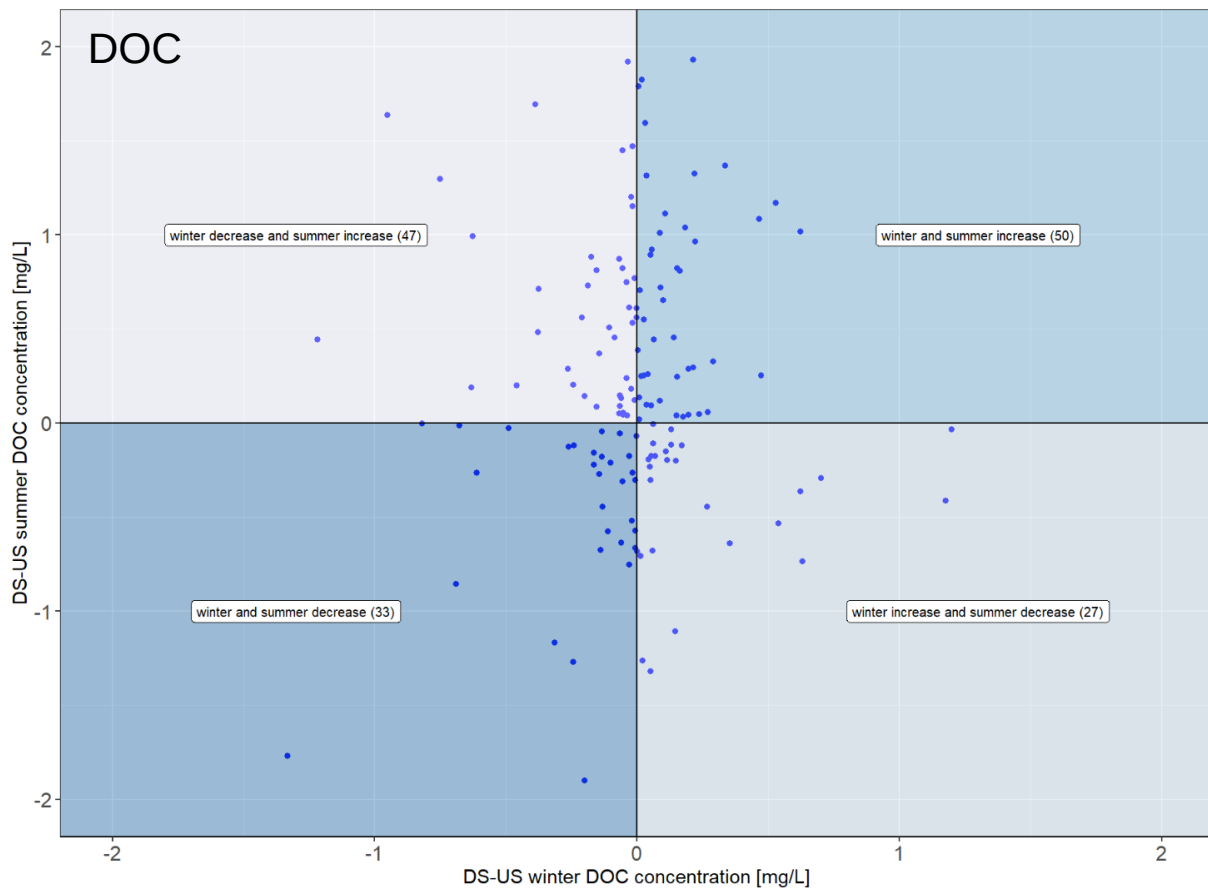


Figure 69: DS – US DOC concentrations in winter and summer. For the sake of clarity, only differences lower than ± 2 mg/l are depicted in this graph. A table of the outlier values (> 2 mg/l), with notably high differences in beaver reach Nr. 67, can be found in Appendix J.

Similar to the nitrate concentrations, the DOC concentrations in the St. Gallen Rhine Valley and the Valais are generally lower compared to the Swiss plateau. The differences between US and DS tend to be higher in summer than in winter (Figure 69, Figure 70 and Figure 71 and Appendix K).

Figure 70 and Figure 71 illustrate the absolute values of concentration changes, while Appendix K presents the changes in relative numbers. Similar to nitrate concentrations, no spatial pattern can be discerned in the differences of DOC concentrations across Switzerland.

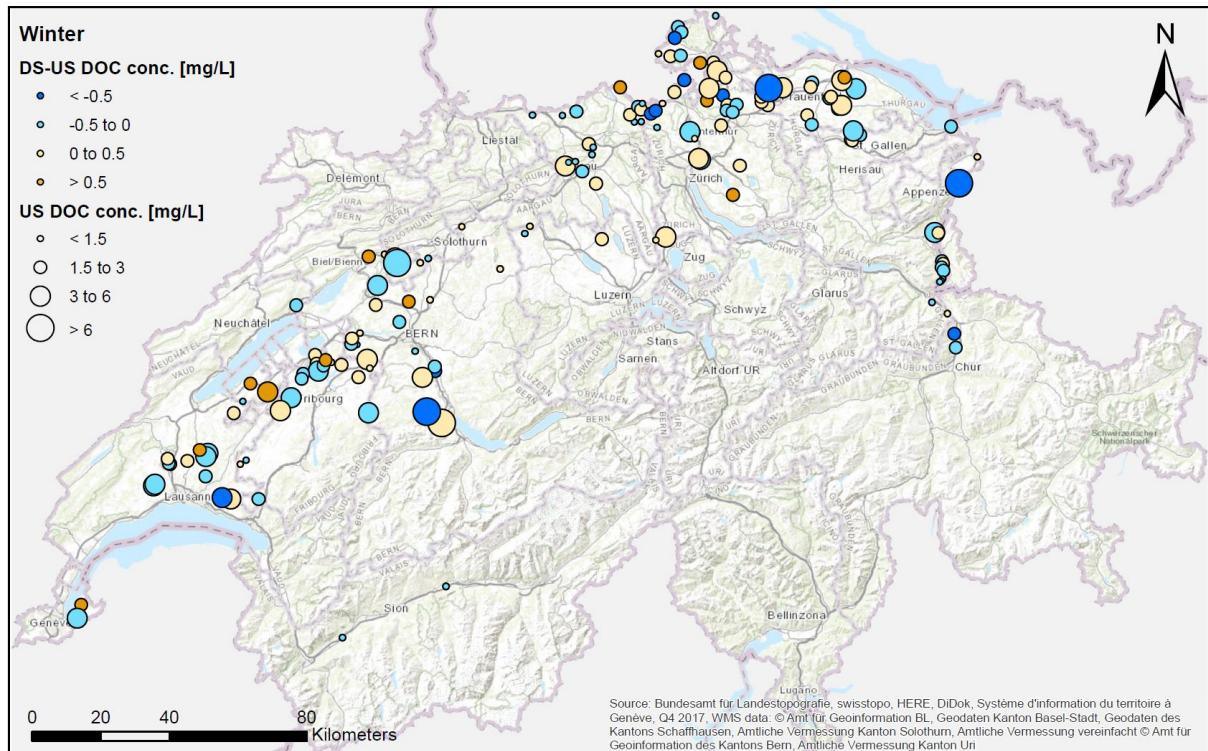


Figure 70: DOC concentrations and changes in winter. Map visualizing the winter US DOC concentrations and the differences between US and DS (DS minus US). Negative values indicate lower DS concentrations. Background map: (swisstopo, 2021).

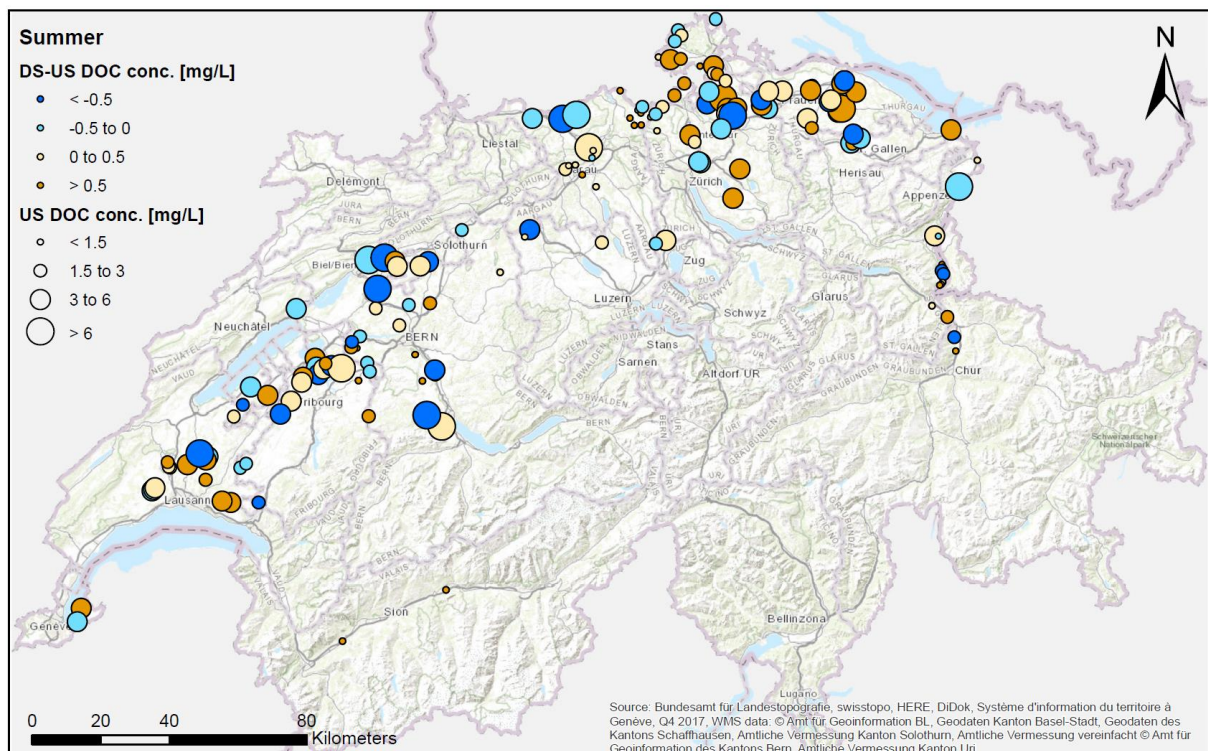


Figure 71: DOC concentrations and changes in summer. Map visualizing the summer US DOC concentrations and the differences between US and DS (DS minus US). Negative values indicate lower DS concentrations. Background map: (swisstopo, 2021).

5.2.3 Total suspended sediment

US and DS sediment measurements are available from 134 beaver reaches in winter and from 144 beaver reaches in summer. 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) (Figure 72). In winter, 74 out of the 134 beaver reaches have a higher sediment load DS compared to US, while in summer, 86 out of the 144 beaver reaches showed higher sediment load DS. However, the differences between US and DS are in both seasons primarily below 10 mg/l (Figure 73).

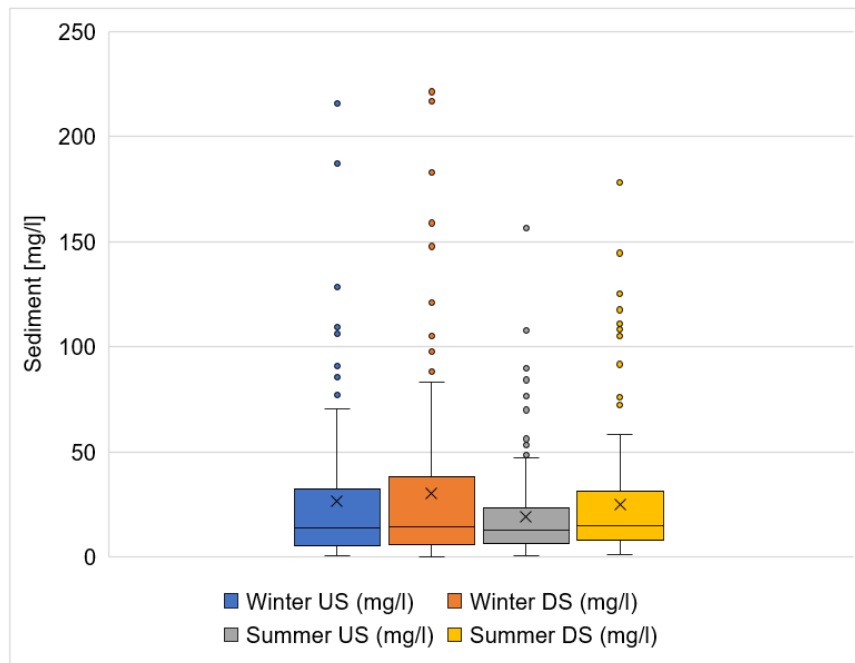


Figure 72: Sediment load boxplots for US and DS in both seasons. For the sake of clarity, three outlier values are excluded from the plot. These outliers are in: reach Nr. 3, summer DS with a sediment load of 592 mg/l; reach Nr. 25, winter DS with a sediment load of 375 mg/l; and reach Nr. 81, summer DS with a sediment load of 1'200 mg/l.

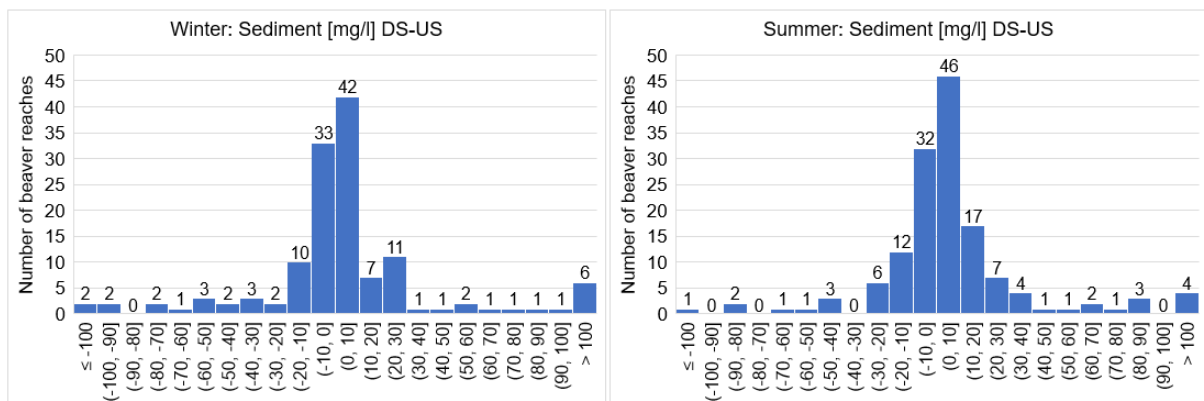


Figure 73: DS-US sediment load in winter (left) and summer (right). Positive values indicate higher sediment loads DS.

5.2.4 Stable isotope composition

The stable isotope dataset is complete for 133 beaver 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, as shown by the $\delta^{18}\text{O}$ values in Figure 74 and the $\delta^2\text{H}$ values in Appendix N. Moreover, in most cases, there are minimal differences between the compositions of US and DS samples, as indicated by the $\delta^{18}\text{O}$ values in Figure 75 and the $\delta^2\text{H}$ values in Appendix N.

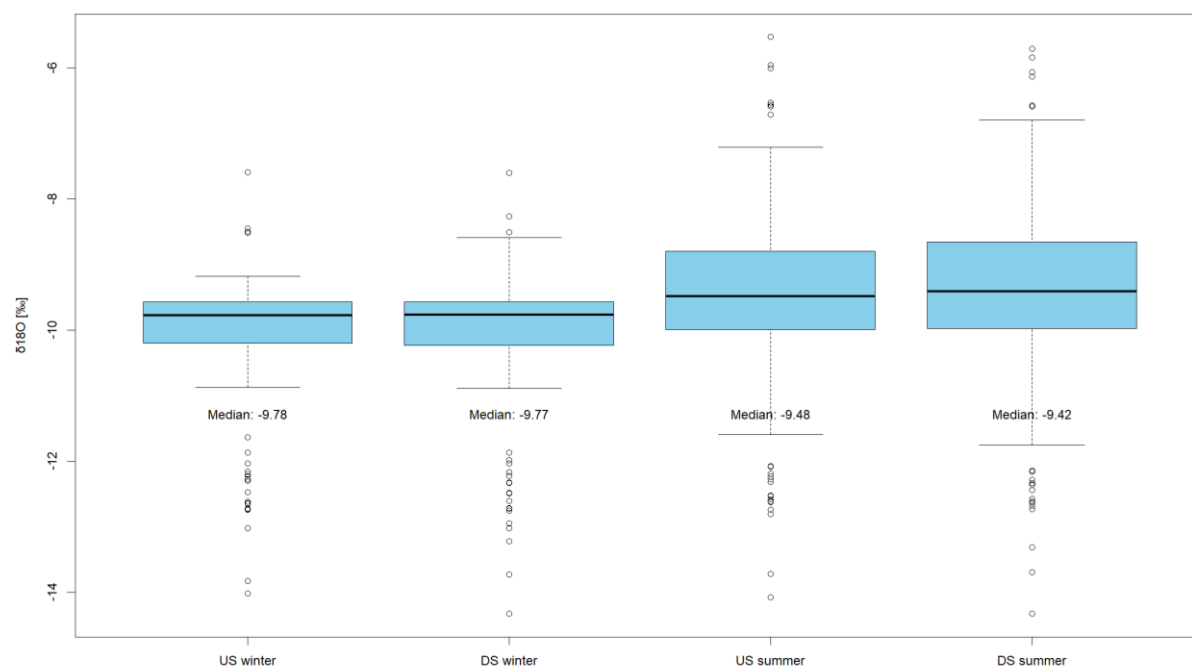


Figure 74: $\delta^{18}\text{O}$ composition US and DS in winter and summer.

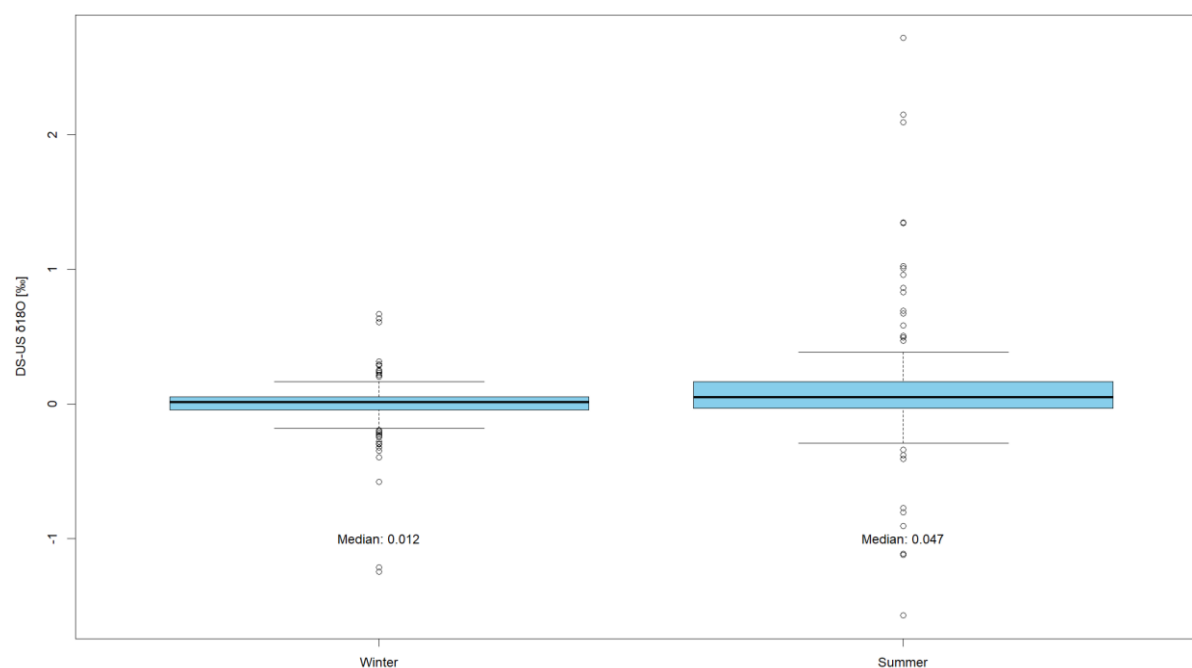


Figure 75: DS minus US $\delta^{18}\text{O}$ compositions in winter and summer.

According to a system where only evaporation determines stable isotope composition, the DS composition for $\delta^2\text{H}$ and $\delta^{18}\text{O}$ should be higher (enriched) compared to the US stable isotope composition. However, it is important to consider other factors such as temperature or groundwater (Boral et al., 2019; Isokangas et al., 2015). As a result, it is sometimes observed that the US compositions are higher than the DS composition (depletion). The sampled water was generally more enriched within the beaver system in summer (Table 18).

Table 18: US vs. DS stable isotope composition. Only reaches with differences higher than the device standard error ($\pm 0.1 \text{ ‰}$ for $\delta^2\text{H}$ and $\pm 0.025 \text{ ‰}$ for $\delta^{18}\text{O}$) are accounted in this table.

	$\delta^2\text{H}$ winter	$\delta^2\text{H}$ summer	$\delta^{18}\text{O}$ winter	$\delta^{18}\text{O}$ summer
DS > US	44	67	35	65
DS < US	26	30	31	30

Given the small differences between US and DS compositions and uncertainties on the impact of temperature and groundwater, as well as possible errors during water sampling and measuring as well as device errors, I decided against the usage of the hydro calculator (chapter: 4.4) for evaporation estimations. Nonetheless, I present some noteworthy findings derived from the stable isotope analysis below.

Distance, slope, volume and residence time (chapter: 4.7) 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, the correlations between changes in stable isotope composition and these characteristics were found to be very low. 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 (chapter: 4.10). 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 19).

Table 19: Correlation matrix: 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

5.2.5 Other water chemistry parameters

In this chapter, a comparison of the median values US and DS in winter and summer for various water chemistry parameters are presented. The median values for ammonium are visualized in Figure 76, while the median values for bromide, calcium, chloride, fluoride, magnesium, potassium, sodium and sulfate can be found in Appendix O.

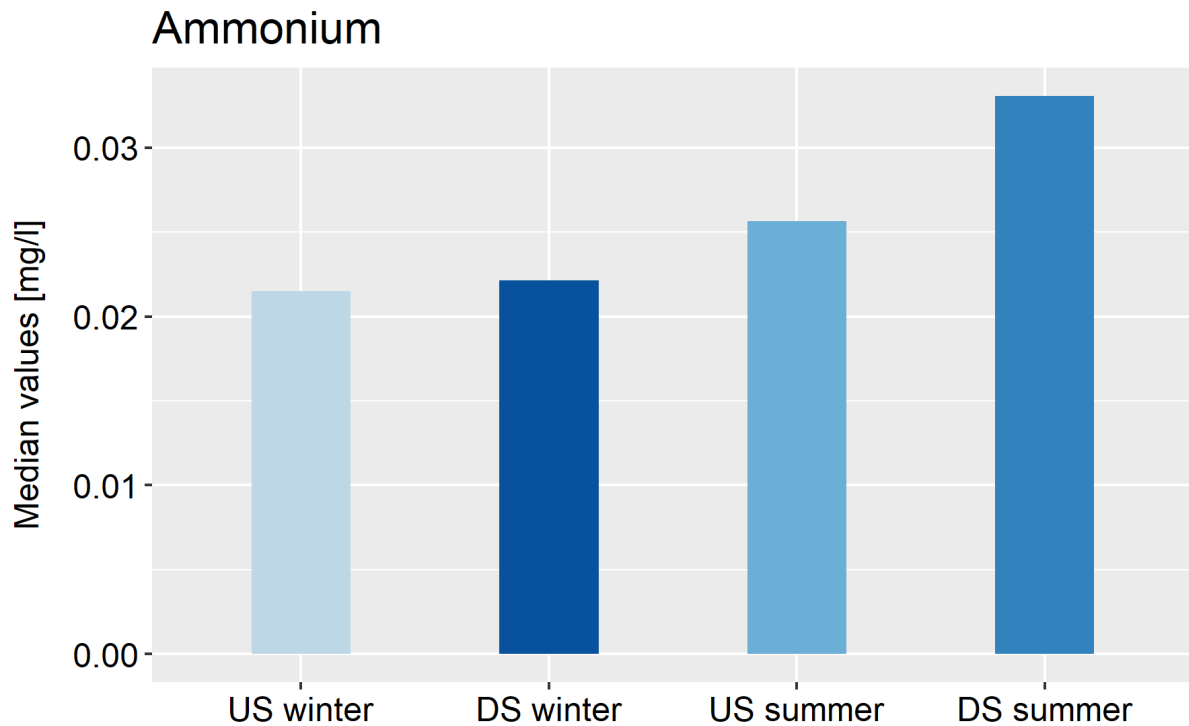


Figure 76: Ammonium: Median concentrations US and DS in winter and summer.

Regarding ammonium, the median values are slightly above the detection limit of 0.02 mg/l, with only the DS summer median exceeding 0.03 mg/l (Figure 76). For bromide, the median concentration remains consistent across all four categories and aligns with the detection limit of 0.05 mg/l, indicating limited reaches with concentrations exceeding this threshold. In the case of calcium, the summer concentrations are lower than the winter concentrations, while for fluoride and potassium, the summer concentrations are higher. Magnesium exhibits similar median concentrations across all four categories. Chloride, sulfate, and sodium also demonstrate similarity between seasons, but the DS median concentrations are slightly higher (Appendix O).

5.3 Areas of interest

I created boxplots, each representing one of the seven *Areas of Interest* (chapter: 4.12.2), for the beaver system characteristics slope, water volume, distance, number of dams and dam age.

Analysis of the median slope of the river (chapter: 4.8) revealed that it is steeper for NO₃: ++ compared NO₃: --. Similarly, the median slope was found to be steeper for DOC: -- than for DOC: ++ (Figure 77). These findings suggest that beaver systems with lower slopes exhibit stronger nitrate removal and a greater gain of DOC.

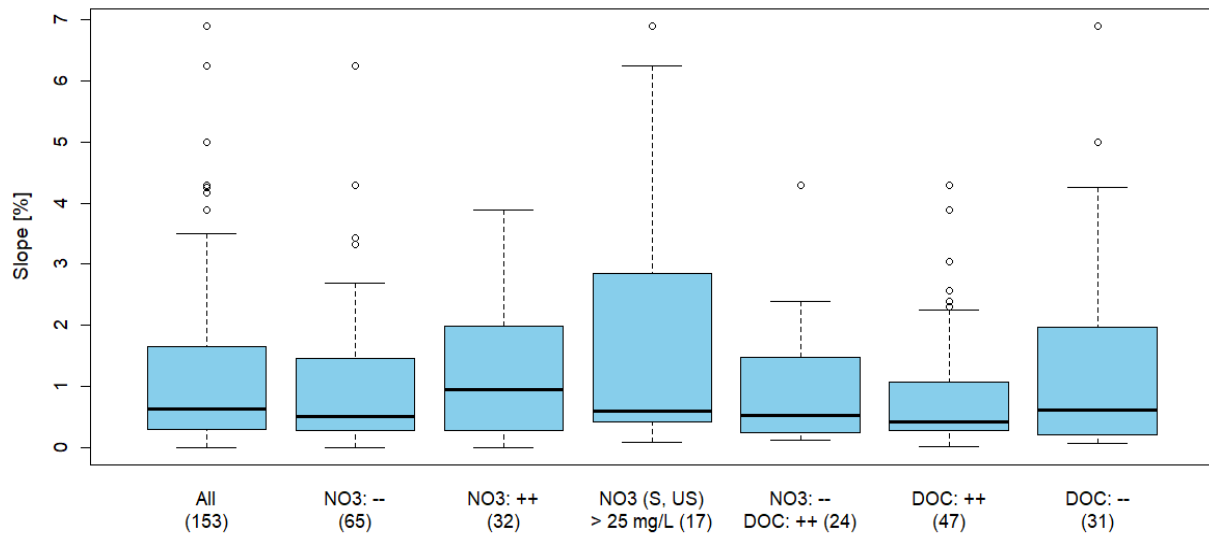


Figure 77: Slope: Boxplots for Areas of Interest.

It is noticeable that the median water volume is low in the *Area of interest* where DOC is reduced in summer and winter (Figure 78). This suggests that a beaver system with a higher water volume has a greater potential for increasing the DOC concentration.

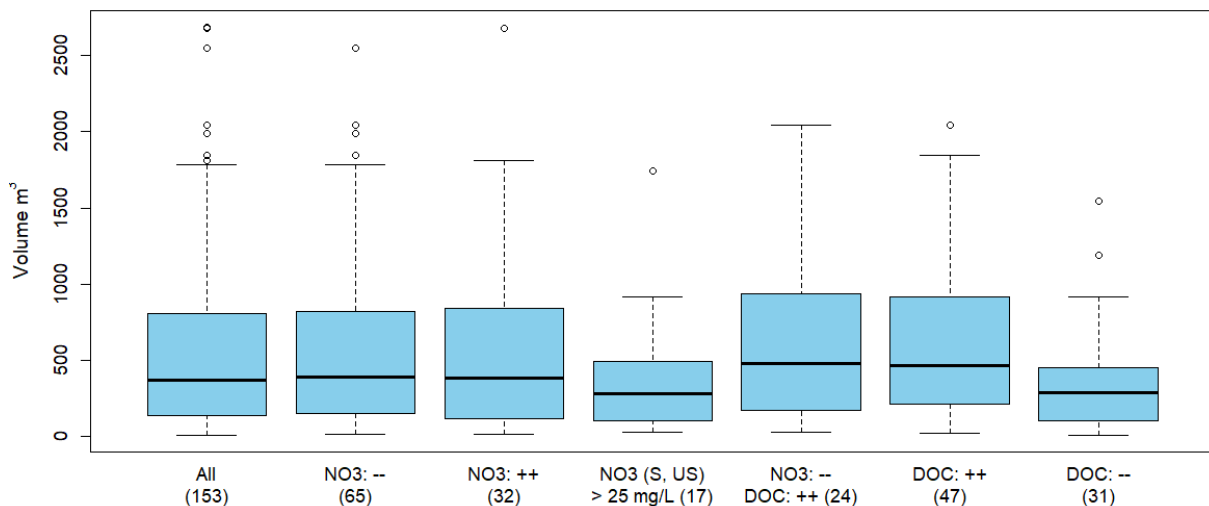


Figure 78: Water volume: Boxplots for Areas of Interest.

The boxplots depicting the distance, number of dams, and dam age for the *Areas of Interest* exhibit minimal variations and do not provide any significant insights (Figure 79).

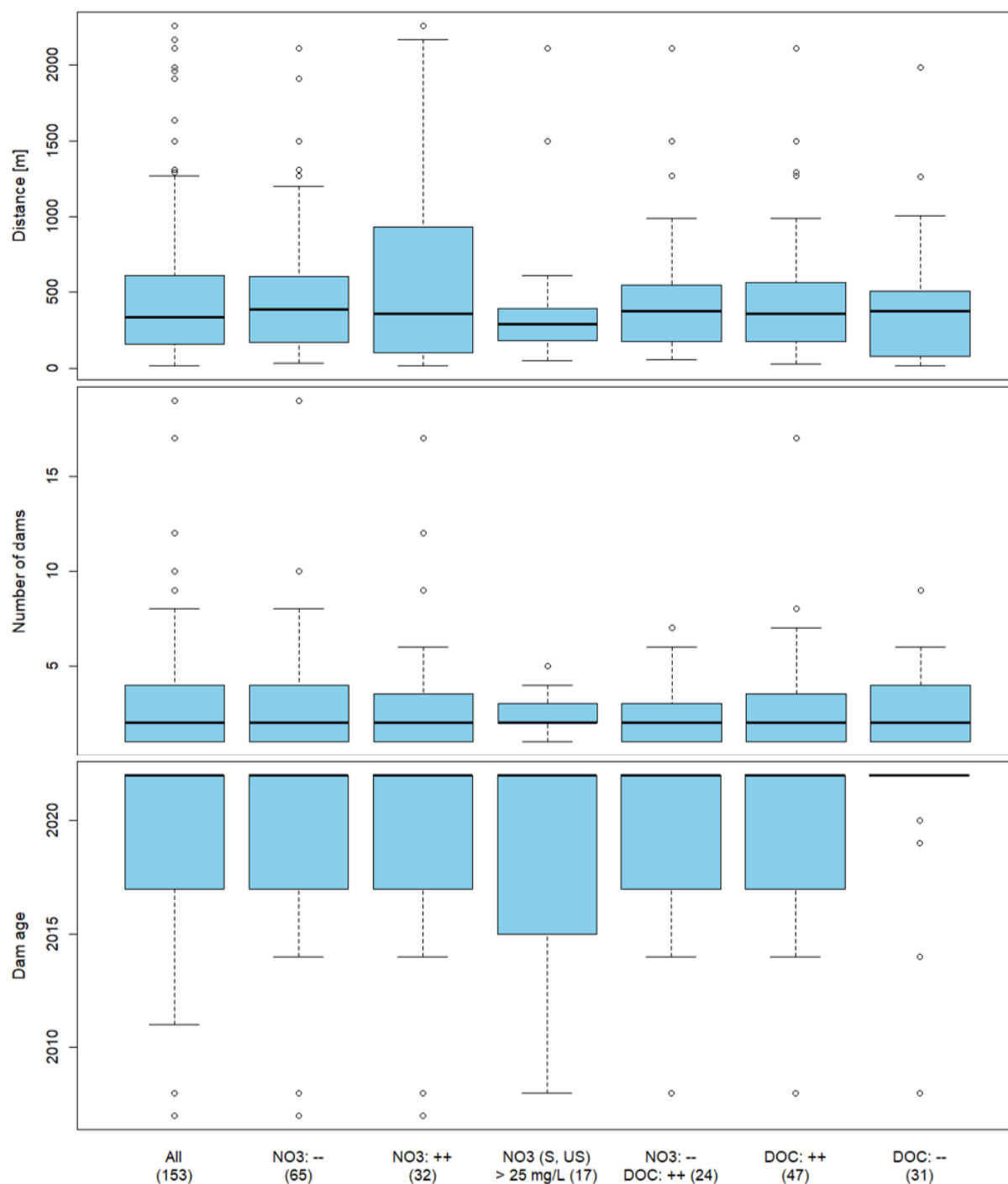


Figure 79: Distance, number of dams and dam age: Boxplots for Areas of Interest.

5.4 Correlation analysis

5.4.1 Characteristics controlling the general US concentrations

Figure 80 presents the significant ($p\text{-value} < 0.05$) Pearson correlation values between the US nitrate and DOC concentrations in winter and summer and the characteristics describing the catchment or the upstream sampling location (chapter: 4.12.3 (Category 1)) for 165 beaver reaches samples in both seasons. The complete correlation table can be found in Appendix P. These correlations provide insights into the general controls on nitrate and DOC concentrations, not necessarily in connection with beaver systems.

The 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). 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.

Furthermore, 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 (Figure 80).

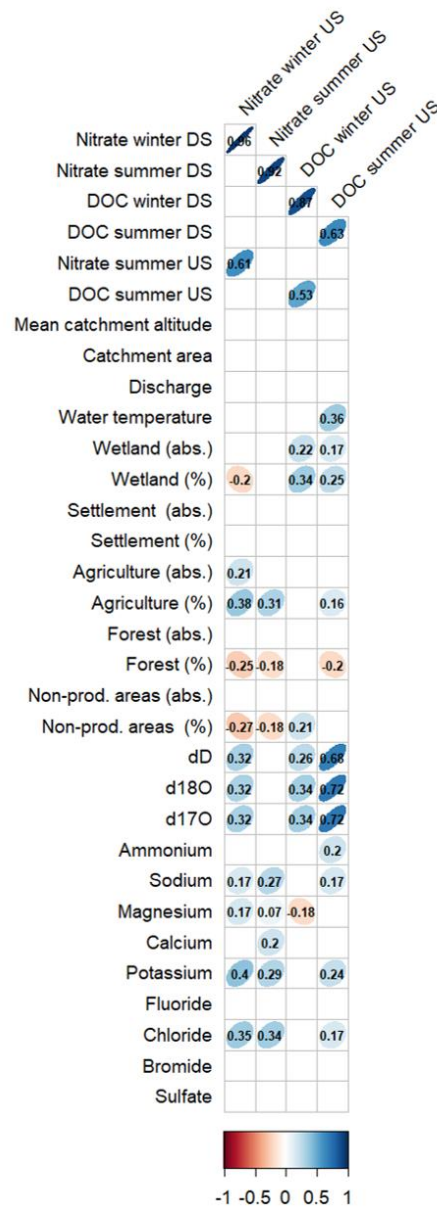


Figure 80: Significant correlations between concentrations and characterizations (chapter: 4.12.3 (Category 1)). abs.= absolute size of this land use in the catchment area and % = proportion of this land use type in relation to the total catchment area size.

5.4.2 Correlations with beaver system characteristics

Figure 81 presents the significant (p -value < 0.05) Pearson correlation coefficient between the changes in nitrate and DOC concentrations from US to DS (positive values indicating an increase) and beaver system characteristics as described in chapter: 4.12.3 (Category 2). The complete correlation table can be found in Appendix Q.

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 (Figure 81).

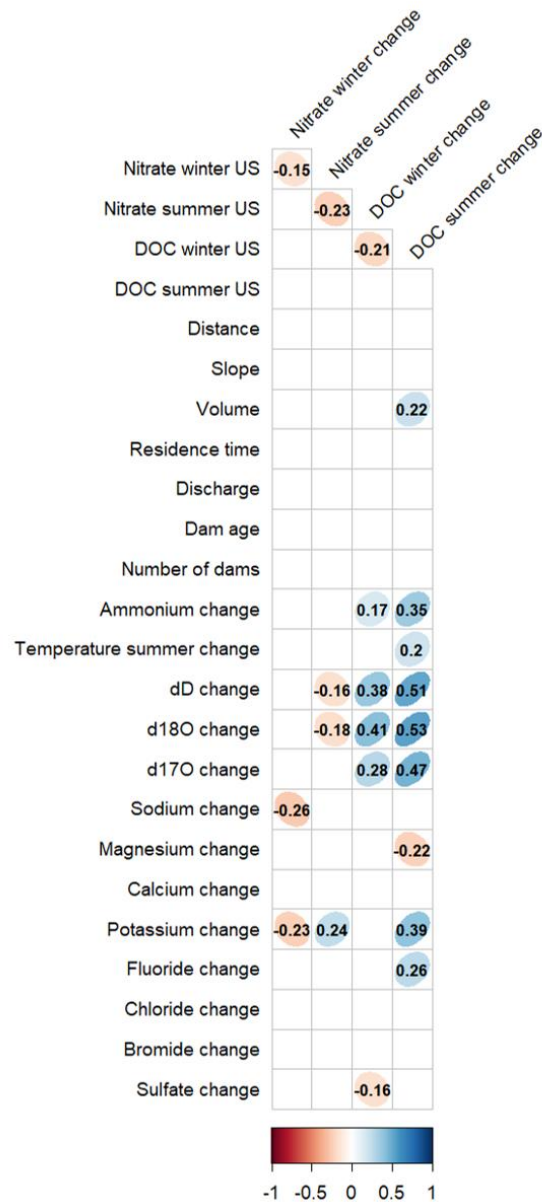


Figure 81: Significant correlations between concentrations and characterizations (chapter: 4.12.3 (Category 2)). Change = DS – US conc. The correlation is always referred to the changes from the same season. So, for example nitrate winter change is compared to winter discharge or DOC summer change compared to potassium summer change.

5.4.3 Correlations with land use

The complete table containing Pearson correlation coefficients between the changes in nitrate and DOC concentrations from US to DS (positive values indicating an increase) and land use in the buffer polygon area, as described in chapter: 4.12.3 (Category 3), can be found in Appendix R.

The analysis reveals that there is no significant correlation ($p\text{-value} < 0.05$) observed between the concentration changes and the proportions and absolute sizes of the land use types stagnant water, forest and agriculture. However, a low positive correlation (Corr.: 0.17 to 0.29) is observed between anthropogenic land use and changes in DOC concentrations in summer.

Noticeable are the correlations of the proportions and absolute sizes of wetland areas within the buffer polygons with the decrease in nitrate and the increase in DOC concentrations. Those correlations are stronger in summer than in winter. In summer the correlation is significant ($p\text{-value} < 0.05$) (Table 20).

Table 20: Correlations between wetland land use and concentration changes. Correlations of the eight wetland categories (buffer 50 m, 25 m, 10 m and 5 m absolute and percentual) 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

5.5 Wetlands

Out of the 165 sampled beaver reaches, 25 beaver reaches were found to have wetlands (chapter: 4.10) within the 50 m buffer area. These 25 beaver reaches are distributed across various locations in Switzerland (Figure 82). The connectivity classification (chapter: 4.12.4) revealed that in 14 out of the 25 beaver reaches, the wetland is directly connected to the river. The results, which are presented in Appendix S, highlight the different behaviors of the changes in nitrate and DOC concentrations observed depending on the connectivity between the wetland and the river.

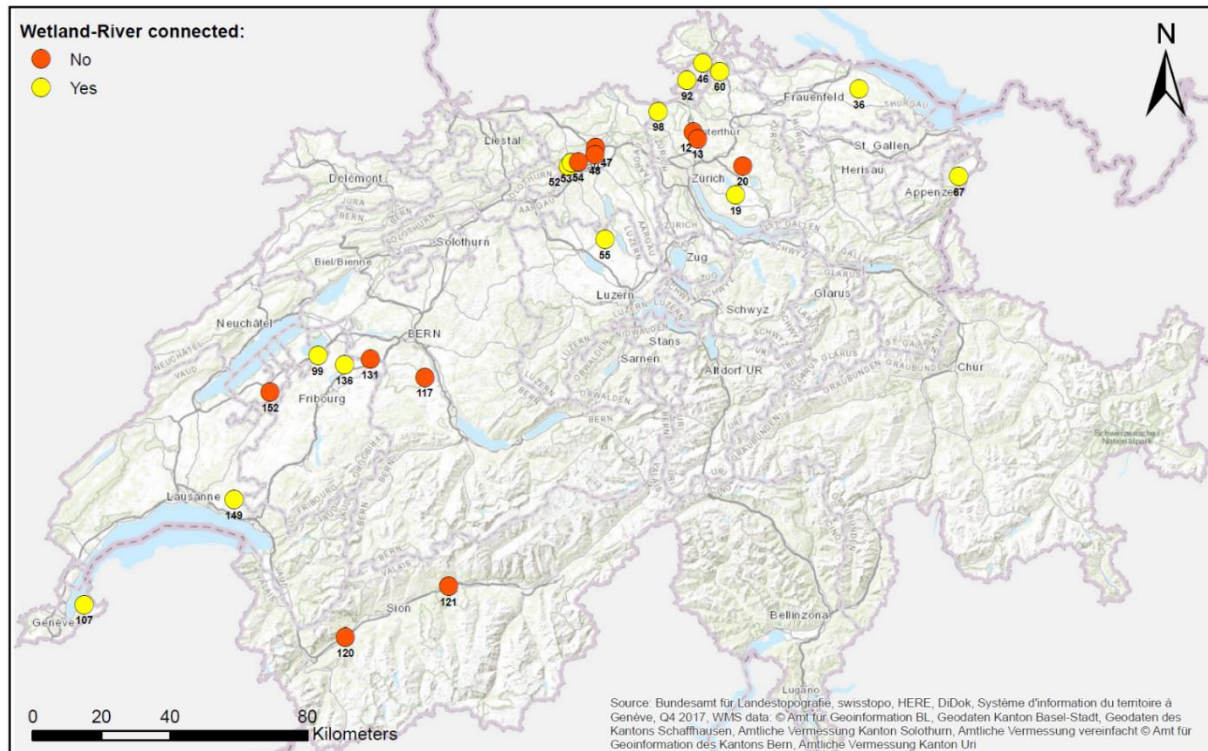


Figure 82: Spatial distribution of beaver reaches with wetland area in the 50 m buffer polygon. Classification into wetland-river connected and not connected as explained in chapter: 4.12.4. Background map: (swisstopo, 2021).

According to information from Christof Angst, Infofauna, only the wetland in beaver reaches Nr. 52 and 136 are directly caused by the damming activity of the beavers (Appendix T). However, it should be noted that most of the wetlands in the other reaches are strongly influenced by beaver damming, and in the absence of beavers, these wetlands would not exist. A table containing the size (m²) of wetlands in the 14 beaver reaches, along with the corresponding coordinates is available in Appendix T.

In terms of water quality, all 14 beaver 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 (Figure 83).

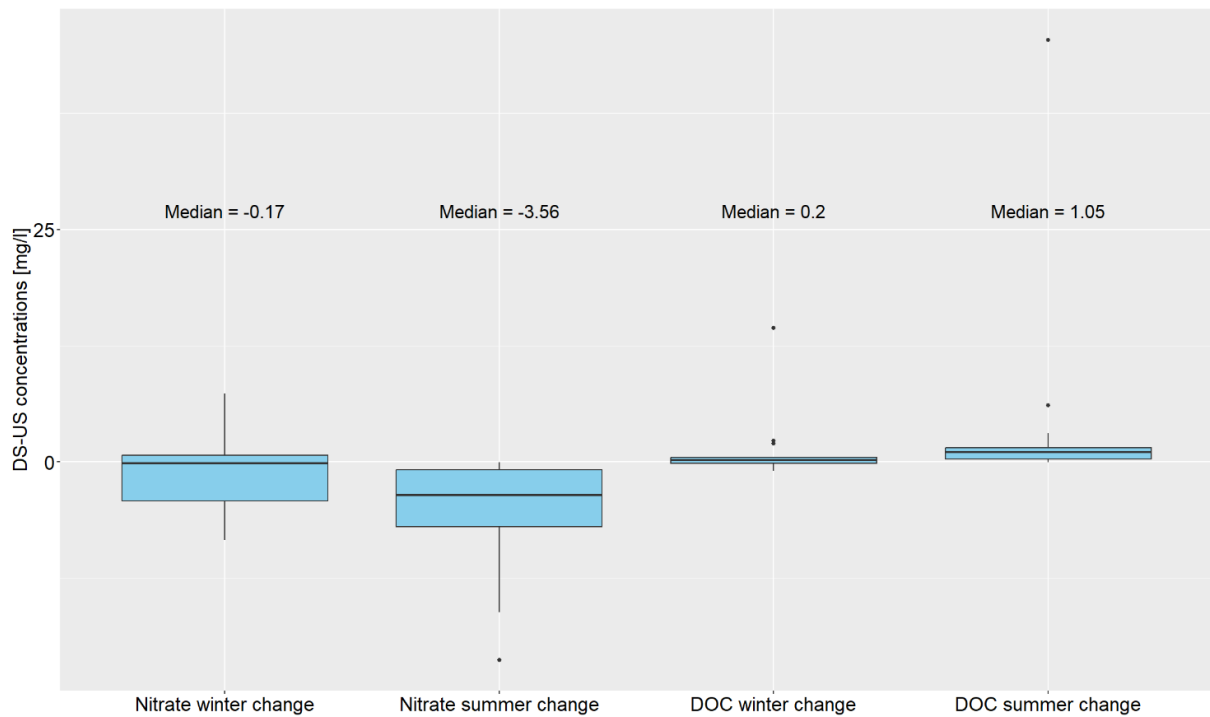


Figure 83: Change in nitrate and DOC concentrations in 14 wetland beaver reaches.

In addition to the consistent finding that all fourteen beaver 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 reaches ranges from 511 and 23'828 m² (Appendix T). Figure 84 and Figure 85 visualize the connection between the size of wetlands and the nitrate removal and DOC gain. Larger wetland sizes are associated with an increased concentration of DOC in both seasons as well as with decreased concentration of nitrate in summer. The plot significantly differs when excluding the extreme values of beaver reach Nr. 67 (Figure 84 and Figure 85).

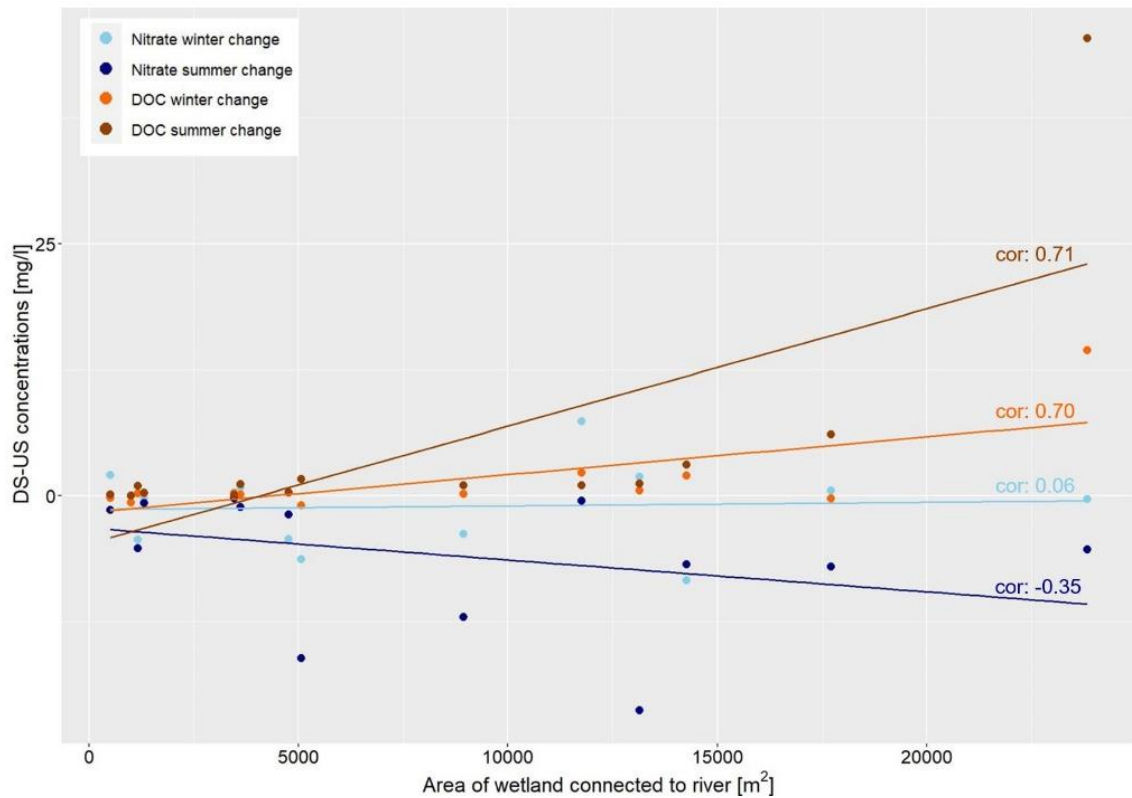


Figure 84: Wetlands size and changes in concentrations (with Nr. 67). Changes in concentrations and area of wetland for fourteen wetland-river connected beaver reaches. With the extreme values of beaver reach Nr. 67 included (values at $x \sim 23'800$).

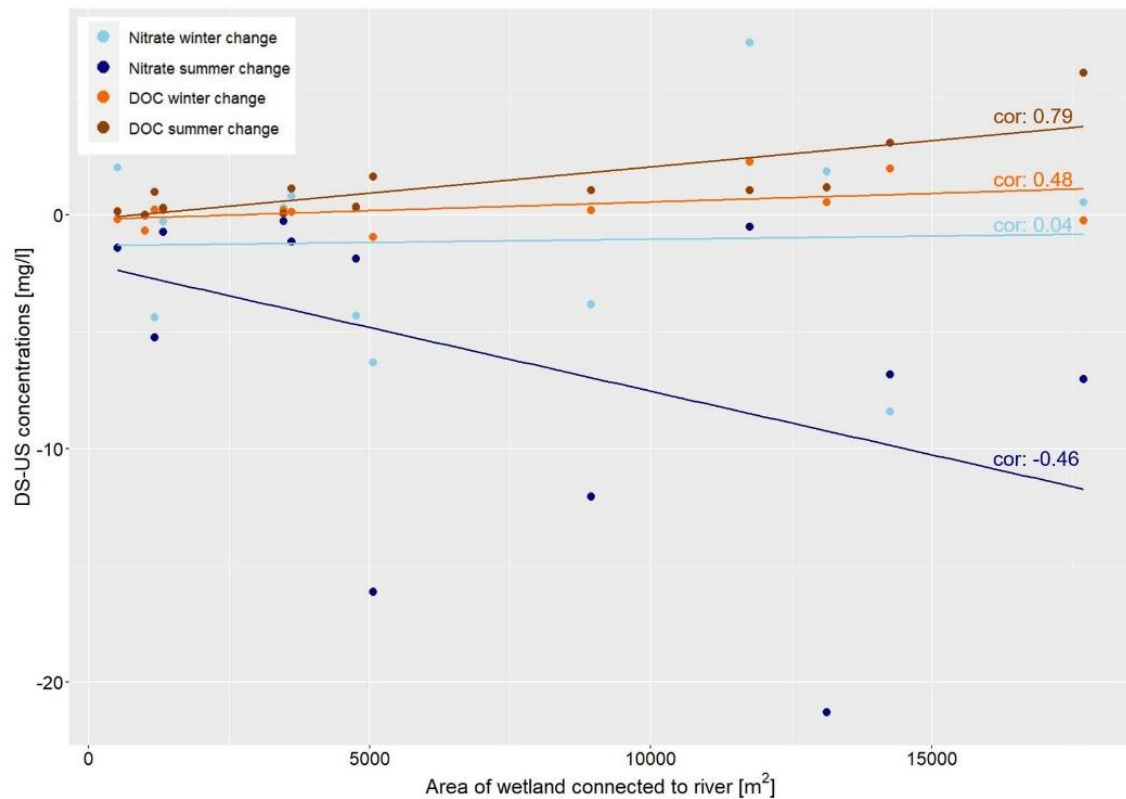


Figure 85: Wetlands size and changes in concentrations (without Nr. 67). Changes in concentrations and area of wetland for thirteen wetland-river connected beaver reaches. Beaver reach Nr. 67 is excluded from this plot due to its extreme values.

5.6 Comparison between wetland-river connected beaver reaches and beaver reaches with nitrate increase in both seasons

In order to investigate potential differences in beaver system characteristics between the 14 wetland-river connected beaver reaches and the 32 beaver reaches with nitrate increase in both seasons (chapter: 4.12.2, Table 17), a comparison was conducted. The variables from category 2 in chapter 4.12.3 were analyzed, and their values are presented as boxplots in Appendix V as well as in Table 21 below.

The results reveal that wetland-river connected beaver 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 reaches with nitrate increases in both seasons tend to have higher median values for slope and discharge (Table 21).

Table 21: Comparison wetlands and nitrate increasing beaver reaches. Median values for 32 beaver reaches with nitrate increases in both seasons and 14 wetland-river connected beaver reaches (Difference = Wetland – increase both seasons).

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

6. Discussion

In this chapter the key findings in relation to the research questions are discussed (Figure 86). Research question 1 is addressed in section 6.1 - 6.4, while research question 2 is addressed in section 6.5 - 6.7. Furthermore, limitations of this study are discussed in section 6.8.

- 1. What are the spatial and seasonal patterns of riverine nitrate and DOC concentrations upstream and downstream of beaver systems throughout Switzerland?**
- 2. Which characteristics of beaver systems (water residence time, number of dams, slope of the beaver reach, etc.) determine the extent of beaver system impacts on riverine nitrate and DOC concentration?**

Figure 86: Recapitulation of the research questions.

6.1 Highest measured nitrate and DOC concentrations on the Swiss plateau

The majority of the mapped beaver dams and sampled beaver reaches are located on the Swiss plateau. Further beaver reaches are located in the St. Gallen Rhine Valley or the Valais (chapter: 2, Figure 14).

Surface water nitrate concentrations measured in this study were found to be highest on the Swiss plateau compared to other regions (Figure 87), which is consistent with findings from the NAWA (chapter: 1.1.1, Figure 1).

The same spatial pattern is also evident for the measured DOC concentrations (Figure 88), although less pronounced than for nitrate levels. Similar findings were made by the DOC measurements in the NAWA (chapter: 1.1.2, Figure 4).

The high nitrate and DOC concentrations on the Swiss plateau are likely a result of the high proportion of intensive agricultural land use and population density in the region. This is supported by a positive correlation between the concentrations and the proportion of agricultural land use in the catchments (chapter: 5.4.1, Figure 80). According to Hürdler et al. (2015) 65 % of the diffuse nitrogen inputs into Swiss waters origin from anthropogenic sources resulting in highest diffuse nitrogen inputs on the Swiss plateau (Figure 87).

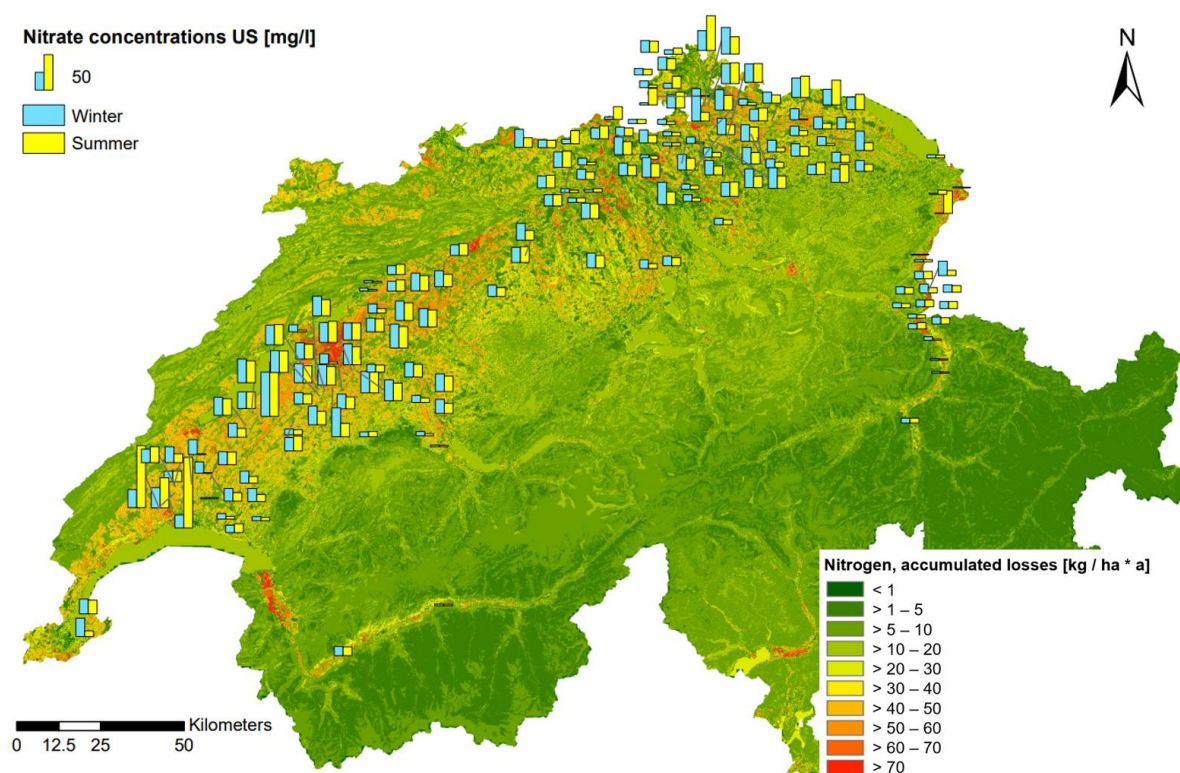


Figure 87: US nitrate concentration in winter and summer. Background map: (swisstopo, 2015).

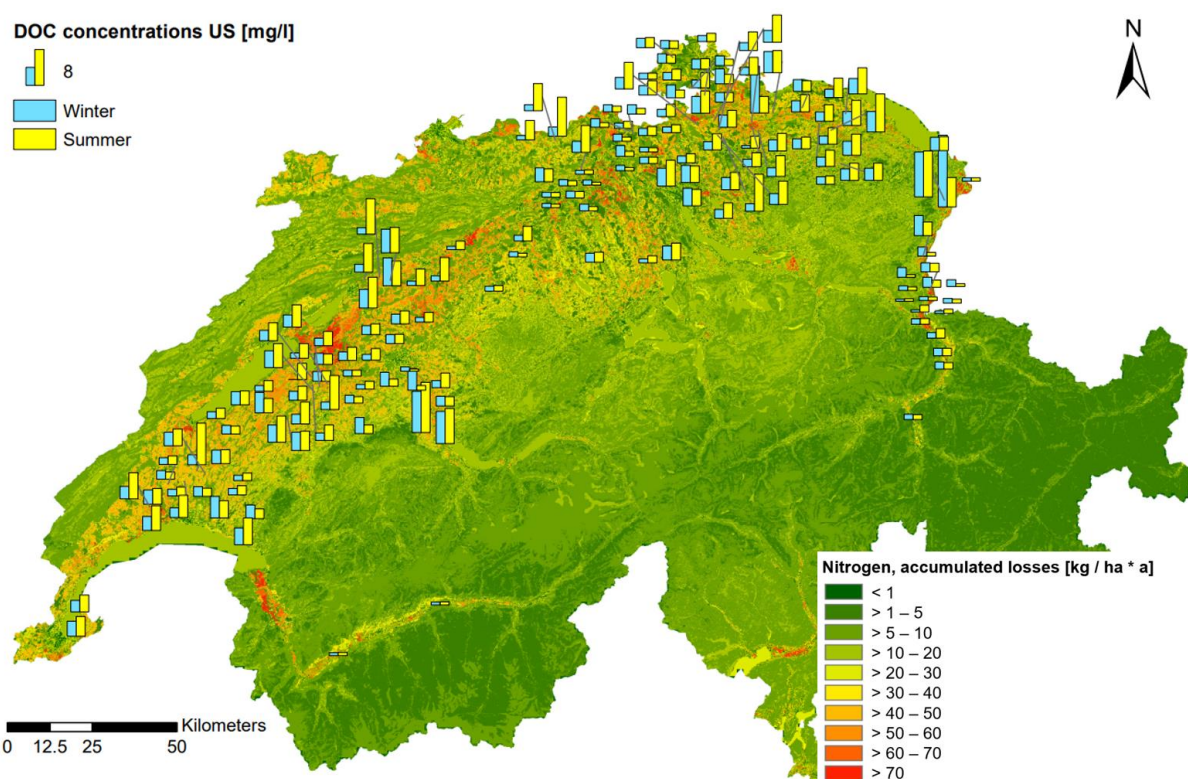


Figure 88: US DOC concentration in winter and summer. Background map: (swisstopo, 2015).

6.2 Higher nitrate concentrations in winter and more apparent nitrate decrease in summer

This study revealed higher nitrate concentrations in the sampled surface waters in winter than in summer (chapter: 5.2.1, Figure 62), which can be attributed to two factors. Firstly, the demand for nitrate by plants is higher in the growing season (spring and summer), resulting in less nitrate available for leaching. Furthermore, the nitrate uptake by aquatic vegetation is increased in the growing season. Secondly, the discharge values in winter 2021/22 were generally higher than in the extremely dry summer 2022 (chapter: 5.1.6, Figure 57), resulting in more nitrate leaching from soils to aquatic systems due to higher drainage (chapter: 1.1.1).

Our findings align with previous studies that show a decreasing trend in nitrate concentrations through beaver systems (chapter: 1.3.4.1, Figure 10 and Figure 11), with the decrease being more apparent in the summer data (median decrease 0.27 mg/l) compared to the winter data (median decrease 0.07 mg/l) (chapter: 5.2.1, Figure 63). The higher nitrate removal in summer could - in addition to the increased nitrate uptake by pond vegetation - be attributed to higher denitrification rates (chapter: 1.1.1) in summer. Even though Harrison et al. (2011) compared denitrification rates in summer and winter and could not determine a clear difference.

In a master thesis (Raphael d'Epagnier, Beaver impacts on the riverine carbon budget in a study area in Marthalen (CH)) which was conducted parallel to this study, US and DS nitrate concentrations in a beaver system in Marthalen were measured biweekly. The nitrate concentrations at the US and DS location were found to be very high, often exceeding the threshold for waters sourcing as drinking waters (25 mg/l). The highest fluctuations in US nitrate concentrations occur between spring and autumn, with no clear seasonal pattern in nitrate changes (Figure 89). Nonetheless, the lower nitrate concentrations at the DS location suggest nitrate removal in the Marthalen beaver system throughout the season, with some exceptions. These findings additionally support the results of the here discussed study.

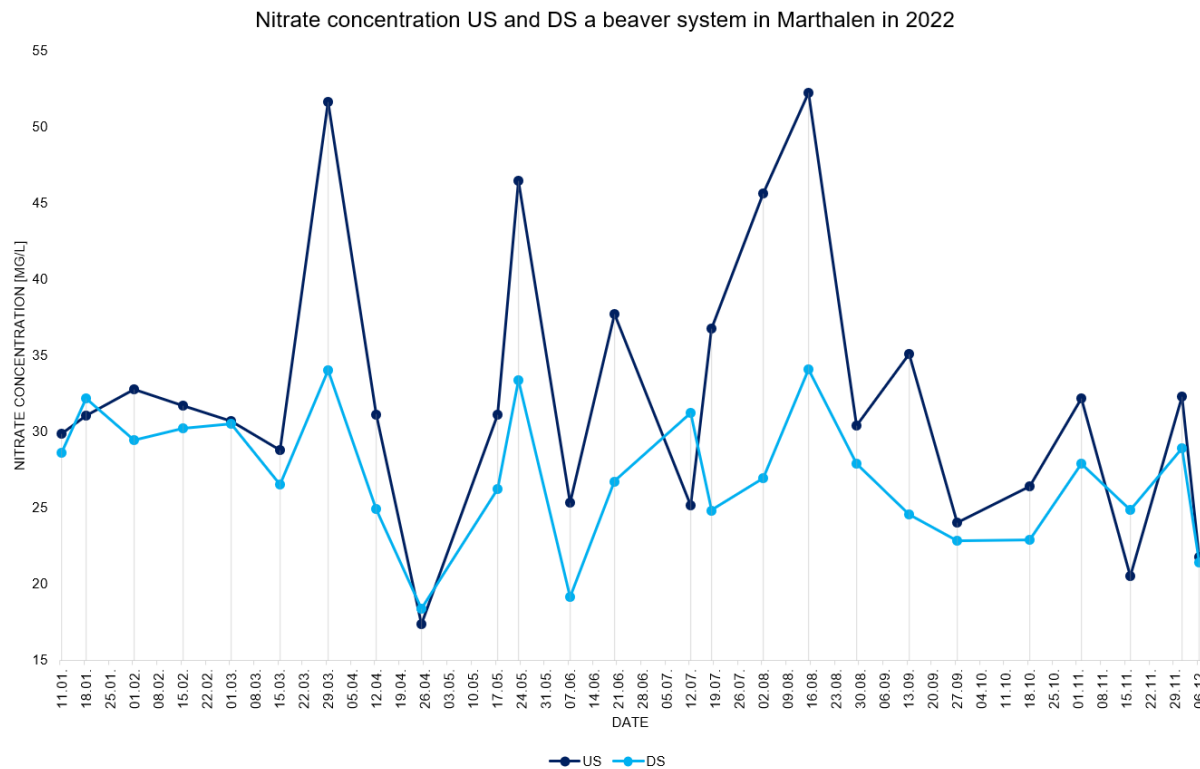


Figure 89: Nitrate concentrations in Marthalen. Sampled biweekly in 2022 US and DS of a beaver system in Marthalen, Switzerland.

6.3 Higher DOC concentrations and DOC increase in summer

The median DOC concentration measured in summer is 0.8 mg/l higher than in winter, with a median of 2.78 mg/l in summer and 1.98 mg/l in winter (chapter: 5.2.2, Figure 67). From the literature, we expected an increase in DOC concentrations through beaver systems (chapter: 1.3.4.1, Figure 10 and Figure 11). This increase was observed in the summer data, where 97 out of 157 beaver reaches had higher DOC concentrations DS. However, in winter the number of beaver reaches with increasing (77) and decreasing (80) DOC concentrations is almost equal (chapter: 5.2.2, Figure 68). The higher DOC concentrations generally and the more apparent increase of DOC in the summer season may be attributed to increased primary productivity of macrophytes in the beaver pond and in aquatic systems US of the beaver systems (Mann & Wetzel 1995).

6.4 No spatial pattern for beaver system impacts on nitrate and DOC concentrations throughout Switzerland identified

The spatial analysis of the data does not reveal any discernible pattern for regions in Switzerland where beaver systems have a stronger or weaker impact on nitrate and DOC concentrations (chapter: 5.2.1 and 5.2.2, Figure 65, Figure 66, Figure 70, Figure 71 and Appendix I and Appendix K).

BAFU (Hrsg.) (2022) found highest nitrogen removal rates at high nitrogen concentrations. This suggests that the nitrate removal should be highest on the Swiss plateau, where the concentrations are generally higher than in the other regions (Figure 87). However, a clear trend of higher nitrate removal in reaches with higher nitrate concentrations is not recognizable (chapter: 5.2.1, Figure 65 and Figure 66).

6.5 No specific beaver system characteristics determining the extent of nitrate and DOC decreases and increases identified

Another aim of this study was to identify the beaver system characteristics that determine the extent of nitrate removal and DOC gain within beaver systems (Figure 86, research question 2).

The classification of nitrate and DOC changes into categories as *Areas of Interest* was used as an analysis approach in this study (chapter: 4.12.2). The aim was to identify any significant beaver system characteristics associated with a particular area of interest. However, no significant results were obtained with this approach. The only noteworthy finding was observed when comparing the median slope of 65 beaver reaches with decreasing nitrate concentrations in both seasons (0.46 %) to the median slope of the 32 beaver reaches with increasing nitrate concentrations in both seasons (0.87 %) (chapter: 5.3). This could be attributed to the lower flow velocity resulting in higher nitrate uptake by pond vegetation and the potential for anaerobic conditions that facilitate denitrification (nitrate removal from beaver systems). However, it is critical to infer from those differences in median slopes, that the slope of the river reach between the US and DS sampling location is determining the extent of nitrate removal, as there are also nitrate-reducing reaches with slopes > 4 % (chapter: 5.3, Figure 77). Furthermore, there is no significant correlation between the slope of the river reaches and the nitrate changes when considering the whole dataset (chapter: 5.4.2, Figure 81).

Another approach was a Pearson correlation analysis to investigate the relationship between beaver system characteristics and nitrate and DOC changes in winter and summer for the entire dataset (chapter: 5.4.2, Figure 81 and Appendix Q). The results showed no significant correlation between nitrate and DOC concentration changes and beaver reach distance, beaver reach slope, water residence time, discharge, dam age and number of dams. However, a significant ($p\text{-value} < 0.05$) positive correlation (Corr.: 0.22) was observed between beaver reach water volume (chapter: 5.4.2, Figure 81) and DOC change in summer. This suggests that larger beaver ponds have the potential for higher primary production, resulting in a stronger increase in DOC concentrations. Nevertheless, it is important to note that the absence of significant correlations between beaver system characteristics and nitrate and DOC changes does not necessarily imply that there is no connection, as the values of the beaver dam characteristics were determined through quantitative approaches that rely on certain assumptions (chapter: 4).

Further analysis approaches used in this study included the calculation of Pearson correlation without extreme values, multiple linear regression, quantile regression, as well as visual reflection of plots between beaver system characteristic values and changes in nitrate and DOC

concentrations. However, due to the low significance of the results obtained from these methods, and for the sake of clarity, I did not include these results in this work.

6.6 Nitrate removal and DOC gain in beaver reaches situated in wetland areas

Based on various types of analysis, we have found that none of the beaver system characteristics examined in this study are able to significantly determine the extent of changes in nitrate and DOC concentrations (chapter: 6.5). These findings suggest that the changes in nitrate and DOC concentrations are likely dependent on a complex combination of multiple factors, which cannot be fully identified with our sample size.

However, the analysis of the land use in the direct surroundings of the river reaches (chapter: 5.4.3) revealed a connection between the proportion of wetlands and the nitrate removal as well as DOC gain. The ability of wetlands to reduce nitrate concentrations and increase DOC concentrations in aquatic systems is already evident in the negative correlations observed between the proportion of wetlands in the catchment area and nitrate changes (Corr. winter - 0.20, Corr. summer - 0.10), as well as the positive correlations between the proportion of wetlands in the catchment area and DOC changes (Corr. winter 0.34, Corr. summer 0.25) (chapter: 5.4.1, Figure 80 and Appendix P).

Moreover, there are significant correlations between the proportion of wetland in the buffer polygons around the river reaches and the nitrate removal (Corr. winter - 0.08, Corr. summer - 0.25) and DOC gain (winter 0.12, summer 0.32) through the beaver system (chapter: 5.4.3, Table 20). The correlation is more pronounced in summer, with the effect being stronger when wetlands are directly connected to the river flowing through the river reach. This is obvious, as the water exchange between river and wetland is easier without solid substrate in between. All the 14 beaver reaches with wetlands directly connected to the river had decreased nitrate and increased DOC concentrations DS in summer. The effect is also recognizable in winter but less pronounced than in summer. The median decrease of nitrate concentrations was 0.17 mg/l in winter and 3.56 mg/l in summer, while the median increase of DOC concentrations was 0.20 mg/l in winter and 1.05 mg/l in summer (chapter: 5.5, Figure 83).

The analysis also revealed that the size of the wetlands plays a crucial role in determining the extent of nitrate removal and DOC gain, especially in summer. The correlation between the wetland area and the nitrate removal (Corr.: 0.46) and DOC gain (Corr.: 0.79) in summer is highly significant (chapter: 5.5, Figure 85).

Extensive literature exists on the potential of wetlands to remove nitrate and increase DOC levels. 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 (Jordan et al., 2011). 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.

The significant potential of wetlands in removing nitrate and increasing DOC levels is exemplified in beaver reach Nr. 67, which is in a substantial wetland area 2 km south of Altstätten SG (Appendix V, Figure 110). The wetland area is recognizable north of the beaver reach (Figure 90). The nature reserve Bannriet is a former peat cutting area (Schmid, 2019).

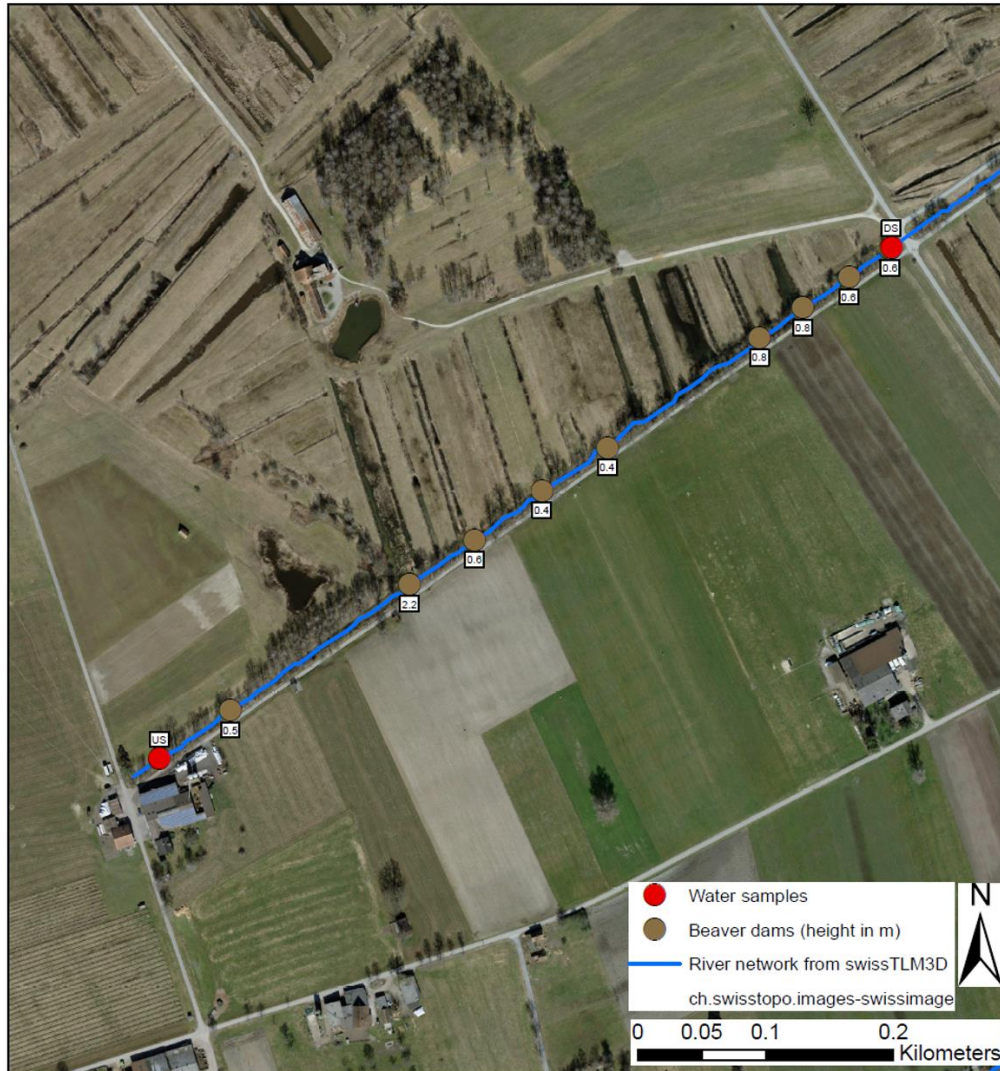


Figure 90: US and DS water sampling location of beaver reach Nr. 67 with its 8 beaver dams. Background map: (swisstopo, 2018).

The water quality values of beaver reach Nr. 67 are striking compared to the values of other beaver reaches (Appendix V, Table 26). The observed changes in this beaver reach are particularly remarkable and underscore the effectiveness of wetlands in promoting favorable changes in water quality. In summer 93 % (in winter 24 %) of the inflowing nitrate (5.74 mg/l) is removed and the inflowing DOC (10.13 mg/l) is increased by 448 % (in winter 145 %). Quantifying the impact of the beaver dams at this site is challenging, as the wetland would exist without beaver dams, albeit perhaps less pronounced.

The identification of this wetland area as a DOC source and nitrate sink is supported by the water quality parameters from a measuring station of the office for water and energy, Canton St. Gallen, installed approximately 5 km downstream of the beaver reach Nr. 67. The DOC concentrations measured at this station are very high (~ 15 mg/l) and the nitrate concentration is rather low with 12.17 mg/l (Appendix V, Figure 111).

6.7 Beaver system characteristics of wetland beaver reaches compared to nitrate source beaver reaches

In order to compare the beaver system characteristics of the 14 wetland beaver reaches (nitrate sinks) to the 32 beaver reaches with nitrate increases in both seasons, I calculated the median value for the characteristics (chapter: 5.6, Table 21). The wetland beaver reaches were found to have a longer distance (+ 67 %), higher water volume (+ 127 %), and longer water residence time (+ 442 % in winter, + 413 % in summer). Conversely, the wetland beaver reaches 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 denitrification.

6.8 Limitations

6.8.1 Citizen science

This study is connected to and based on the national beaver monitoring, a citizen science project. Thanks to all the volunteers we were able to compile probably one of the largest existing dataset of water quality measurements in beaver systems. The large number of people involved is a potential source of errors. Despite a thorough data cleaning process (chapter: 4.1.2, Table 3), some errors may still persist in the dataset, and therefore cannot be entirely ruled out. Another challenge was to collect the water samples from the volunteers without damaging the samples. In particular the collection of the ammonium samples on the hot summer days (17, 18 and 23 May 2022) required extra precautions to keep them frozen during transportation.

6.8.2 Estimations in discharge and volume

It should be noted that the discharge values presented in this study are associated with some uncertainties, as they are modeled values (chapter: 4.7.1). In addition, the creation of the catchment polygons, on which the discharge model is based, was sometimes challenging (chapter: 4.6), which can also contribute to uncertainties in the discharge values. Furthermore, the pond volume determination method used in this study provides only an estimation (chapter: 4.7.2). These uncertainties in both discharge and volume estimation can result in residence time estimations that may deviate from the actual residence times.

6.8.3 Semi-comparable US and DS water samples

US and DS water samples were taken approximately within 15 minutes time difference. Median residence time of the water in the beaver system is 2.4 h in winter and 10.2 h in summer. Therefore, not the identical water is sampled US and DS. Furthermore, the DS water sample could be affected by groundwater inputs or tributaries.

6.8.4 Concentrations instead of fluxes

It is important to note that the measurements discussed in this study refer to nitrate and DOC concentrations expressed in mg/l, rather than fluxes. In order to compare US and DS nitrate and DOC fluxes we would need precise discharge values for US and DS sampling locations. In this study we have an estimated daily discharge rate for the DS coordinate (chapter: 5.1.6).

However, due to the scope of this project, a precise determination of the discharge rate at the exact sampling times for the US and DS sampling location was not feasible. The higher discharge values observed in winter 2021/22 compared to those in the dry summer 2022 resulted in mostly higher nitrate and DOC fluxes in winter than in summer (Figure 91). The median nitrate flux is 623 mg/s in winter and 107 mg/s in summer, while the median DOC flux is 89 mg/s in winter and 34 mg/s in summer.

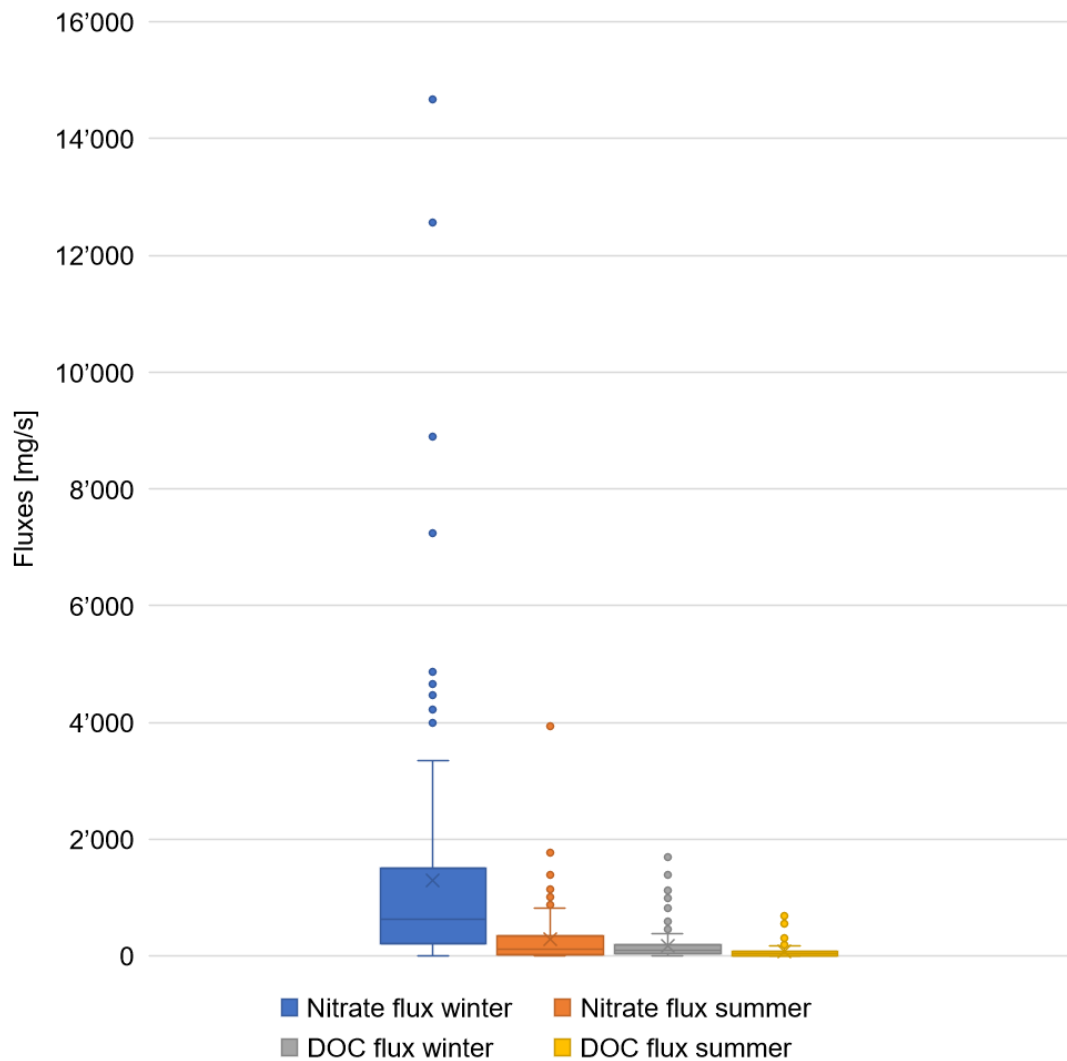


Figure 91: Nitrate and DOC fluxes in winter and summer.

7. Conclusion

The goal of this study was to assess the spatial and seasonal variability of beaver system impacts on nitrate and DOC concentrations, as well as to identify the beaver system characteristics that determine the extent of nitrate removal and DOC gain. The results are based on nitrate concentrations measured upstream and downstream of beaver systems across Switzerland in winter 2021/22 and summer 2022.

In terms of spatial variation we observed generally the highest nitrate and DOC concentrations in the beaver reaches located on the Swiss plateau, the region in Switzerland with the highest population density and the highest proportion of intense agricultural land use, both leading to high nitrogen inputs into streams (chapter: 6.1).

When comparing the two seasons we found higher nitrate concentrations in winter than in summer. This can be attributed to more nitrate leaching in winter (nitrate input into surface waters) and more nitrate uptake by aquatic vegetation in summer (nitrate removal from surface waters). Previous literature has suggested that beaver systems tend to decrease the nitrate and increase the DOC concentrations in surface waters. This decrease in nitrate and increase in DOC is more apparent in the summer data than in the winter data. The decrease in nitrate can be explained by the increased nitrate uptake by pond vegetation. The increase in DOC is likely due to enhanced primary productivity in summer. However, there is no spatial pattern observed for beaver system impacts on nitrate and DOC concentrations (chapter: 6.2 - 6.4).

We could not identify a significant beaver system character determining the extent of nitrate removal or DOC gain. Land use analysis in the direct surroundings of the beaver 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 in wetlands increases the denitrification rates where nitrate is converted to atmospheric nitrogen (N_2). DOC concentrations increase due to enhanced ecosystem productivity in wetlands (chapter: 6.5 - 6.6).

Based on the results of this study, we can conclude 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 create dams that can cause water levels to rise and potentially create wetlands. Long-term floodplain inundation due to the beavers damming activity can lead to wetland conditions. Moreover, Dewey et al. (2022) demonstrated the potential for nitrate reduction from a beaver dam only 0.5 m high in a meandering river (Appendix A).

Therefore, if watercourses are given more space as part of revitalization efforts (e.g. allowing flooding of floodplain areas and meandering), the important ecological benefit of nitrate removal from beaver damming activity can be increased.

Outlook

While our dataset is already quite extensive (165 beaver reaches in both seasons and 79 beaver reaches in one season), there are still opportunities for more precise and comprehensive measurements. For instance, using autosamplers or more frequent sampling could help us better understand seasonal and diurnal variations in nitrate and DOC concentrations. Additionally, local discharge measurements US and DS with the salt dilution method could provide higher accuracy of the nitrate and DOC fluxes and enable a full mass balance. Furthermore, the impact of local groundwater could be estimated by measuring the local groundwater levels and water quality in existing or newly built piezometers. However, such additional measurements would be associated with high efforts and costs.

This study has shown that the capacity of nitrate removal in beaver systems is in connection with the potential for wetland creation through the beavers' damming activity. Parallel to this study, a project is ongoing where a floodplain model for Switzerland is created. This model incorporates water retention potential for beaver systems in Switzerland, with the aim of identifying areas that could potentially be inundated by the damming activity. When combining the findings of the floodplain model project (wetland areas that could be created through damming activity) and this study (potential of nitrate removal in wetlands) we could estimate the extent of nitrate removal in beaver systems in Switzerland. However, in order to express the potential nitrate removal in beaver system in numbers, further research is needed.

References

- American Heritage Dictionary. (2018). *Eutrophia* - definition of eutrophia by The Free Dictionary. <https://www.thefreedictionary.com/eutrophia> (access: 01.04.2023).
- Amt für Wasser und Energie, K. St. G. (2022). *Mittlerer Seegraben (Balgacher Riet). Beurteilung der Wasser- und Gewässerqualität*.
- Angst, C. (2010). Mit dem Biber leben Bestandeserhebung 2008. Perspektiven für den Umgang mit dem Biber in der Schweiz. *Umwelt-Wissen Nr. 1008. Bundesamt Für Umwelt, Bern, Und Schweizer Zentrum Für Die Kartographie Der Fauna, Neuenburg*.
- BAFU (Hrsg.). (2013). NAWA – Nationale Beobachtung Oberflächengewässerqualität. *Bundesamt Für Umwelt, Bern. Umwelt-Wissen Nr. 1327*.
- BAFU (Hrsg.). (2016). Zustand der Schweizer Fließgewässer. Ergebnisse der Nationalen Beobachtung der Oberflächengewässerqualität (NAWA) 2011-2024. *Umwelt-Zustand Nr. 1620*.
- BAFU (Hrsg.). (2019). Zustand und Entwicklung Grundwasser Schweiz. Ergebnisse der Nationalen Grundwasserbeobachtung NAQUA, Stand 2016. *Umwelt-Zustand Nr. 1901*.
- BAFU (Hrsg.). (2022). Gewässer in der Schweiz. Zustand und Massnahmen. *Umwelt-Zustand Nr. 2207*, 90.
- Bashir, M. T., Ali, S., Ghauri, M., Adris, A., & Harun, R. (2013). Impact of excessive nitrogen fertilizers on the environment and associated mitigation strategies. *Asian J. Microbiol. Biotechnol. Environ. Sci.*, 15(2), 213–221.
- Battin, T. J., Besemer, K., Bengtsson, M. M., Romani, A. M., & Packmann, A. I. (2016). The ecology and biogeochemistry of stream biofilms. *Nature Reviews Microbiology* 2016 14:4, 14(4), 251–263. <https://doi.org/10.1038/nrmicro.2016.15>
- BFS, B. für S. (2006). *Arealstatistik Schweiz - Standardnomenklatur NOAS04: Grundkategorien und Aggregationen*.
- BFS, B. für S. (2021). *Geodaten in Hektarauflösung zur Arealstatistik nach Nomenklatur 2004*.
- Blumer, F. (2015). *Ein Blick in die Klimaklassifikation - Wetterfrage - SRF*. 2015. <https://www.srf.ch/audio/wetterfrage/ein-blick-in-die-klimaklassifikation?id=10766617> (Access: 27.01.2023).
- Boral, S., Sen, I. S., Ghosal, D., Peucker-Ehrenbrink, B., & Hemingway, J. D. (2019). Stable water isotope modeling reveals spatio-temporal variability of glacier meltwater contributions to Ganges River headwaters. *Journal of Hydrology*, 577, 123983. <https://doi.org/10.1016/J.JHYDROL.2019.123983>
- Brender, J. D., & Brender, J. D. (2020). Human Health Effects of Exposure to Nitrate, Nitrite, and Nitrogen Dioxide. *Just Enough Nitrogen*, 283–294. https://doi.org/10.1007/978-3-030-58065-0_18
- Brooks, R. T., & Hayashi, M. (2002). Depth-area-volume and hydroperiod relationships of ephemeral (vernal) forest pools in Southern New England. *Wetlands*, 22(2), 247–255. [https://doi.org/10.1672/0277-5212\(2002\)022\[0247:DAVAHR\]2.0.CO;2](https://doi.org/10.1672/0277-5212(2002)022[0247:DAVAHR]2.0.CO;2)
- Bundesrat. (1998). *Gewässerschutzverordnung (GSchV) (status 01.01.2021)*.
- Burchsted, D., Daniels, M., Thorson, R., & Vokoun, J. (2010). The river discontinuum: Applying beaver modifications to baseline conditions for restoration of forested headwaters. *BioScience*, 60(11), 908–922. <https://doi.org/10.1525/BIO.2010.60.11.7>
- Burgin, A., & Hamilton, S. (2007). Have we overemphasized the role of denitrification in aquatic ecosystems? A review of nitrate removal pathways. *Frontiers in Ecology and the Environment*, 5(2), 89–96.
- Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (1998). NONPOINT POLLUTION OF SURFACE WATERS WITH PHOSPHORUS AND NITROGEN. *Ecological Applications*, 8(3), 559–568. <https://doi.org/10.1890/1051-0761>
- Cavalli, M., Tarolli, P., Marchi, L., & Dalla Fontana, G. (2008). The effectiveness of airborne LiDAR data in the recognition of channel-bed morphology. *CATENA*, 73(3), 249–260. <https://doi.org/10.1016/J.CATENA.2007.11.001>
- Chaubey, I., & Ward, G. (2006). Hydrologic Budget Analysis of a Small Natural Wetland in Southeast USA. *Journal of Environmental Informatics*, 8(1), 10–21. <https://doi.org/10.3808/JEI.200600073>
- Cheng, F. Y., Van Meter, K. J., Byrnes, D. K., & Basu, N. B. (2020). Maximizing US nitrate removal through wetland protection and restoration. *Nature* 2020 588:7839, 588(7839), 625–630. <https://doi.org/10.1038/s41586-020-03042-5>
- Craig, H. (1961). Standard for Reporting Concentrations of Deuterium and Oxygen-18 in Natural Waters. *Science*, 133(3467), 1833–1834. <https://doi.org/10.1126/SCIENCE.133.3467.1833>
- Craig, H., & Gordon, L. (1965). *Deuterium and oxygen 18 variations in the ocean and the marine atmosphere*.
- Daily, G. C., & Matson, P. A. (2008). Ecosystem services: From theory to implementation. *Proceedings of the National Academy of Sciences*, 105(28), 9455–9456. <https://doi.org/10.1073/PNAS.0804960105>

- Devito, K. J., & Dillon, P. J. (1993). The importance of runoff and winter anoxia to P and N dynamics of a beaver pond. *Canadian Journal of Fisheries and Aquatic Sciences*, 50(10), 2222–2234. <http://atrium.lib.uoguelph.ca/xmlui/handle/10214/15788>
- Dewey, C., Fox, P. M., Bouskill, N. J., Dwivedi, D., Nico, P., & Fendorf, S. (2022). Beaver dams overshadow climate extremes in controlling riparian hydrology and water quality. *Nature Communications* 2022 13:1, 13(1), 1–9. <https://doi.org/10.1038/s41467-022-34022-0>
- Di, H. J., & Cameron, K. C. (2002). Nitrate leaching in temperate agroecosystems: Sources, factors and mitigating strategies. *Nutrient Cycling in Agroecosystems*, 64(3), 237–256. <https://doi.org/10.1023/A:1021471531188/METRICS>
- Djoshkin, W. W., & Safanov, V. G. (1972). *Der Biber der alten und neuen Welt*. A. Ziemsen Verlag.
- Dudenredaktion. (2020). *Duden - Die deutsche Rechtschreibung* (28. Aufl.). Dudenverlag.
- esri, E. S. R. I. (2016). *Surface Volume—Help | ArcGIS for Desktop*. <https://desktop.arcgis.com/en/arc-map/10.3/tools/3d-analyst-toolbox/surface-volume.htm>
- Follett, R. F., & Delgado, J. A. (2002). Nitrogen fate and transport in agricultural systems. *Journal of Soil and Water Conservation*, 57(6), 402–408.
- Francis, M. M., Naiman, R. J., & Melillo, J. M. (1985). Nitrogen fixation in subarctic streams influenced by beaver (*Castor canadensis*). *Hydrobiologia*, 121(3), 193–202. <https://doi.org/10.1007/BF00017543/METRICS>
- Geoportal Kanton St. Gallen. (2023). *Gewässerqualität DOC Kt*. <https://www.geoportal.ch/ktsqg/map/1314?y=2763845.44&x=1248979.01&scale=50000&rotation=0>
- Grudzinski, B. P., Fritz, K., Golden, H. E., Newcomer-Johnson, T. A., Rech, J. A., Levy, J., Fain, J., McCarty, J. L., Johnson, B., Vang, T. K., & Maurer, K. (2022). A global review of beaver dam impacts: Stream conservation implications across biomes. *Global Ecology and Conservation*, 37, e02163. <https://doi.org/10.1016/J.GECCO.2022.E02163>
- Halley, D. J., Saveljev, A. P., & Rosell, F. (2021). Population and distribution of beavers *Castor fiber* and *Castor canadensis* in Eurasia. *Mammal Review*, 51(1), 1–24. <https://doi.org/10.1111/MAM.12216>
- Harrison, M. D., Groffman, P. M., Mayer, P. M., Kaushal, S. S., & Newcomer, T. A. (2011). Denitrification in Alluvial Wetlands in an Urban Landscape. *Journal of Environmental Quality*, 40(2), 634–646. <https://doi.org/10.2134/JEQ2010.0335>
- Heard, D. (2014). Rodents. *Zoo Animal and Wildlife Immobilization and Anesthesia: Second Edition*, 893–903. <https://doi.org/10.1002/9781118792919.CH66>
- Hedges, J. I. (1992). Global biogeochemical cycles: progress and problems. *Marine Chemistry*, 39(1–3), 67–93. [https://doi.org/10.1016/0304-4203\(92\)90096-S](https://doi.org/10.1016/0304-4203(92)90096-S)
- Houser, J. N., Bade, D. L., Cole, J. J., & Pace, M. L. (2003). The dual influences of dissolved organic carbon on hypolimnetic metabolism: Organic substrate and photosynthetic reduction. *Biogeochemistry*, 64(2), 247–269. <https://doi.org/10.1023/A:1024933931691/METRICS>
- Hürdler, J., Prasuhn, V., & Spiess, E. (2015). *Abschätzung diffuser Stickstoff- und Phosphoreinträge in die Gewässer der Schweiz MODIFFUS 3.0. Bericht im Auftrag des Bundesamtes für Umwelt (BAFU)*.
- Infofauna, B. (2008). *Verbreitung 2008 bei der letzten gesamtschweizerischen Bestandeserhebung*. <http://www.cscf.ch/cscf/de/home/biberfachstelle/informationen-zum-biber/biber-in-der-schweiz/verbreitung-2008.html> (access: 24.05.2023).
- Infofauna, B. (2021a). *Anleitung zur Wasser Probennahme während der nationalen Biber-Bestandeserhebung 2021/2022*.
- Infofauna, B. (2021b). *Anleitung für die Feldarbeit der nationalen Biber-Bestandeserhebung*.
- Isokangas, E., Rozanski, K., Rossi, P. M., Ronkanen, A. K., & Kløve, B. (2015). Quantifying groundwater dependence of a sub-polar lake cluster in Finland using an isotope mass balance approach. *Hydrology and Earth System Sciences*, 19(3), 1247–1262. <https://doi.org/10.5194/HESS-19-1247-2015>
- James, L. A., Watson, D. G., & Hansen, W. F. (2007). Using LiDAR data to map gullies and headwater streams under forest canopy: South Carolina, USA. *CATENA*, 71(1), 132–144. <https://doi.org/10.1016/J.CATENA.2006.10.010>
- Johnston, C. A. (2014). Beaver pond effects on carbon storage in soils. *Geoderma*, 213, 371–378. <https://doi.org/10.1016/J.GEODERMA.2013.08.025>
- Jordan, S. J., Stoffer, J., & Nestlerode, J. A. (2011). Wetlands as Sinks for Reactive Nitrogen at Continental and Global Scales: A Meta-Analysis. *Ecosystems*, 14(1), 144–155. <https://doi.org/10.1007/S10021-010-9400-Z/TABLES/3>
- Kalinin, A., Covino, T., & McGlynn, B. (2016). The influence of an in-network lake on the timing, form, and magnitude of downstream dissolved organic carbon and nutrient flux. *Water Resources Research*, 52(11), 8668–8684. <https://doi.org/10.1002/2016WR019378>

- Karran, D. J., Westbrook, C. J., Wheaton, J. M., Johnston, C. A., & Bedard-Haughn, A. (2017). Rapid surface-water volume estimations in beaver ponds. *Hydrology and Earth System Sciences*, 21(2), 1039–1050. <https://doi.org/10.5194/hess-21-1039-2017>
- Kiss, G., Varga, B., Galambos, I., & Ganszky, I. (2002). Characterization of water-soluble organic matter isolated from atmospheric fine aerosol. *Journal of Geophysical Research: Atmospheres*, 107(D21), ICC 1-1. <https://doi.org/10.1029/2001JD000603>
- Knobeloch, L., Salna, B., Hogan, A., Postle, J., & Anderson, H. (2000). Blue babies and nitrate-contaminated well water. *Environmental Health Perspectives*, 108(7), 675–678. <https://doi.org/10.1289/EHP.00108675>
- Kritzbberg, E. S., Cole, J. J., Pace, M. L., Granéli, W., & Bade, D. L. (2004). Autochthonous versus allochthonous carbon sources of bacteria: Results from whole-lake ¹³C addition experiments. *Limnology and Oceanography*, 49(2), 588–596. <https://doi.org/10.4319/LO.2004.49.2.0588>
- Larsen, A., Larsen, J. R., & Lane, S. N. (2021). Dam builders and their works: Beaver influences on the structure and function of river corridor hydrology, geomorphology, biogeochemistry and ecosystems. *Earth-Science Reviews*, 218(April), 103623. <https://doi.org/10.1016/j.earscirev.2021.103623>
- Lazar, J. G., Addy, K., Gold, A. J., Groffman, P. M., McKinney, R. A., & Kellogg, D. Q. (2015). Beaver Ponds: Resurgent Nitrogen Sinks for Rural Watersheds in the Northeastern United States. *Journal of Environmental Quality*, 44(5), 1684–1693. <https://doi.org/10.2134/JEQ2014.12.0540>
- Mann, C. J., & Wetzel, R. G. (1995). Dissolved organic carbon and its utilization in a riverine wetland ecosystem. *Biogeochemistry*, 31(2), 99–120. <https://doi.org/10.1007/BF00000941/METRICS>
- Medford, A. J., & Hatzell, M. C. (2017). Photon-Driven Nitrogen Fixation: Current Progress, Thermodynamic Considerations, and Future Outlook. *ACS Catalysis*, 7(4), 2624–2643. https://doi.org/10.1021/ACSCATAL.7B00439/ASSET/IMAGES/LARGE/CS-2017-00439R_0011.JPEG
- MeteoSchweiz. (2014). *'Klimaszenarien Schweiz - eine regionale Übersicht'*, *Fachbericht MeteoSchweiz*, 243, 36 pp.
- MeteoSchweiz. (2022a). *Klimabulletin Sommer 2022*.
- MeteoSchweiz. (2022b). *Klimabulletin Winter 2021/22*.
- Minnig, S., Angst, C., & Jacob, G. (2016). Genetic monitoring of Eurasian beaver (*Castor fiber*) in Switzerland and implications for the management of the species. *Russian Journal of Theriology*, 15(1), 20–27. <https://doi.org/10.15298/RUSJTHERIOL.15.1.04>
- Müller, G., & Watling, J. (2016). The engineering in beaver dams. *River Flow - Proceedings of the International Conference on Fluvial Hydraulics, RIVER FLOW 2016*, 2094–2100. <https://doi.org/10.1201/9781315644479-326>
- Müller-Wenk, R. (2003). *Landnutzung in potentiellen Fließgewässer-Auen-Artengefährdung und Ökobilanzen*.
- Murdoch, A., Gray, D. K., Korosi, J., Vucic, J. M., Cohen, R. S., & Sharma, S. (2021). Drivers of fish biodiversity in a rapidly changing permafrost landscape. *Freshwater Biology*, 66(12), 2301–2321. <https://doi.org/10.1111/FWB.13834>
- Mus, F., Crook, M. B., Garcia, K., Costas, A. G., Geddes, B. A., Kouri, E. D., Paramasivan, P., Ryu, M. H., Oldroyd, G. E. D., Poole, P. S., Udvardi, M. K., Voigt, C. A., Ané, J. M., & Peters, J. W. (2016). Symbiotic nitrogen fixation and the challenges to its extension to nonlegumes. *Applied and Environmental Microbiology*, 82(13), 3698–3710. <https://doi.org/10.1128/AEM.01055-16/ASSET/AD958A31-D795-47FF-8758-67A5455890B7/ASSETS/GRAPHIC/ZAM9991172150004.JPEG>
- Naiman, R. J., & Melillo, J. M. (1984). Nitrogen budget of a subarctic stream altered by beaver (*Castor canadensis*). *Oecologia*, 62(2), 150–155. <https://doi.org/10.1007/BF00379007/METRICS>
- Naiman, R. J., Pinay, G., Johnston, C. A., & Pastor, J. (1994). Beaver Influences on the Long-Term Biogeochemical Characteristics of Boreal Forest Drainage Networks. *Ecology*, 75(4), 905–921. <https://doi.org/10.2307/1939415>
- Nixon, S. W., Ammerman, J. W., Atkinson, L. P., Berounsky, V. M., Billen, G., Boicourt, W. C., Boynton, W. R., Church, T. M., Ditoro, D. M., Elmgren, R., Garber, J. H., Giblin, A. E., Jahnke, R. A., Owens, N. J. P., Pilson, M. E. Q., & Seitzinger, S. P. (1996). The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. *Biogeochemistry*, 35(1), 141–180. <https://doi.org/10.1007/BF02179826/METRICS>
- Nummi, P., Vehkaoja, M., Pumpanen, J., & Ojala, A. (2018). Beavers affect carbon biogeochemistry: both short-term and long-term processes are involved. *Mammal Review*, 48(4), 298–311. <https://doi.org/10.1111/MAM.12134>
- Pan, Y. P., Wang, Y. S., Tang, G. Q., & Wu, D. (2012). Wet and dry deposition of atmospheric nitrogen at ten sites in Northern China. *Atmospheric Chemistry and Physics*, 12(14), 6515–6535. <https://doi.org/10.5194/ACP-12-6515-2012>
- Picarro. (2015). *L2140-i, L2130-i or L2120-i Analyzer and Peripherals User's Manual*.

- Polvi, L. E., & Wohl, E. (2012). The beaver meadow complex revisited – the role of beavers in post-glacial floodplain development. *Earth Surface Processes and Landforms*, 37(3), 332–346. <https://doi.org/10.1002/ESP.2261>
- Ratkowsky, D. A., Olley, J., McMeekin, T. A., & Ball, A. (1982). Relationship between temperature and growth rate of bacterial cultures. *Journal of Bacteriology*, 149(1), 1. <https://doi.org/10.1128/JB.149.1.1-5.1982>
- Rees, R. M., Bingham, I. J., Baddeley, J. A., & Watson, C. A. (2005). The role of plants and land management in sequestering soil carbon in temperate arable and grassland ecosystems. *Geoderma*, 128(1–2), 130–154. <https://doi.org/10.1016/J.GEODERMA.2004.12.020>
- Robertson, G. P., & Paul, E. A. (2000). Decomposition and Soil Organic Matter Dynamics. *Methods in Ecosystem Science*, 104–116. https://doi.org/10.1007/978-1-4612-1224-9_8
- Saunders, D. L., & Kalff, J. (2001). Nitrogen retention in wetlands, lakes and rivers. *Hydrobiologia*, 443(1), 205–212. <https://doi.org/10.1023/A:1017506914063/METRICS>
- Schindler, D. W. (1977). Evolution of phosphorus limitation in lakes. *Science*, 195(4275), 260–262. <https://doi.org/10.1126/SCIENCE.195.4275.260/ASSET/CD9751DC-20A9-484E-85E8-F0881327FF27/ASSETS/SCIENCE.195.4275.260.FP.PNG>
- Schmid, B. (2019). *Hohe Belastung im Naturschutzgebiet Bannriet und Spitzmäder*.
- Schumann, U., & Huntrieser, H. (2007). The global lightning-induced nitrogen oxides source. *Atmospheric Chemistry and Physics*, 7(14), 3823–3907. <https://doi.org/10.5194/ACP-7-3823-2007>
- Skrzypek, G., Mydlowski, A., Dogramaci, S., Hedley, P., Gibson, J. J., & Grierson, P. F. (2015). Estimation of evaporative loss based on the stable isotope composition of water using Hydrocalculator. *Journal of Hydrology*, 523, 781–789. <https://doi.org/10.1016/J.JHYDROL.2015.02.010>
- Smith, V. H., Joye, S. B., & Howarth, R. W. (2006). Eutrophication of freshwater and marine ecosystems. *Limnology and Oceanography*, 51(1part2), 351–355. https://doi.org/10.4319/LO.2006.51.1_PART_2.0351
- Socolow, R. H. (1999). Nitrogen management and the future of food: Lessons from the management of energy and carbon. *Proceedings of the National Academy of Sciences of the United States of America*, 96(11), 6001–6008. <https://doi.org/10.1073/PNAS.96.11.6001>
- Stein, L. Y., & Klotz, M. G. (2016). The nitrogen cycle. *Current Biology*, 26(3), R94–R98. <https://doi.org/10.1016/J.CUB.2015.12.021>
- Stocker, G. (1985). Biber (Castor fiber L.) in der Schweiz. *Swiss Federal Institute of Forestry Research*, 149.
- swisstopo, B. für L. (2015). *Diffuse Gesamt-Stickstoffeinträge in die Gewässer (Bundesamt für Umwelt BAFU)*. <https://www.agroscope.admin.ch/agroscope/de/home/themen/umwelt-ressourcen/boden-gewaesser-naehrstoffe/landwirtschaftlicher-gewaesserschutz/modiffus.html> (access: 17.05.2023).
- swisstopo, B. für L. (2018). *SWISSIMAGE 10 cm*. <https://www.swisstopo.admin.ch/de/geodata/images/ortho/swiss-image10.html> (access: 16.11.2022).
- swisstopo, B. für L. (2021). *LV95 Swiss Topographic Map*. <https://livingatlas-dcdev.opendata.arcgis.com/maps/EsriCH-Content:lv95-swiss-topographic-map/about> (access: 12.05.2023)
- swisstopo, B. für L. (2022a). *swissALTI3D*. <https://www.swisstopo.admin.ch/en/geodata/height/alti3d.html> (access: 18.07.2022)
- swisstopo, B. für L. (2022b). *swissTLM3D*. <https://www.swisstopo.admin.ch/de/geodata/landscape/tlm3d.html> (access: 16.11.2022).
- Tan, Z. X., Lal, R., Smeck, N. E., & Calhoun, F. G. (2004). Relationships between surface soil organic carbon pool and site variables. *Geoderma*, 121(3–4), 187–195. <https://doi.org/10.1016/J.GEODERMA.2003.11.003>
- Turney, S. (2022). *Pearson Correlation Coefficient (r) | Guide & Examples*. <https://www.scribbr.com/statistics/pearson-correlation-coefficient/> (access: 28.03.2023).
- UN, U. N. (2015). *Transforming our World: The 2030 Agenda for Sustainable Development*.
- Updegraff, K., Pastor, J., Bridgman, S. D., & Johnston, C. A. (1995). Environmental and substrate controls over carbon and nitrogen mineralization in northern wetlands. *Ecological Applications*, 5(1), 151–163. <https://doi.org/10.2307/1942060>
- Vallet-Coulomb, C., Couapel, M., & Sonzogni, C. (2021). Improving memory effect correction to achieve high-precision analysis of $\delta^{17}\text{O}$, $\delta^{18}\text{O}$, $\delta^2\text{H}$, ^{17}O -excess and d-excess in water using cavity ring-down laser spectroscopy. *Rapid Communications in Mass Spectrometry*, 35(14). <https://doi.org/10.1002/RCM.9108>
- Wang, C. K., & Philpot, W. D. (2007). Using airborne bathymetric lidar to detect bottom type variation in shallow waters. *Remote Sensing of Environment*, 106(1), 123–135. <https://doi.org/10.1016/J.RSE.2006.08.003>
- Wang, X., Shaw, E. L., Westbrook, C. J., & Bedard-Haughn, A. (2018). Beaver Dams Induce Hyporheic and Biogeochemical Changes in Riparian Areas in a Mountain Peatland. *Wetlands*, 38(5), 1017–1032. <https://doi.org/10.1007/S13157-018-1059-9/FIGURES/9>

- Ward, M. H., Jones, R. R., Brender, J. D., de Kok, T. M., Weyer, P. J., Nolan, B. T., Villanueva, C. M., & van Breda, S. G. (2018). Drinking Water Nitrate and Human Health: An Updated Review. *International Journal of Environmental Research and Public Health*, 15(7). <https://doi.org/10.3390/IJERPH15071557>
- WHO. (2022). Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda. *World Health Organization*, 1–614.
- Winterdahl, M., Laudon, H., Lyon, S. W., Pers, C., & Bishop, K. (2016). Sensitivity of stream dissolved organic carbon to temperature and discharge: Implications of future climates. *Journal of Geophysical Research: Biogeosciences*, 121(1), 126–144. <https://doi.org/10.1002/2015JG002922>
- Wohl, E., & Beckman, N. D. (2014). Leaky rivers: Implications of the loss of longitudinal fluvial disconnectivity in headwater streams. *Geomorphology*, 205, 27–35. <https://doi.org/10.1016/J.GEOMORPH.2011.10.022>
- Wright, J. P., Jones, C. G., & Flecker, A. S. (2002). An ecosystem engineer, the beaver, increases species richness at the landscape scale. *Oecologia*, 132(1), 96–101. <https://doi.org/10.1007/S00442-002-0929-1/METRICS>
- Zahner, V. (1997). *Einfluß des Bibers auf gewässer-nahe Wälder. Ausbreitung der Population sowie Ansätze zur Integration des Bibers in die Forstplanung und Waldbewirtschaftung in Bayern*. Utz, Wiss.
- Zahner, V., Schmidbauer, M., Schwab, G., & Angst, C. (2021). *Der Biber. Baumeister mit Biss*. SüdOst Verlag. Regenstauf.
- Zarnetske, J. P., Haggerty, R., Wondzell, S. M., & Baker, M. A. (2011). Dynamics of nitrate production and removal as a function of residence time in the hyporheic zone. *Journal of Geophysical Research: Biogeosciences*, 116(G1), 1025. <https://doi.org/10.1029/2010JG001356>
- Zarnetske, J. P., Haggerty, R., Wondzell, S. M., Bokil, V. A., & González-Pinzón, R. (2012). Coupled transport and reaction kinetics control the nitrate source-sink function of hyporheic zones. *Water Resources Research*, 48(11). <https://doi.org/10.1029/2012WR011894>

Appendix

Appendix A: Case study for nitrate removal in beaver systems

Dewey et al. (2022) highlight the importance of hyporheic exchange (exchange of water between river channels and shallow subsurface) in relation of water quality impacts of floodplains. Whether the hyporheic zone acts as a source or sink of nitrate concentration in the stream is dependent on the residence time of the water in this zone and the rate of oxygen consumption (Zarnetske et al., 2012). Higher residence times corresponds to a higher level of denitrification, whereas shorter residence times are associated with higher rates of oxygen consumption for nitrification (Figure 92) (Zarnetske et al., 2011).

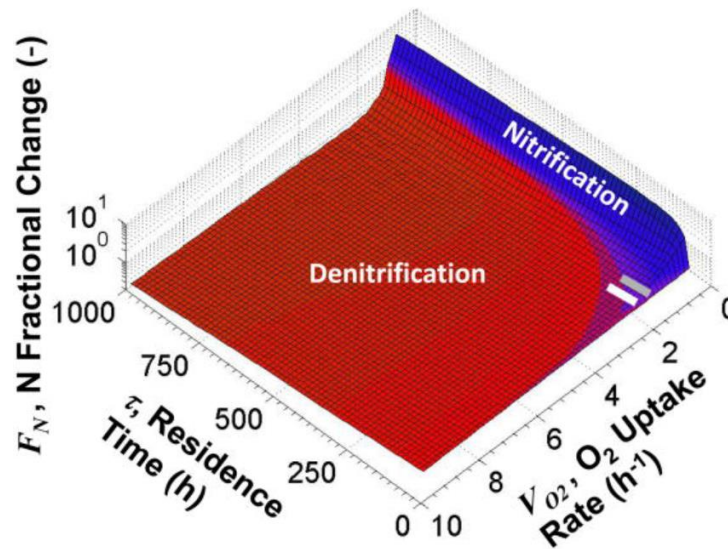


Figure 92: Water residence time and nitrogen fractional change. Illustration of the effect from residence time and O_2 uptake on the nitrogen fractional change determined in a field study in 2007 from (Zarnetske et al., 2011) (Illustration from: (Zarnetske et al., 2012)).

Dewey et al. (2022) examined the impact of beaver dams on nitrogen and oxygen fluxes in the riparian area, as well as the alteration of riverine water quality. The study site was a meandering tributary of the Colorado River, USA, where a beaver dam was constructed between July and October 2018 (Figure 93). The construction of the beaver dam resulted in elevated water levels upstream, while the downstream water level stayed unchanged. This led to an increased hydraulic gradient across the riparian hyporheic zone, which reached 161.5 % of the average gradient observed in the absence of the dam. The raising water level expanded the aerobic conditions in the riparian zone (Dewey et al., 2022).

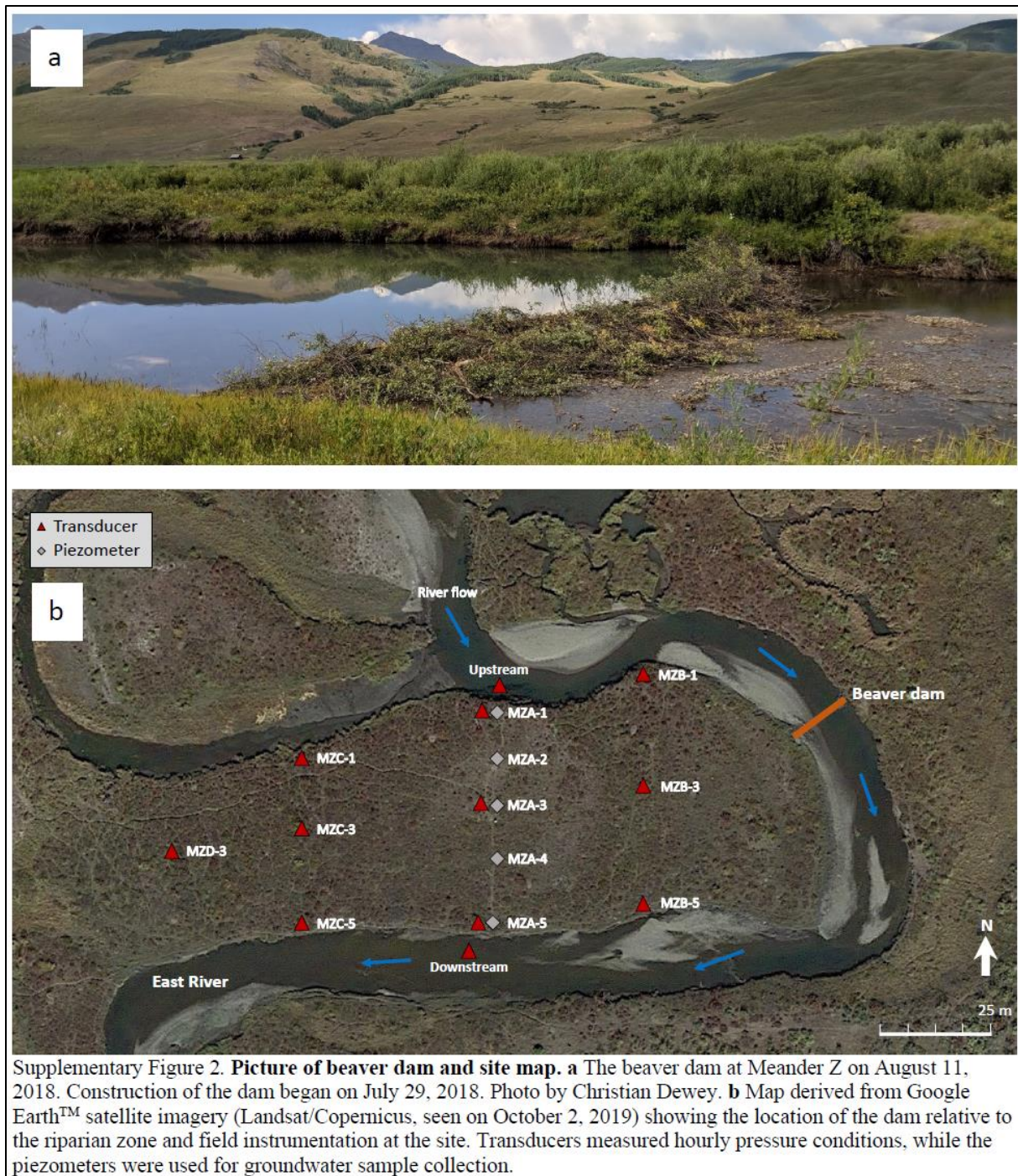


Figure 93: Study setup from Dewey et al. (2022).

Dewey et al. (2022) utilized Damköhler (Da_{DO}) number to compare the influence of transport and reaction processes on dissolved oxygen, with the aim of distinguishing aerobic ($Da_{DO} < 1$) from anaerobic ($Da_{DO} > 1$) conditions. The raised water level extended the aerobic zone 4.37 m into the riparian zone (Dewey et al., 2022). Within the aerobic zone, the mineralization of organic forms of nitrogen contributes to an increase in nitrate concentration. Additionally, nitrate is produced by nitrification if dissolved oxygen and ammonium is available leading to a decrease in ammonium concentration. Another nitrogen source in the aerobic zone is the mineralization of organic forms of nitrogen. In contrast, the anaerobic zone experiences low dissolved oxygen supply, promoting denitrification along the flow path until the nitrate is depleted

and the ammonium concentration are rebound due to ammonification of organic forms of nitrogen (Figure 94) (Zarnetske et al., 2012).

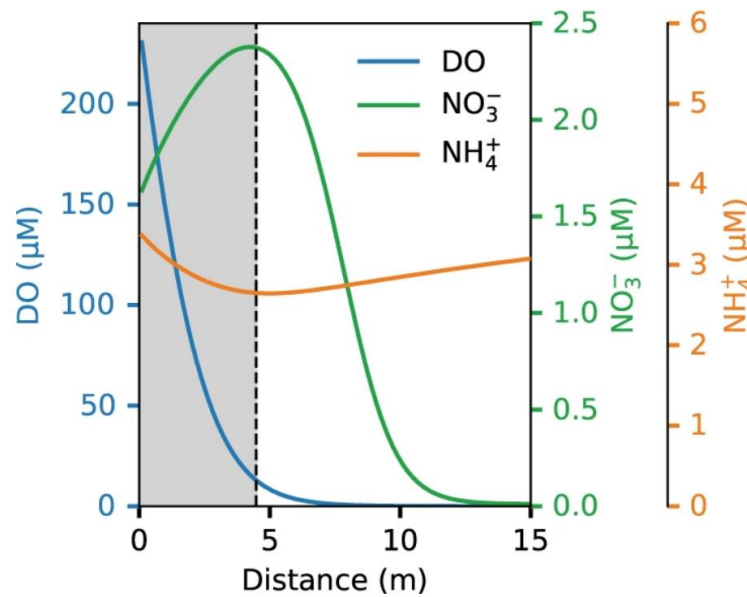


Figure 94: Expansion of aerobic zone and nitrification. Illustration from Dewey et al. (2022). The aerobic zone (grey shading) extended 4.37 m (DaDO = 1). In this zone the nitrate concentration increases through mineralization of organic nitrogen and nitrification which leads to a decrease in ammonium and dissolved oxygen. In the anaerobic the nitrate concentration decreases due to the denitrification process.

The increased nitrate input into the hyporheic zone creates conditions for nitrate removal through denitrification. The length of the flow path within the hyporheic zone plays a crucial role in ensuring the complete removal of the imported nitrate (Figure 95). Dewey et al. (2022) found nitrate removal across the riparian area 44.2% higher than in the absence of the beaver dam (Figure 95). Specifically, the nitrate removal rate was 3.0×10^{-4} mol nitrate/m²/day with the dam, whereas it was 2.1×10^{-4} mol nitrate/m²/day without the beaver dam (Dewey et al., 2022).

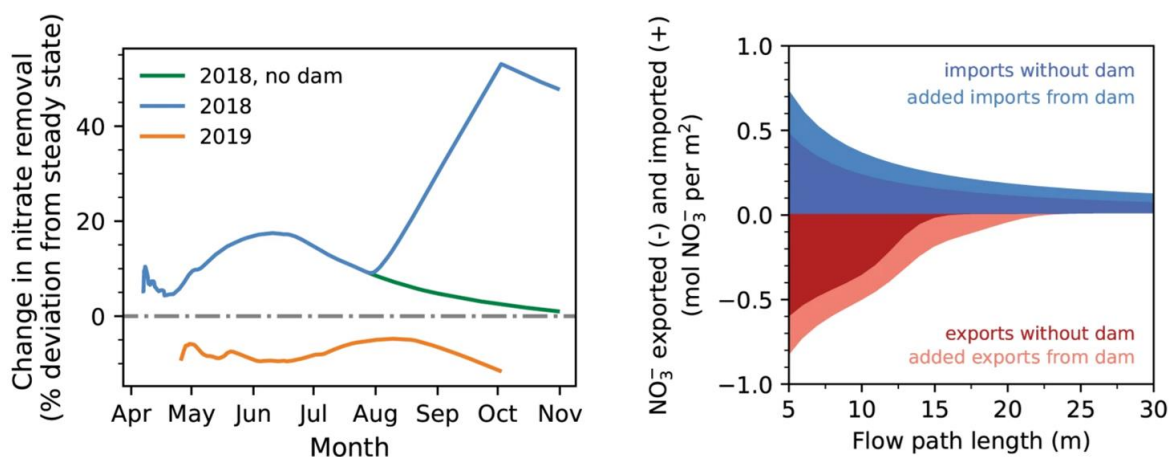


Figure 95: Nitrate removal along the flow path. Illustrations from Dewey et al. (2022). An increased flux of nitrate into the riparian area increases the available nitrate amount for denitrification leading to a removal in nitrate along the flow path (left). When comparing the nitrate imports and exports into the floodplain area. The increased import of nitrate in connection with the beaver dam can only be removed when the flow path length is long enough (right).

Appendix B: Instructions water sampling

Nationale Biber-Bestandserhebung 2021/2022

BIBERFACHSTELLE

Anleitung zur Wasser Probennahme während der nationalen Biber-Bestandserhebung 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-Bestandserhebung 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-Bestandserhebung](#), da diese auch zusammen durchgeführt werden. **Wichtig: Sicherheit kommt immer zuerst!**

Vorbereitung zu Hause

Eine gute Vorbereitung der Behälter für die Wasserproben ist Voraussetzung für eine erfolgreiche Durchführung der Probenahme. Hierzu gehört die **Zusammenstellung der Materialien**:

- 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)

Nationale Biber-Bestandserhebung 2021/2022

BIBERFACHSTELLE

- 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)

- 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)

- 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

- 1 -

- 2 -

Nationale Biber-Bestandserhebung 2021/2022

BIBERFACHSTELLE

- Spritze (1 x pro Tag)**, Spritze wechseln, wenn Gewässer gewechselt werden



Spritze, steril verpackt

Beschriftung - Vorbereitung

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

Beschriftung – Im Gelände

- 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).
- Name des Beprobungsortes.** 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:
- [Standardwahl für Wasserprobenentnahme](#)
- [Verschiedene Wasserprobenentnahmen](#)
- 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:

Nationale Biber-Bestandserhebung 2021/2022

BIBERFACHSTELLE

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 Biberbachs in der frei fließenden Strecke beprobt wurde, würde demnach das Folgende geschrieben sein:

DOC US_BE_AEG1_1_9 25/12/21 12:35

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

Nationale Biber-Bestandserhebung 2021/2022

BIBERFACHSTELLE

Protokollblatt für Wasserbeprobung während der Biber-Bestandserhebung 2021/2022

Besuchter Name: (Name) Ort: (Ort) Datum: (Datum) Uhrzeit: (Uhrzeit) Koordinaten: (Koordinaten) BSC: (BSC) W: (W) A: (A) Sediment: (Sediment) Beprobungstyp: (Beprobungstyp)

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	4°C	März 2022 (wird abgeholt)
Ammonium	A	Falcon tube	-20°C Gefrierschrank	März 2022 (wird abgeholt)
Nährstoffe/Nitrat	N	Falcon tube	4°C	Maximal 1 Woche
Dissolved Organic Carbon	DOC	Falcon tube	4°C	Maximal 1 Woche

- 3 -

- 4 -

Nationale Biber-Bestandeserhebung 2021/2022

Versenden der Proben

- 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.
- Proben müssen Montags, Dienstags oder Mittwochs 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.
- 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 Dammes eines Reviers genommen, wo der Bach noch frei fließt, also bevor der Rückstaubereich des Biberdammes beginnt (= backwater effect »). Die zweite Probe liegt unterhalb des letzten Dammes in der Fließstrecke (entweder ist nur ein Damm im Biberrevier oder mehrere Dämme, also eine Dammkaskadewieder). Bitte aufpassen, dass unterhalb/bachabwärts vom vom Biber angelegten Seitengewässern beprobt wird. Um das etwas anschaulicher zu machen, bitte das Video zur [Wahl der Beprobungsstandorte](#) anschauen.

Bachabschnitt mit 1 Biberdamm

Probe oberhalb Biberreich, «UpStream»
Flaschenbeschriftung: US_BE_AEG1_1_1

Probe unterhalb Biberreich, «DownStream»
Flaschenbeschriftung: DS_BE_AEG1_1_1

Kartierrichtung von oben nach unten

- 5 -

Nationale Biber-Bestandeserhebung 2021/2022

Bachabschnitt mit 1 Biberdamm und Umgehungsgerinne

Probe oberhalb Biberreich, «UpStream»
Flaschenbeschriftung: US_BE_AEG1_1_1

Probe unterhalb Biberreich, «DownStream»
Flaschenbeschriftung: DS_BE_AEG1_1_1

Kartierrichtung von oben nach unten

Bachabschnitt mit mehreren Biberdämmen, Biberdammkaskade

Probe oberhalb Biberreich, «UpStream»
Flaschenbeschriftung: US_BE_AEG1_1_1

Probe unterhalb Biberreich, «DownStream»
Flaschenbeschriftung: DS_BE_AEG1_1_4

Kartierrichtung von oben nach unten

Wie beproben? (5 Wasserprobentypen 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 Stromtrich 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 Stromtrich/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 -

Nationale Biber-Bestandeserhebung 2021/2022

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 Probenahme 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 Probenahme 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 aufgefrieren 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.

- 7 -

Appendix C: Catchment delineation

Table 22: Different methods to calculate the catchment polygons.

Pro-gram	Tools	Resolu-tion DTM	Prepro-cessing DTM?	Outlet point	Quality of re-sulting poly-gon
ArcMap	Spatial Analyst	0.5 m	No	DS coordinate	Poor
ArcMap	Spatial Analyst	0.5 m	Yes	DS coordinate	Good
ArcMap	Spatial Ana-lyst	2 m	Yes	DS coordinate	Good
QGIS	GRASS	2 m	Yes	manually, in the region of the DS coordinate	Good

Table 23: 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

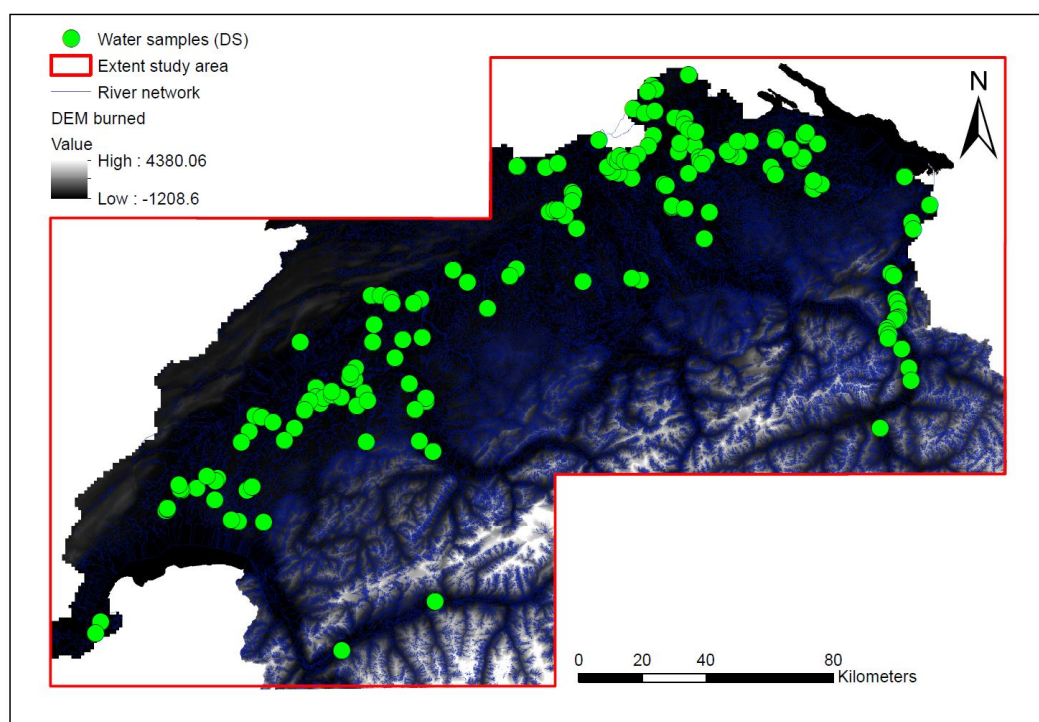


Figure 96: Data basis for catchment area calculations in QGIS. DEM burn calculated on the basis of (swisstopo, 2022a) (Basemap: (swisstopo, 2022b).

Table 24: 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 D: Email swisstopo (lidar)

Ich kann zu dem Produkt swissALTI3D gerne Auskunft geben.

Eigentlich sind die kleinen Fliessgewässern mit bathymetrischen Daten nicht korrigiert. Immerhin ist es möglich, dass für kleine Fliessgewässer mit gut durchsichtigem Wasser, der Boden von den LiDAR-Aufnahmen gut erfasst wurde. Es mag auch der Fall sein, dass bei dem Erfassungsdatum kaum- bis kein Wasser in den Fliessgewässern vorhanden war (bei herbstlichen Aufnahmen). Für mehr Informationen über Erfassungsdatum können Sie dem GPS-Time aus dem swissSURFACE3D Daten benutzen → [swissSURFACE3D - swisstopo \(admin.ch\)](#).

Ich hoffe Ihre Frage geantwortet zu haben

Freundliche Grüsse

~~~~~  
Florian Gandor

Topographie – Modèles altimétriques

Département fédéral de la défense,  
de la protection de la population et des sports DDPS  
Office fédéral de topographie swisstopo

Seftigenstrasse 264, 3084 Wabern

Tél +41 58 469 01 11 centrale

Tél +41 58 469 01 89 direct

Fax +41 58 469 04 59

[Florian.Gandor@swisstopo.ch](mailto:Florian.Gandor@swisstopo.ch)

[\[www.swisstopo.ch\]](http://www.swisstopo.ch)[www.swisstopo.ch](http://www.swisstopo.ch)

## Appendix E: GIS volume calculation tools

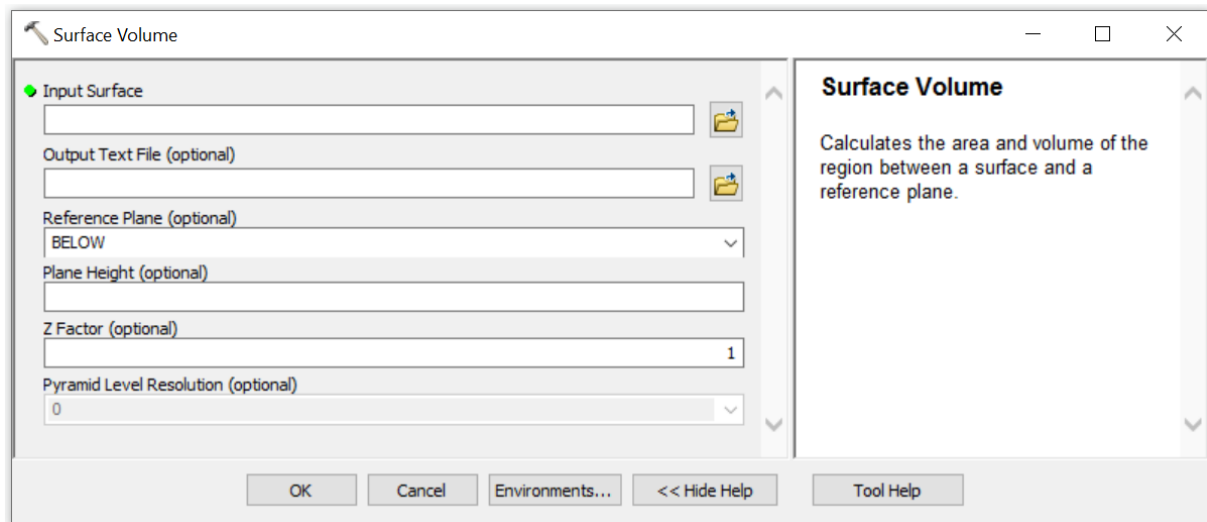


Figure 97: Surface Volume tool in ArcMap. The input surface is the DEM clipped to the beaver reach area and the plane height is the altitude of the top of the beaver dam.

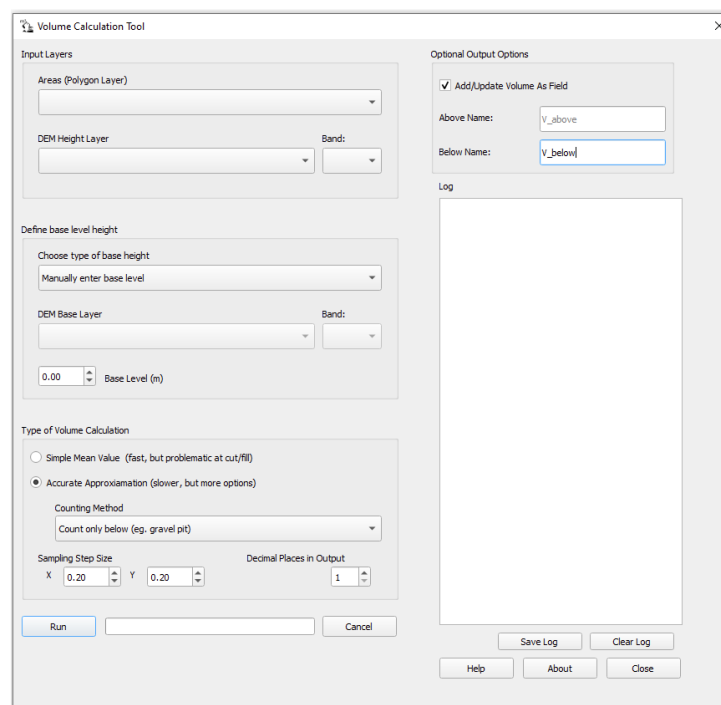
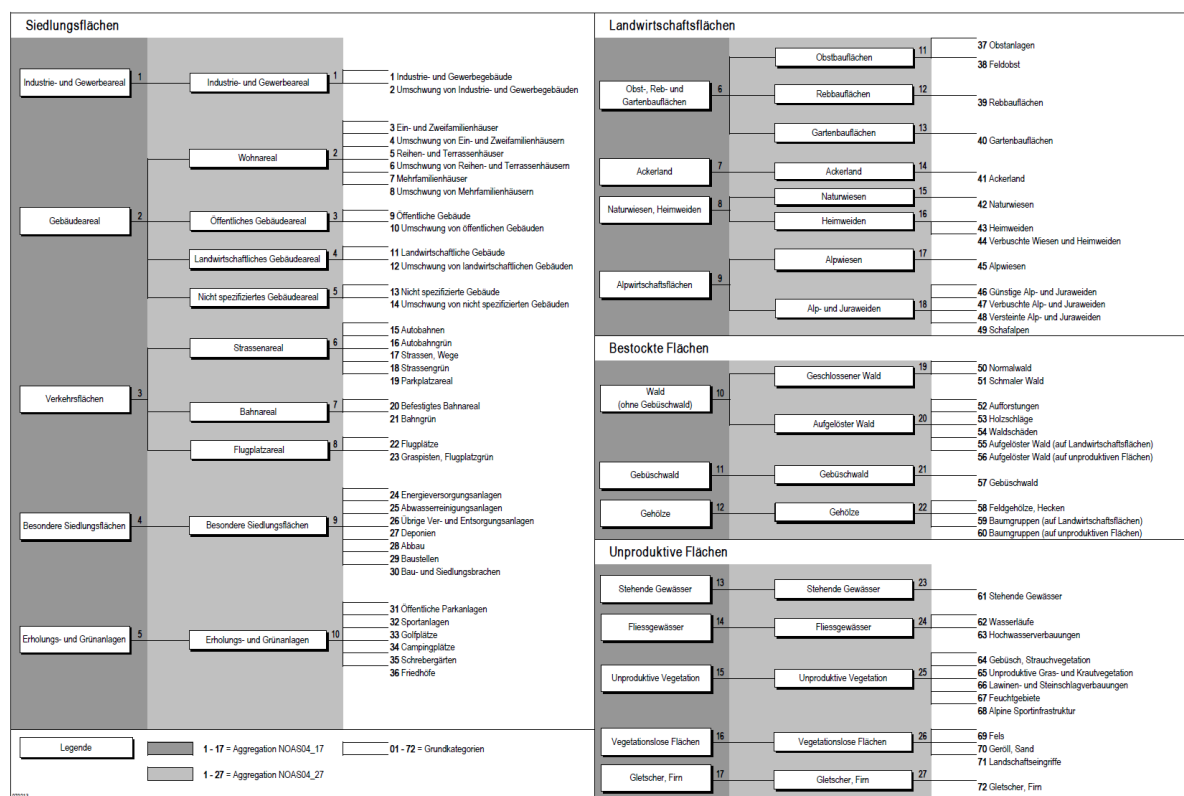


Figure 98: Volume Calculation Tool from QGIS. The area is a polygon around the beaver reach extracted from the aerial image and the DEM height layer is the DEM clipped to this polygon. The base level is identical to the plane height in the ArcMap.

## Appendix F: Area statistics Switzerland - Standard nomenclature NOAS04



## Appendix G: Email swisstopo (wetlands)

Es freut mich, dass sie aufs TLM aufmerksam geworden sind. Die Objektart Feuchtgebiet ist für uns im (Infrarot-) Luftbild schwer zu beurteilen, darum machen wir möglichst wenig daran.

Ursprünglich stammen die meisten Feuchtgebiete im TLM aus den alten Landeskarten. In Vector25 wurden diese digitalisiert und Vector 25 wurde auch für die «Erstbefüllung» des TLM verwendet. Wie die Feuchtgebiete in die Landeskarte kamen, kann ich nicht genau sagen. Vermutlich spielten Feldarbeiten dabei auch eine grössere Rolle. Folgende arbeiten machen wir im TLM

- Die Feuchtgebiete aus Vector 25 wurden im TLM ans Gelände angepasst.
- Dann haben wir noch das Moorinventar vom BAFU zu Hilfe genommen. Wo wir noch kein Feuchtgebiet hatten, wurden im TLM neue Feuchtgebiete erfasst, häufig etwas kleiner als im Inventar.
- Auch Daten der amtlichen Vermessung nahmen wir zu Hilfe. Wo die amtliche Vermessung ein Feuchtgebiet erfasst hat prüfen wir, ob es im Luftbild auch feucht aussieht und unsere Minimalfläche erfüllt und haben dann auch ein Fachgebiet erfasst. Regional haben wir aber sehr grosse Unterschiede in der AV festgestellt.
- Wenn wir im Luftbild eindeutig vernässte Stellen sehen, (auch in Luftbildern aus früheren Jahren), erfassen wir vereinzelt auch neue Feuchtgebiete.
- Feuchtgebiet überlagernd auf Gewässern bedeutet Schilf. Das kann man im Luftbild gut beurteilen und wird entsprechend angepasst (häufig am Neuenburgersee)

Falls Sie weitere Fragen haben, melden Sie sich ungeniert.

Freundliche Grüsse

Hans Bärtschi

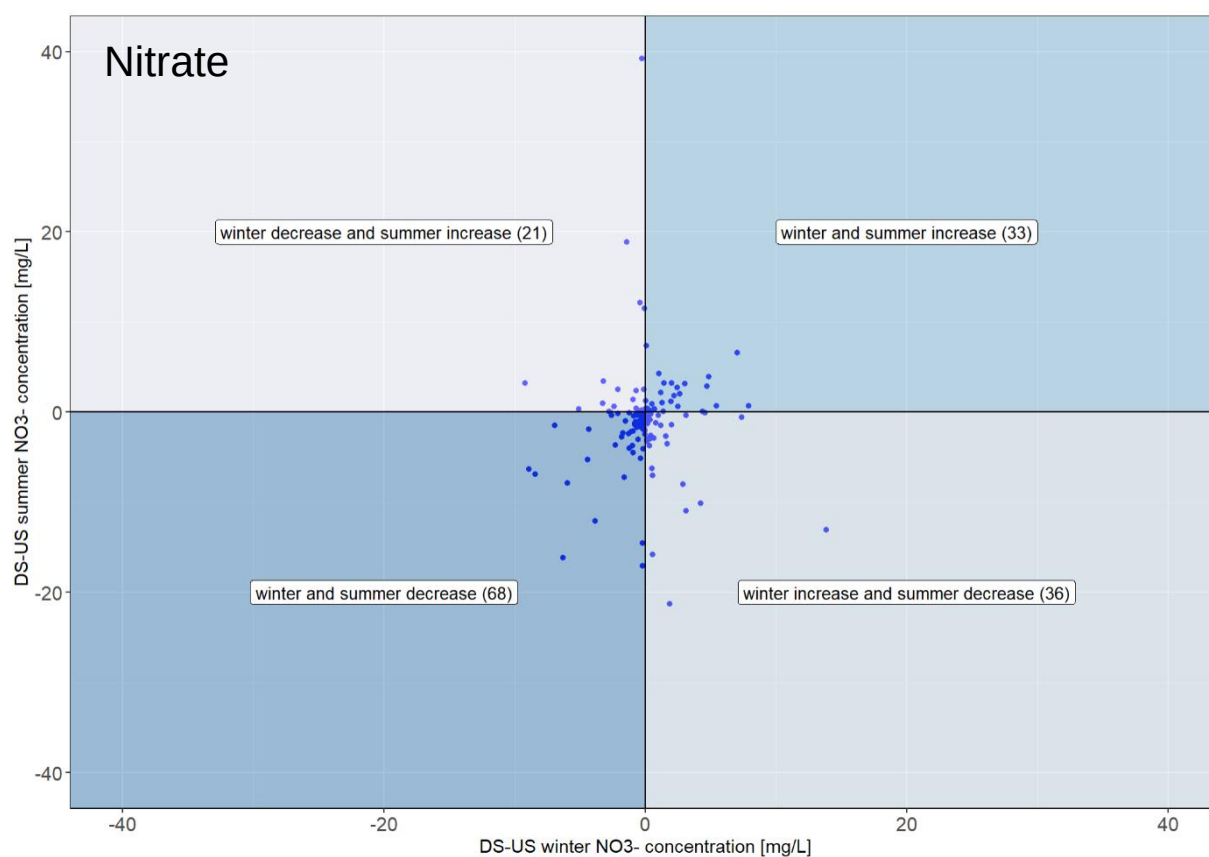
Hans Bärtschi

Teilprozessleiter TLM Produktionsgruppe A

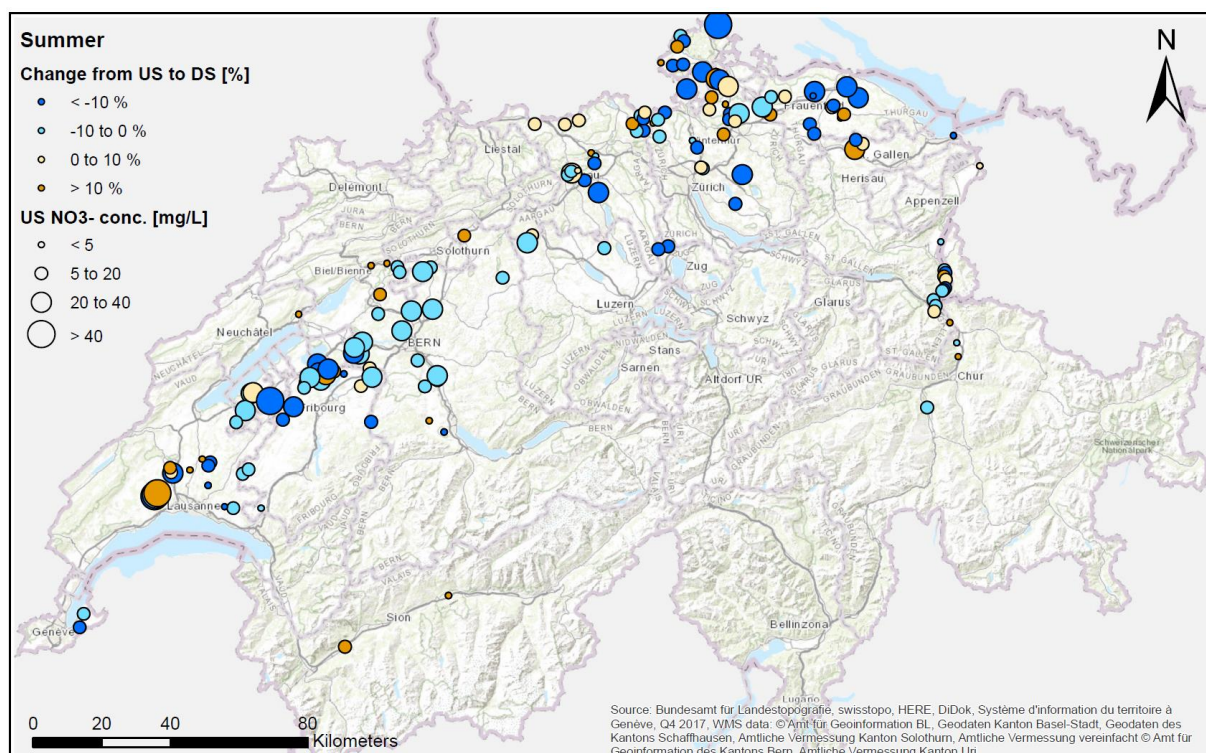
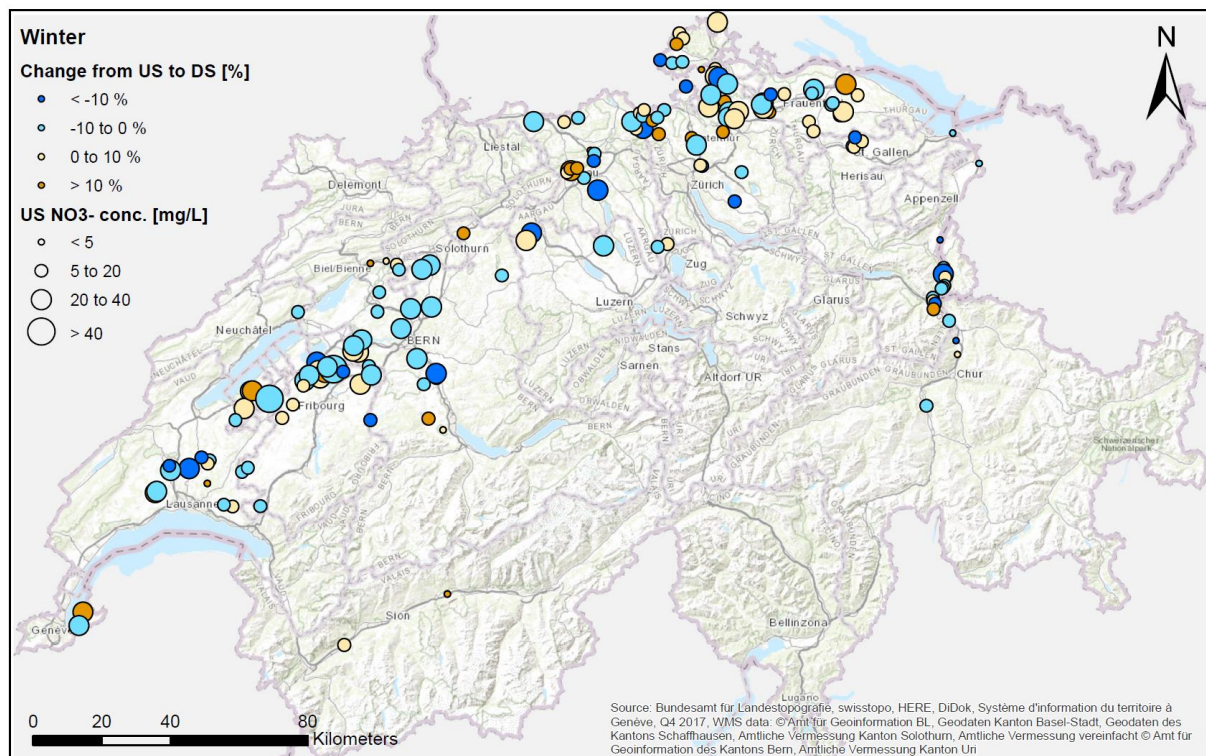
Eidgenössisches Departement für Verteidigung Bevölkerungsschutz und Sport  
Bundesamt für Landestopografie swisstopo  
Bereich Topografie

Seftigenstrasse 264, CH - 3084 Wabern  
+41 58 469 03 23 (Tel. direkt)  
+41 58 469 01 11 (Tel. Loge)

<mailto:hans.baertschi@swisstopo.ch>  
[www.swisstopo.ch](http://www.swisstopo.ch)

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

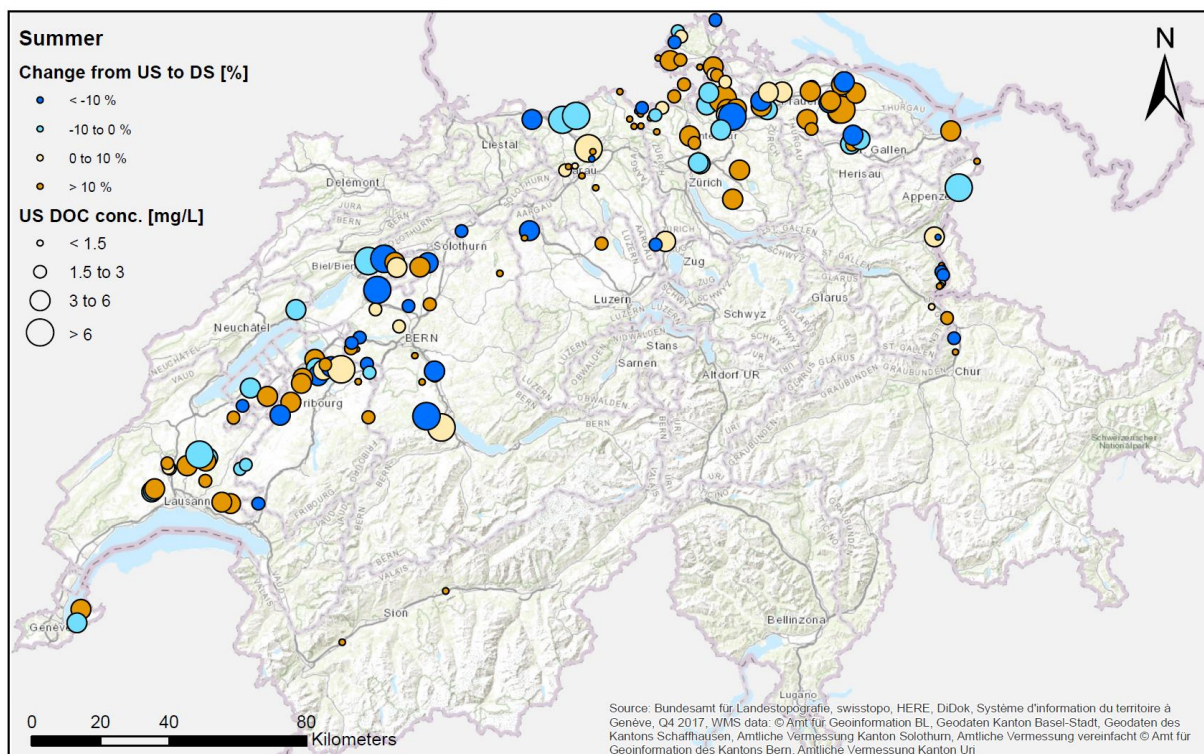
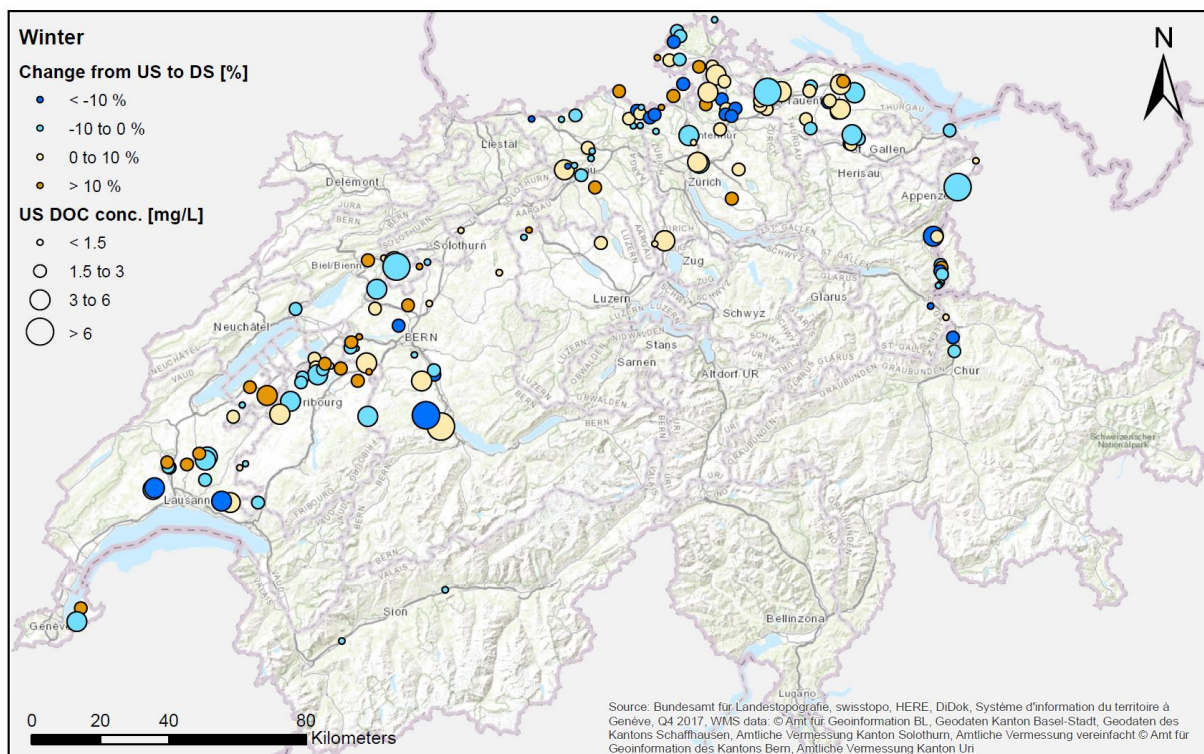
## Appendix I: Relative changes in nitrate concentrations



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

| Beaver reach | decrease: ↓<br>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 K: Relative changes in DOC concentrations



## Appendix L: 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 100). 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 99).

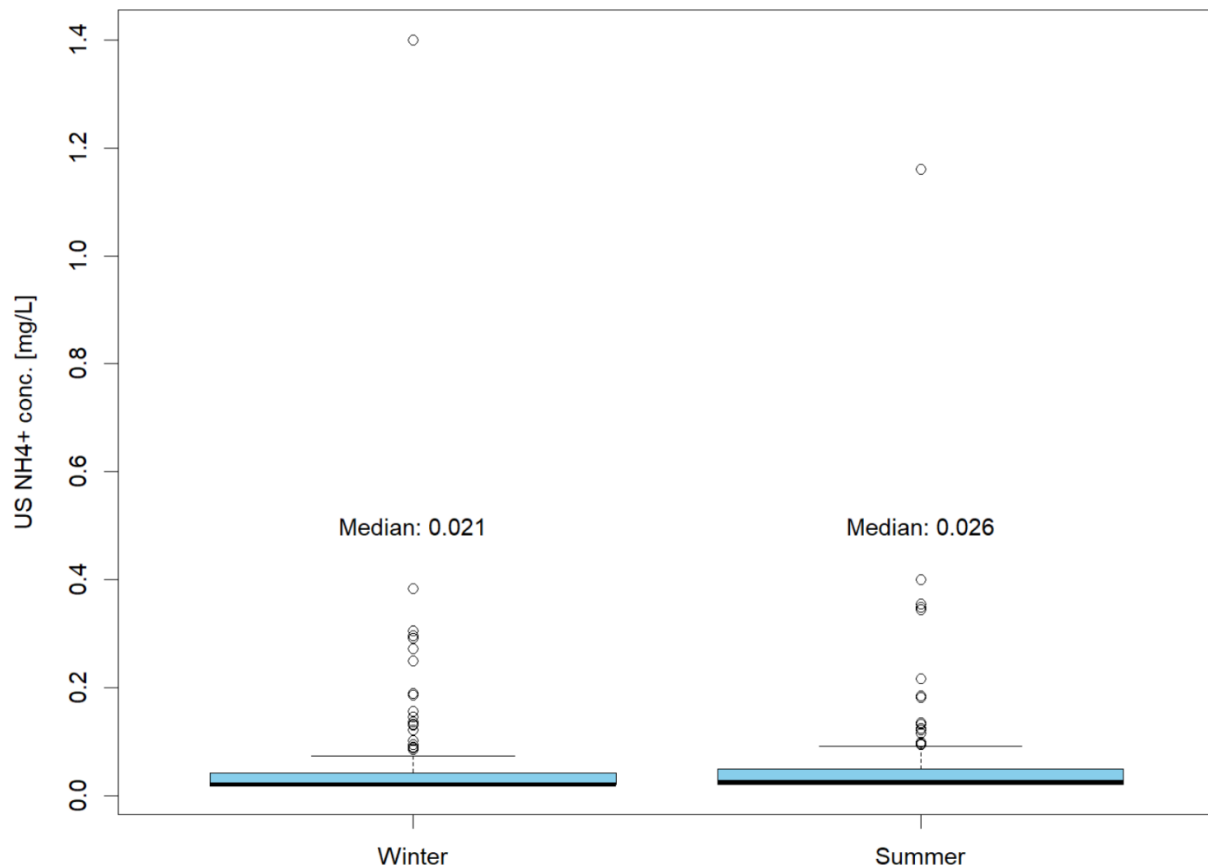


Figure 99: US ammonium concentrations in winter and summer.

In winter, a comparable number of beaver 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 100).

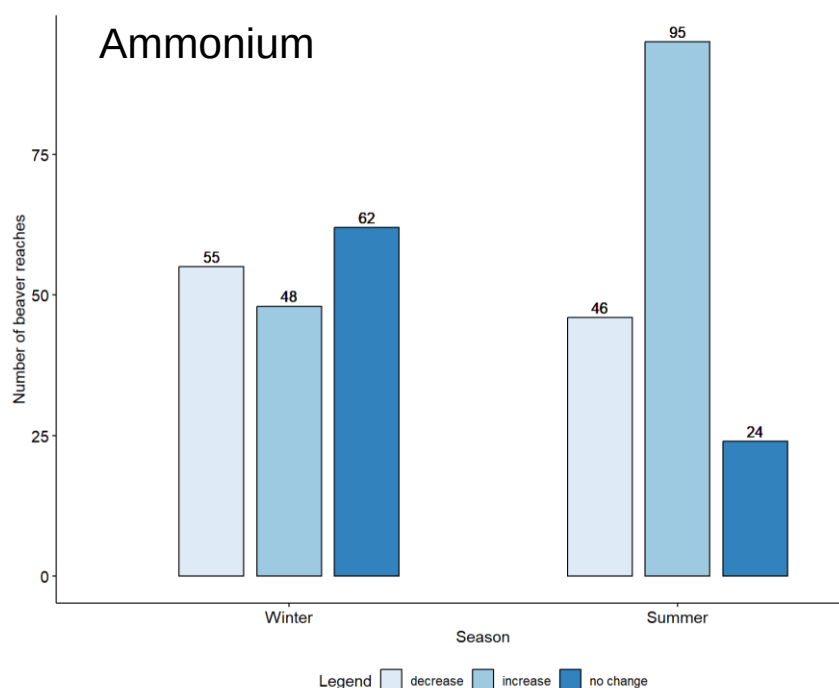


Figure 100: Change in ammonium concentrations within beaver systems. Decrease means that the DS  $\text{NH}_4^+$  concentration is lower.

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 101).

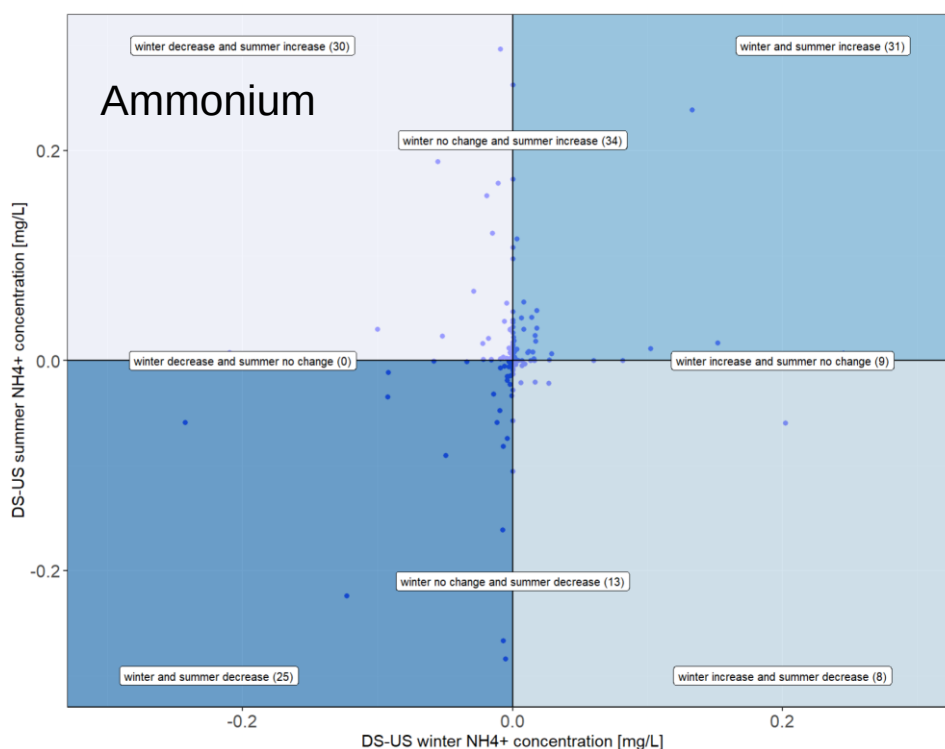


Figure 101: DS – US ammonium concentrations in winter and summer. For the sake of clarity, only differences of  $\pm 0.3$  mg/l are depicted in this graph. The outlier differences ( $> 0.3$  mg/l) are presented in Table 25, with notably high differences in beaver reach Nr. 67.

Out of all the beaver 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 25).

Table 25: Ammonium concentrations differences > 0.3 mg/l.

| Beaver reach | decrease: ↓<br>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                           |

Figure 102 and Figure 103 do not reveal any discernible spatial pattern in terms of US ammonium concentrations and the changes in ammonium concentrations within the beaver systems.

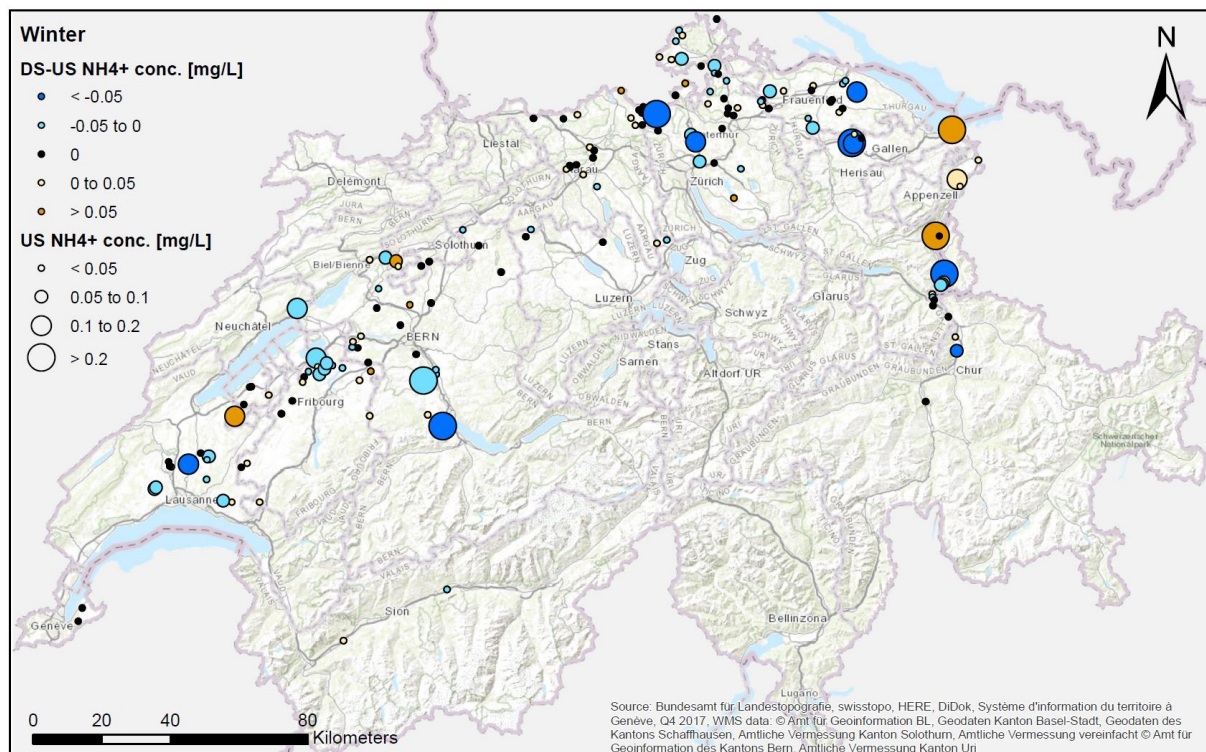


Figure 102: US ammonium concentration and concentration changes in winter. Negative values indicate lower DS concentrations. Background map: (swisstopo, 2021).

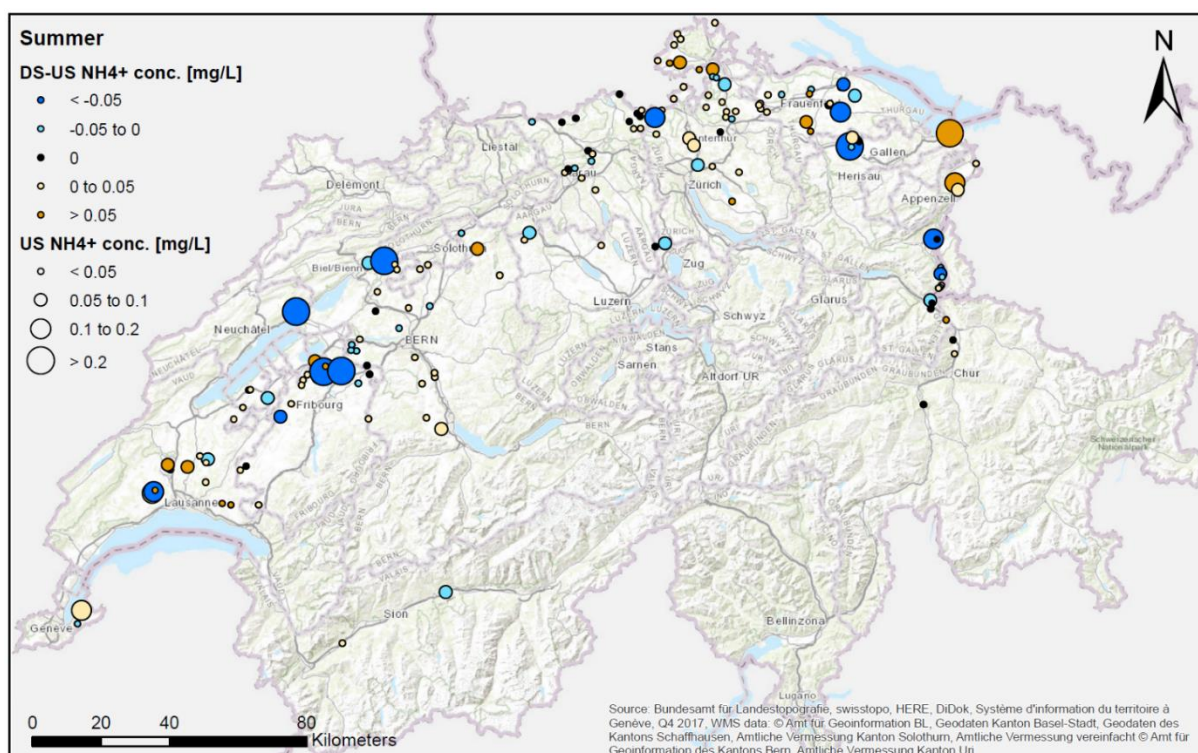
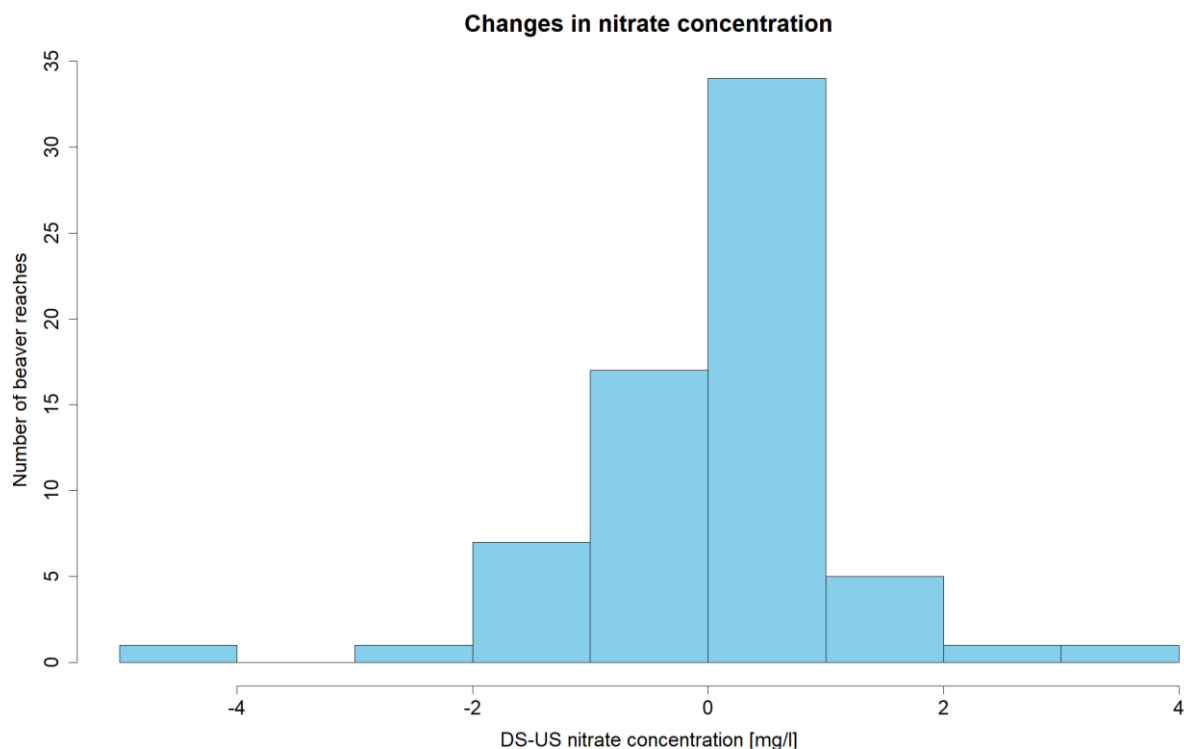


Figure 103: US ammonium concentration and concentration changes in summer. Negative values indicate lower DS concentrations. Background map: (swisstopo, 2021).

### Appendix M: Concentrations in beaver reaches only sampled in one season

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

For the 72 beaver reaches sampled only in winter, the median nitrate concentration shows an increase within the beaver system of 0.04 mg/l (Figure 104). This is in contrast to the findings for the beaver reaches sampled in both seasons, where the median nitrate concentration is 0.08 mg/l lower downstream (chapter: 5.2.1).



*Figure 104: Nitrate changes from US to DS. Positive values represent an increase in nitrate concentration. This plot presents the changes in 68 beaver reaches. In four beaver 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 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 105).

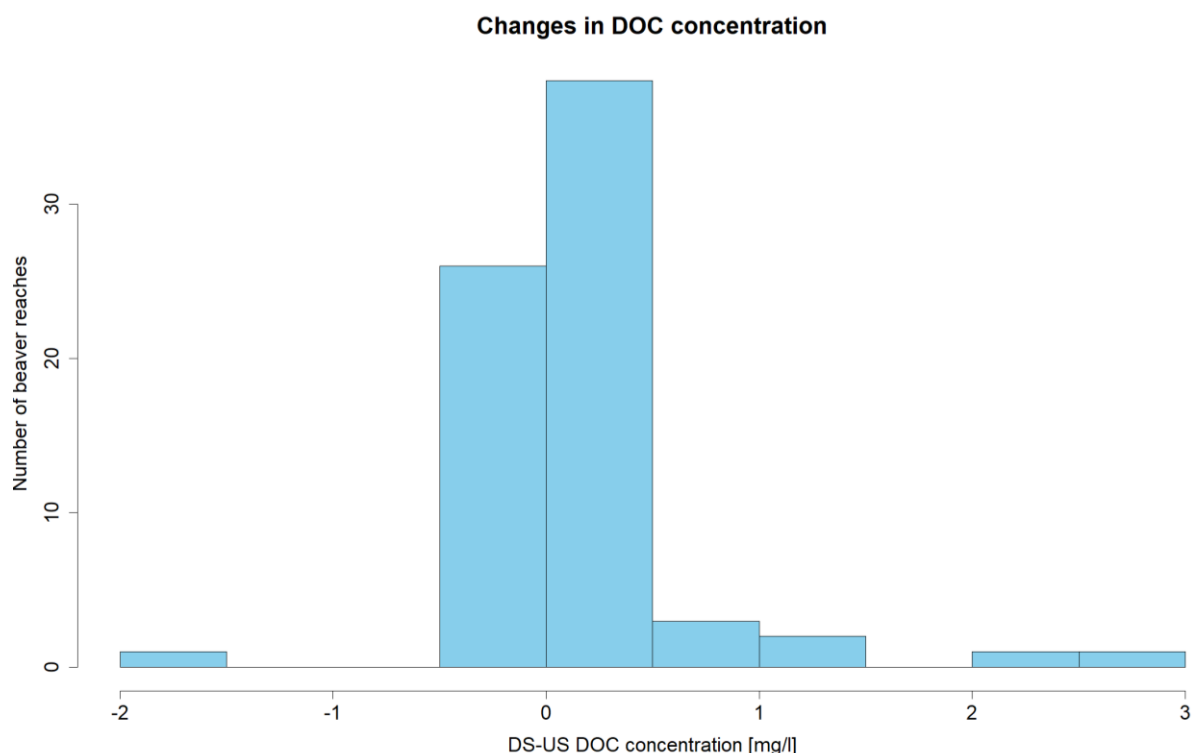


Figure 105: DOC changes from US to DS. Positive values represent an increase in DOC concentration. This plot presents the changes in 72 beaver reaches.

The US and DS water quality parameters from the 7 beaver reaches only samples in summer were compared (Nitrate and DOC (Figure 106), other parameters (Figure 107)). 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 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 reaches (Figure 106). Regarding the other water quality parameters, no clear trends in increasing or decreasing concentrations were observed for the seven beaver reaches (Figure 107).

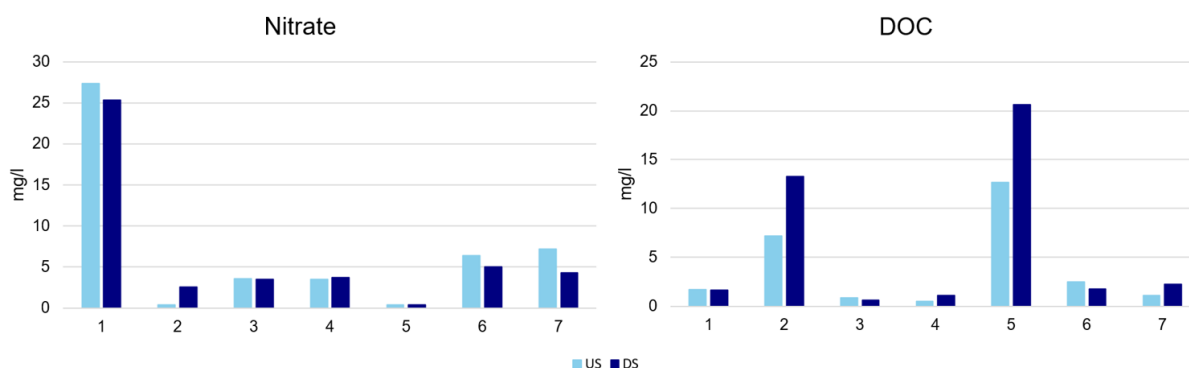


Figure 106: Comparison of the US and DS nitrate and DOC concentrations from the seven beaver reaches only sampled in summer.

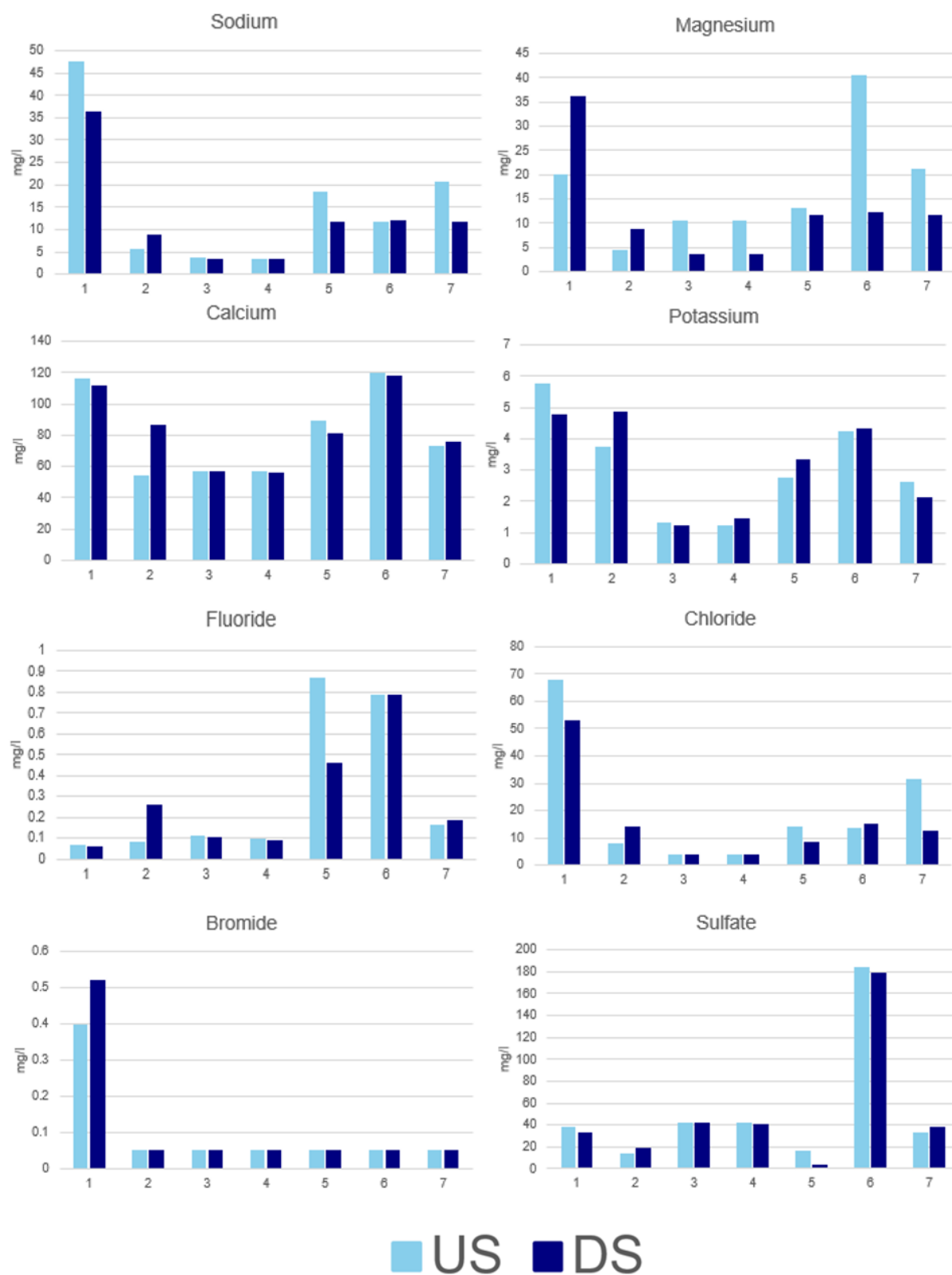
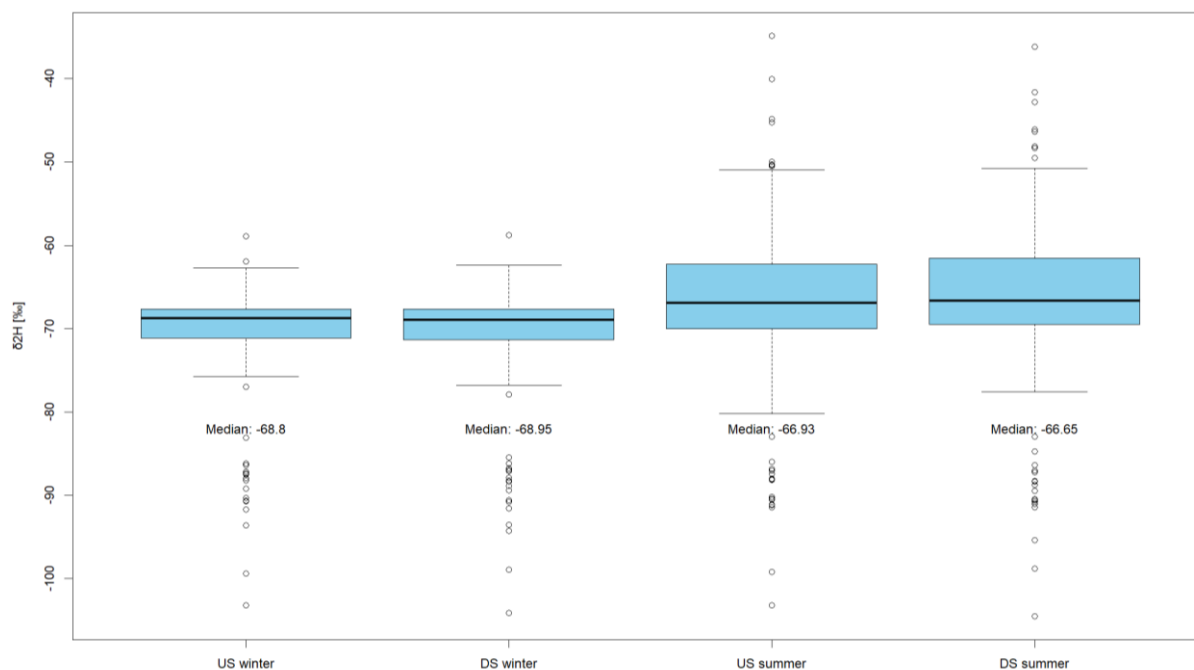
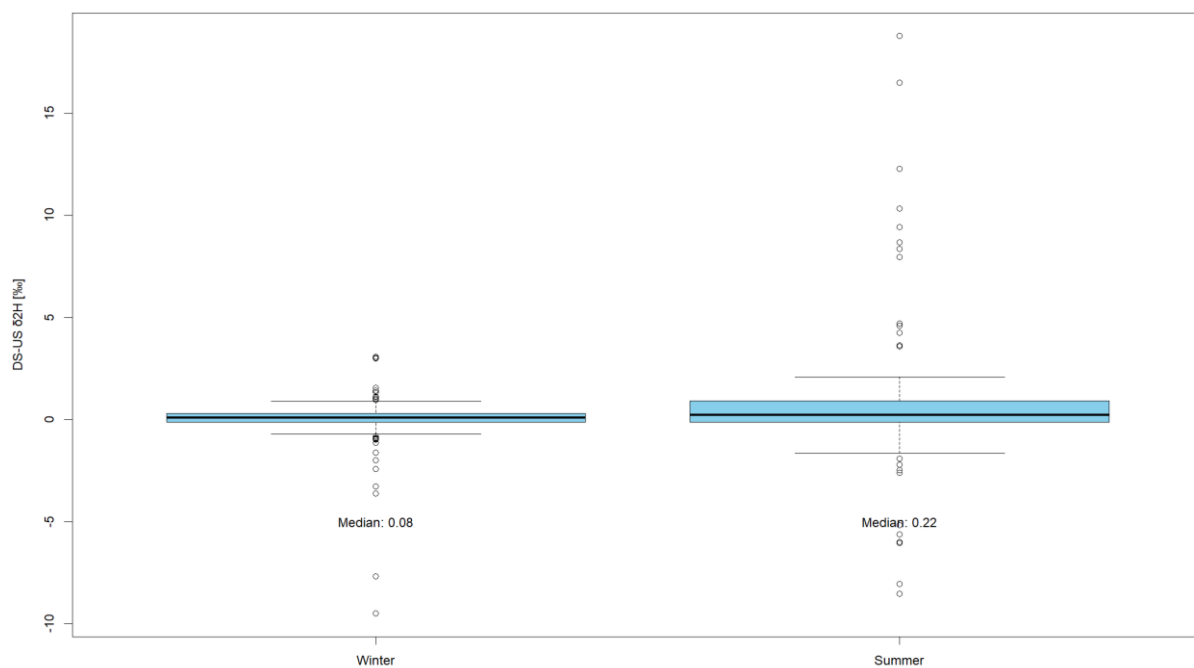
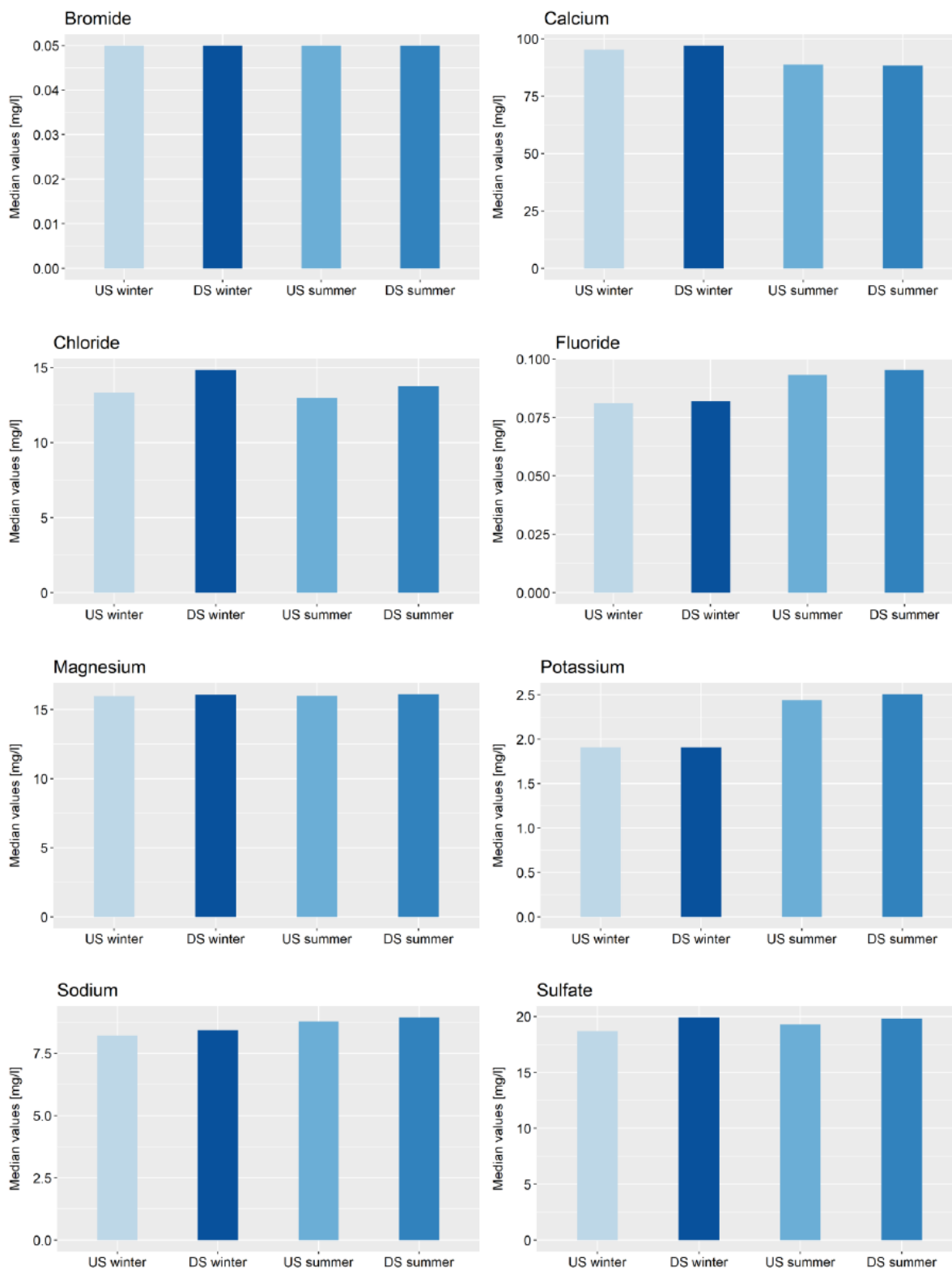


Figure 107: Comparison of the US and DS concentrations (Bromide etc.) from the seven beaver reaches only sampled in summer.

## Appendix N: Results stable isotope analysis

Figure 108:  $\delta^2\text{H}$  composition US and DS in winter and summer.Figure 109: DS minus US  $\delta^2\text{H}$  compositions in winter and summer.

**Appendix O: Median water quality concentrations**

## Appendix P: Corr. US concentrations and catchment characteristics

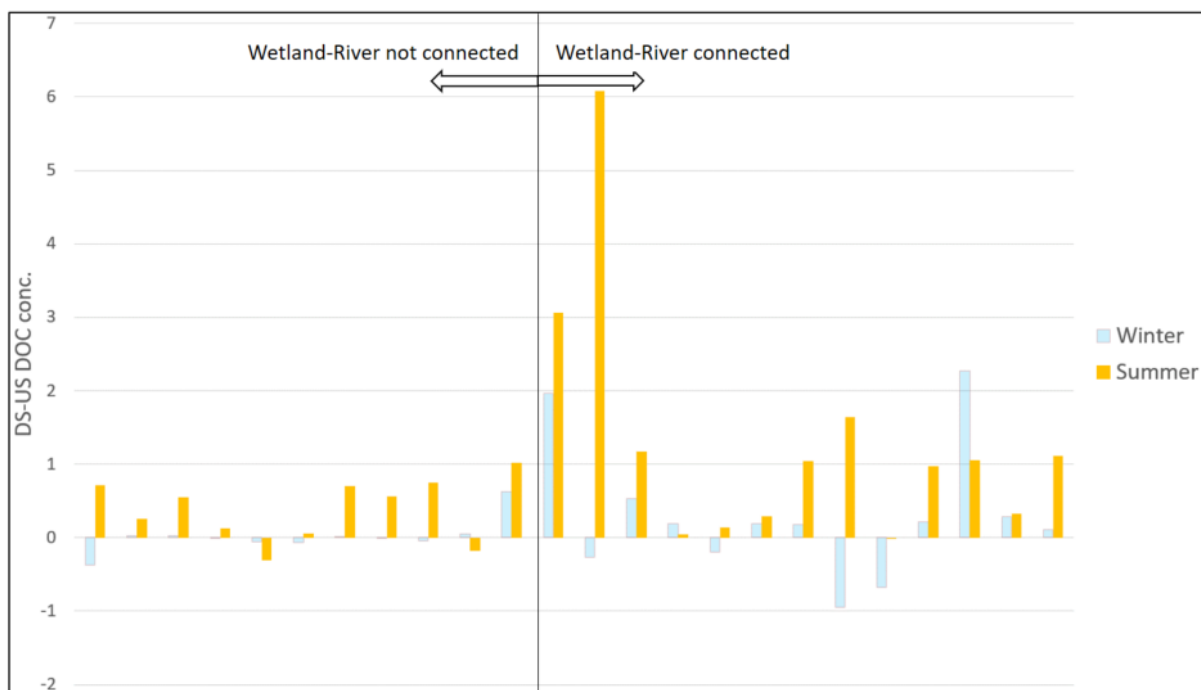
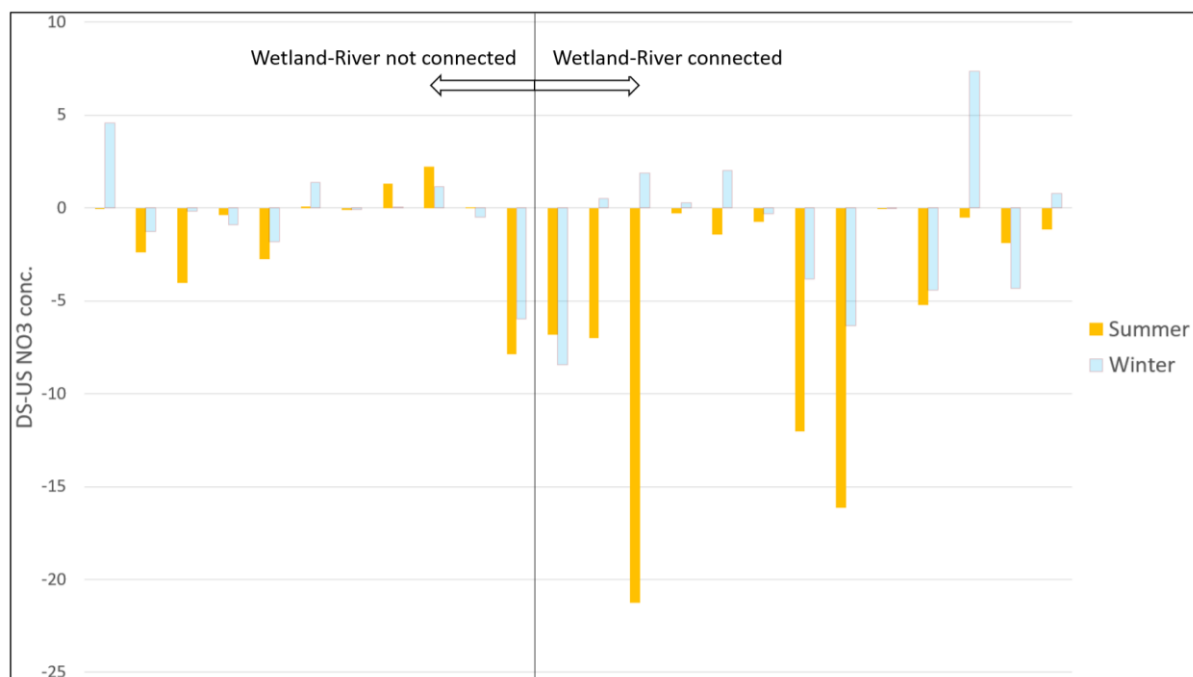
| Variable                            | Median<br>Winter Summer | Unit            | Observations | NO3 winter US<br>Median: 16.24 mg/l<br>Correlation P-value | NO3 summer US<br>Median: 12.70 mg/l<br>Correlation P-value | DOC winter US<br>Median: 1.95 mg/l<br>Correlation P-value | DOC summer US<br>Median: 2.66 mg/l<br>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                                                     | 0.21                                                      |
| Discharge summer                    | 10.12                   | l/s             | 157          |                                                            | 0.27                                                       |                                                           | 1.00                                                      |
| Catchment area                      | 4.24                    | km <sup>2</sup> | 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 winter US                       | 12.70                   | mg/l            | 163          | 0.61                                                       | < 0.05                                                     |                                                           | 0.94                                                      |
| NO3 winter DS                       | 16.42                   | mg/l            | 163          | 0.96                                                       | < 0.05                                                     |                                                           |                                                           |
| NH4 summer US                       | 0.03                    | mg/l            | 165          |                                                            |                                                            |                                                           | 0.20                                                      |
| DOC summer US                       | 2.66                    | mg/l            | 163          |                                                            | 0.83                                                       | 0.53                                                      | < 0.05                                                    |
| NO3 summer DS                       | 12.05                   | mg/l            | 165          |                                                            | 0.92                                                       | < 0.05                                                    |                                                           |
| DOC winter DS                       | 1.97                    | mg/l            | 163          |                                                            |                                                            | 0.87                                                      | < 0.05                                                    |
| DOC summer DS                       | 3.18                    | mg/l            | 165          |                                                            |                                                            |                                                           |                                                           |
| US wetland (abs.)                   | 0.00                    | m <sup>2</sup>  | 163          | 0.04                                                       | 0.59                                                       | 0.22                                                      | 0.63                                                      |
| US wetland (%)                      | 0.00                    | %               | 163          | -0.20                                                      | < 0.05                                                     | < 0.05                                                    | < 0.05                                                    |
| US Settlement (abs.)                | 46.00                   | hectares        | 163          | 0.10                                                       | 0.19                                                       | 0.34                                                      | 0.25                                                      |
| US Settlement (%)                   | 9.95                    | %               | 163          | -0.11                                                      | 0.15                                                       | 0.04                                                      | 0.05                                                      |
| 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                                                     | -0.20                                                     |
| US non productive areas (%)         | 0.37                    | %               | 163          | -0.27                                                      | < 0.05                                                     | 0.10                                                      | 0.07                                                      |
| dD US                               | -68.77                  | ‰               | 146 / 154    | 0.32                                                       | < 0.05                                                     | 0.21                                                      | 0.12                                                      |
| d18O US                             | -9.76                   | ‰               | 146 / 154    | 0.32                                                       | < 0.05                                                     | < 0.05                                                    | 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                                                      | 0.72                                                      |
| 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                                                      | 0.62                                                       | 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                                                       | 0.95                                                       | -0.02                                                     | 0.17                                                      |
| Sulfate US                          | 18.76                   | mg/l            | 163 / 165    | -0.12                                                      | 0.28                                                       | -0.04                                                     | 0.10                                                      |
|                                     |                         |                 |              |                                                            |                                                            | -0.09                                                     | -0.09                                                     |
|                                     |                         |                 |              |                                                            |                                                            | 0.25                                                      | 0.27                                                      |

## Appendix Q: Corr. concentration changes and beaver reach characteristics

| Variable                  | Winter | Median | Summer | Unit           | Observations | NO3 change winter<br>Median: -0.07 mg/l<br>Correlation P-value | NO3 change summer<br>Median: -0.27 mg/l<br>Correlation P-value | DOC change winter<br>Median: 0 mg/l<br>Correlation P-value | DOC change summer<br>Median: 0.13 mg/l<br>Correlation P-value |
|---------------------------|--------|--------|--------|----------------|--------------|----------------------------------------------------------------|----------------------------------------------------------------|------------------------------------------------------------|---------------------------------------------------------------|
| Distance                  | 336.63 |        |        | mg/l           | 162-165      | 0.01                                                           | 0.89                                                           | 0.07                                                       | 0.11                                                          |
| Slope                     | 0.598  |        |        | %              | 162-165      | 0.08                                                           | 0.30                                                           | -0.04                                                      | -0.15                                                         |
| Volume                    | 379.7  |        |        | m <sup>3</sup> | 162-165      | 0.11                                                           | 0.15                                                           | 0.05                                                       | 0.22                                                          |
| Residence time winter     | 2.5    |        |        | h              | 153 / 152    | -0.03                                                          | 0.76                                                           | 0.07                                                       | 0.39                                                          |
| Residence time summer     |        | 10.3   |        | h              | 157 / 156    |                                                                | 0.95                                                           |                                                            | 0.04                                                          |
| Discharge winter          | 38.74  |        |        | l/s            | 153 / 152    | 0.06                                                           | 0.48                                                           | -0.07                                                      | 0.40                                                          |
| Discharge summer          |        | 10.12  |        | l/s            | 157 / 156    |                                                                | 0.10                                                           |                                                            | -0.08                                                         |
| Dam age                   |        | 2022   |        | year           | 162-165      | -0.12                                                          | 0.11                                                           | -0.10                                                      | 0.21                                                          |
| Number of dams            |        | 2      |        | count          | 162-165      | -0.13                                                          | 0.09                                                           | -0.12                                                      | 0.08                                                          |
| NO3 winter US             | 16.24  |        |        | mg/l           | 163          | -0.15                                                          | < 0.05                                                         |                                                            | 0.09                                                          |
| NO3 summer US             |        | 12.7   |        | mg/l           | 165          |                                                                | -0.23                                                          |                                                            | 0.26                                                          |
| DOC winter US             | 1.954  |        |        | mg/l           | 162          |                                                                |                                                                | -0.21                                                      | < 0.05                                                        |
| DOC summer US             |        | 2.614  |        | mg/l           | 164          |                                                                | 0.60                                                           | -0.05                                                      | 0.55                                                          |
| NO3 winter change         | -0.07  |        |        | mg/l           | 163          |                                                                |                                                                |                                                            |                                                               |
| NO3 summer change         |        | -0.27  |        | mg/l           | 163 / 164    | 0.04                                                           | 0.60                                                           |                                                            |                                                               |
| DOC winter change         | 0      |        |        | mg/l           | 163          | -0.03                                                          | 0.74                                                           |                                                            | -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                                                          | 0.30                                                           | 0.17                                                       | < 0.05                                                        |
| NH4 summer change         |        | 0.002  |        | mg/l           | 165 / 164    |                                                                | -0.05                                                          |                                                            | 0.35                                                          |
| Temperature summer US     |        | 17.2   |        | °C             | 158          |                                                                | -0.01                                                          |                                                            | 0.10                                                          |
| Temperature summer change |        | 0.2    |        | °C             | 158          |                                                                | -0.06                                                          |                                                            | 0.20                                                          |
| dD change                 | 0.082  | 0.217  |        | %              | 144-150      | 0.06                                                           | 0.47                                                           | 0.38                                                       | < 0.05                                                        |
| d18O change               | 0.009  | 0.047  |        | %              | 144-150      | 0.04                                                           | 0.63                                                           | 0.41                                                       | < 0.05                                                        |
| d17O change               | 0.004  | 0.018  |        | %              | 144-150      | 0.06                                                           | 0.48                                                           | 0.28                                                       | < 0.05                                                        |
| Sodium change             | 0.016  | -0.001 |        | mg/l           | 162-165      | -0.26                                                          | < 0.05                                                         | -0.09                                                      | 0.04                                                          |
| Magnesium change          | -0.007 | 0.014  |        | mg/l           | 162-165      | 0.03                                                           | 0.69                                                           | -0.12                                                      | -0.22                                                         |
| Calcium change            | 0.085  | -0.065 |        | mg/l           | 162-165      | 0.04                                                           | 0.64                                                           | -0.10                                                      | -0.07                                                         |
| Potassium change          | -0.001 | 0.014  |        | mg/l           | 162-165      | -0.23                                                          | < 0.05                                                         | 0.12                                                       | 0.39                                                          |
| Fluoride change           | 0      | -0.05  |        | mg/l           | 162-165      | -0.06                                                          | 0.42                                                           | -0.07                                                      | 0.26                                                          |
| Chloride change           | 0.014  | 0.008  |        | mg/l           | 162-165      | -0.13                                                          | 0.10                                                           | -0.05                                                      | 0.06                                                          |
| Bromide change            | 0      | 0      |        | mg/l           | 162-165      | -0.06                                                          | 0.49                                                           | -0.02                                                      | -0.03                                                         |
| Sulfate change            | 0.021  | -0.069 |        | mg/l           | 162-165      | -0.05                                                          | 0.49                                                           | -0.16                                                      | 0.03                                                          |

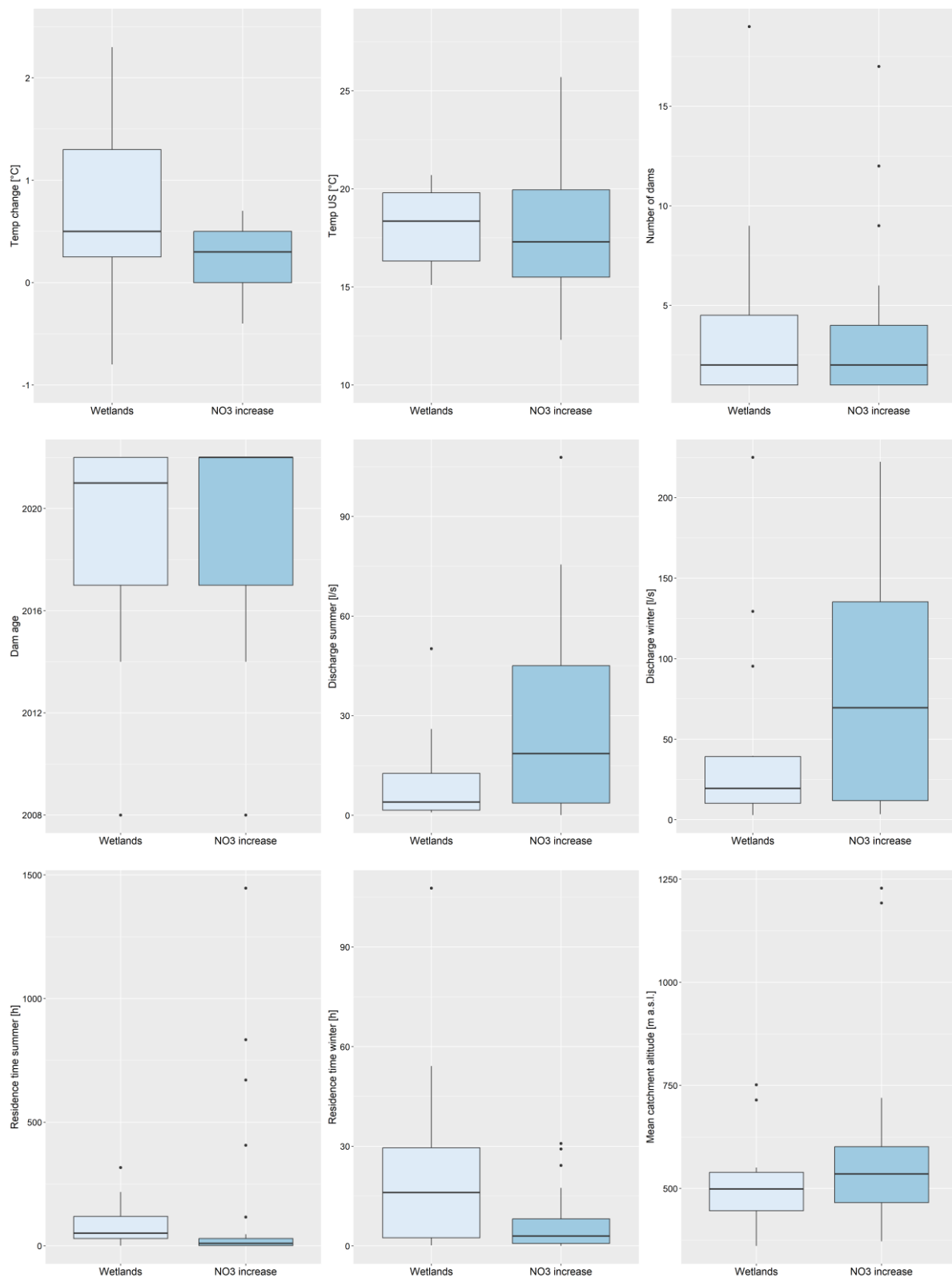
## Appendix R: Corr. with land use in buffer polygon

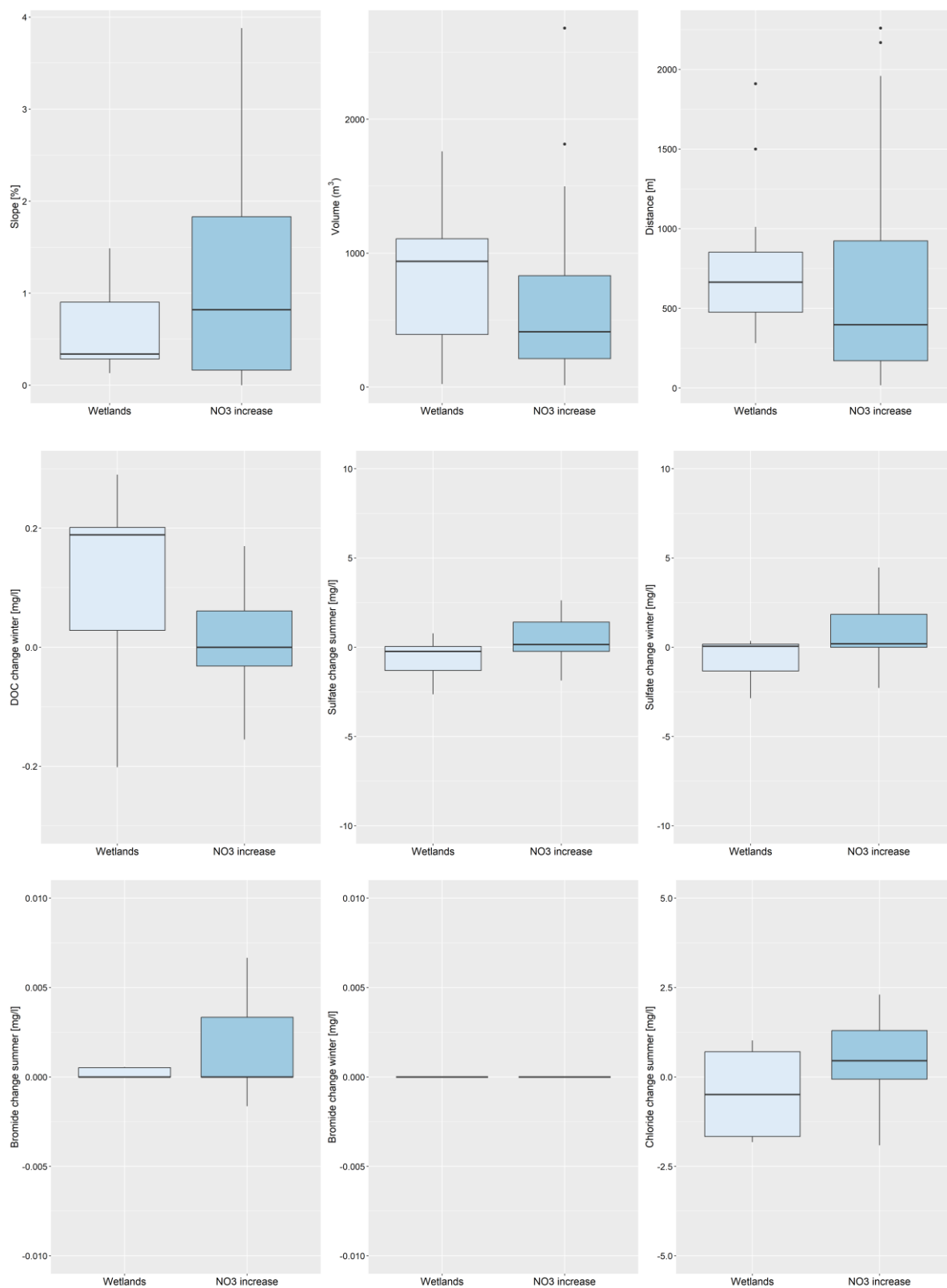
| Variable                            | Median | Unit           | Observations | NO3 change winter<br>Median: -0.07 mg/l |         | NO3 change summer<br>Median: -0.27 mg/l |         | DOC change winter<br>Median: 0 mg/l |         | DOC change summer<br>Median: 0.13 mg/l |         |
|-------------------------------------|--------|----------------|--------------|-----------------------------------------|---------|-----------------------------------------|---------|-------------------------------------|---------|----------------------------------------|---------|
|                                     |        |                |              | Correlation                             | P-value | Correlation                             | P-value | Correlation                         | P-value | Correlation                            | P-value |
| Stagnant water (buffer 50 m) (abs.) | 0      | m <sup>2</sup> | 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      | m <sup>2</sup> | 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      | m <sup>2</sup> | 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      | m <sup>2</sup> | 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   | m <sup>2</sup> | 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   | m <sup>2</sup> | 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   | m <sup>2</sup> | 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   | m <sup>2</sup> | 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      | m <sup>2</sup> | 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      | m <sup>2</sup> | 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      | m <sup>2</sup> | 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      | m <sup>2</sup> | 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    | m <sup>2</sup> | 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    | m <sup>2</sup> | 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     | m <sup>2</sup> | 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     | m <sup>2</sup> | 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  | m <sup>2</sup> | 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   | m <sup>2</sup> | 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   | m <sup>2</sup> | 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    | m <sup>2</sup> | 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    |

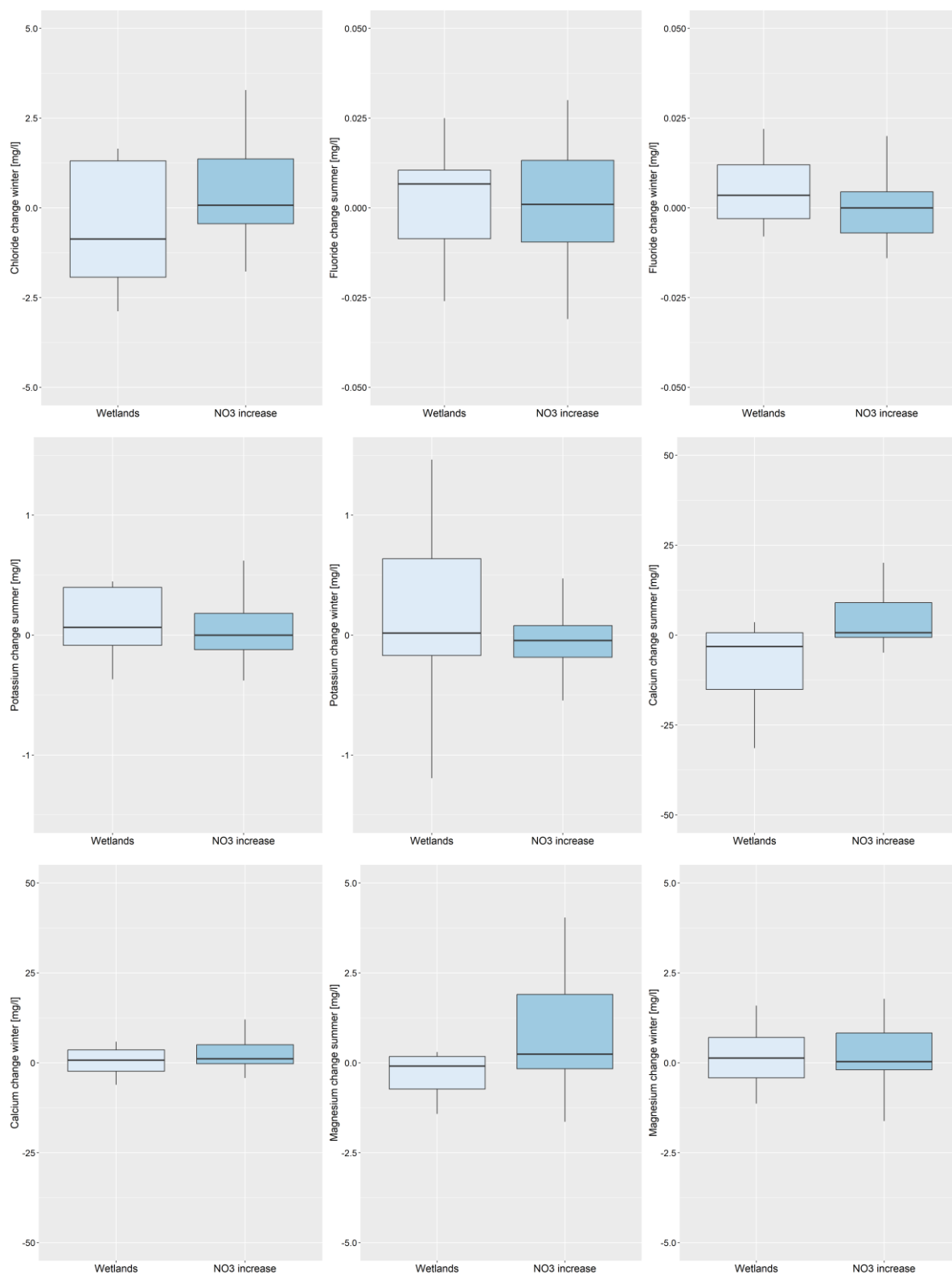
**Appendix S: Nitrate and DOC concentration changes for wetlands**

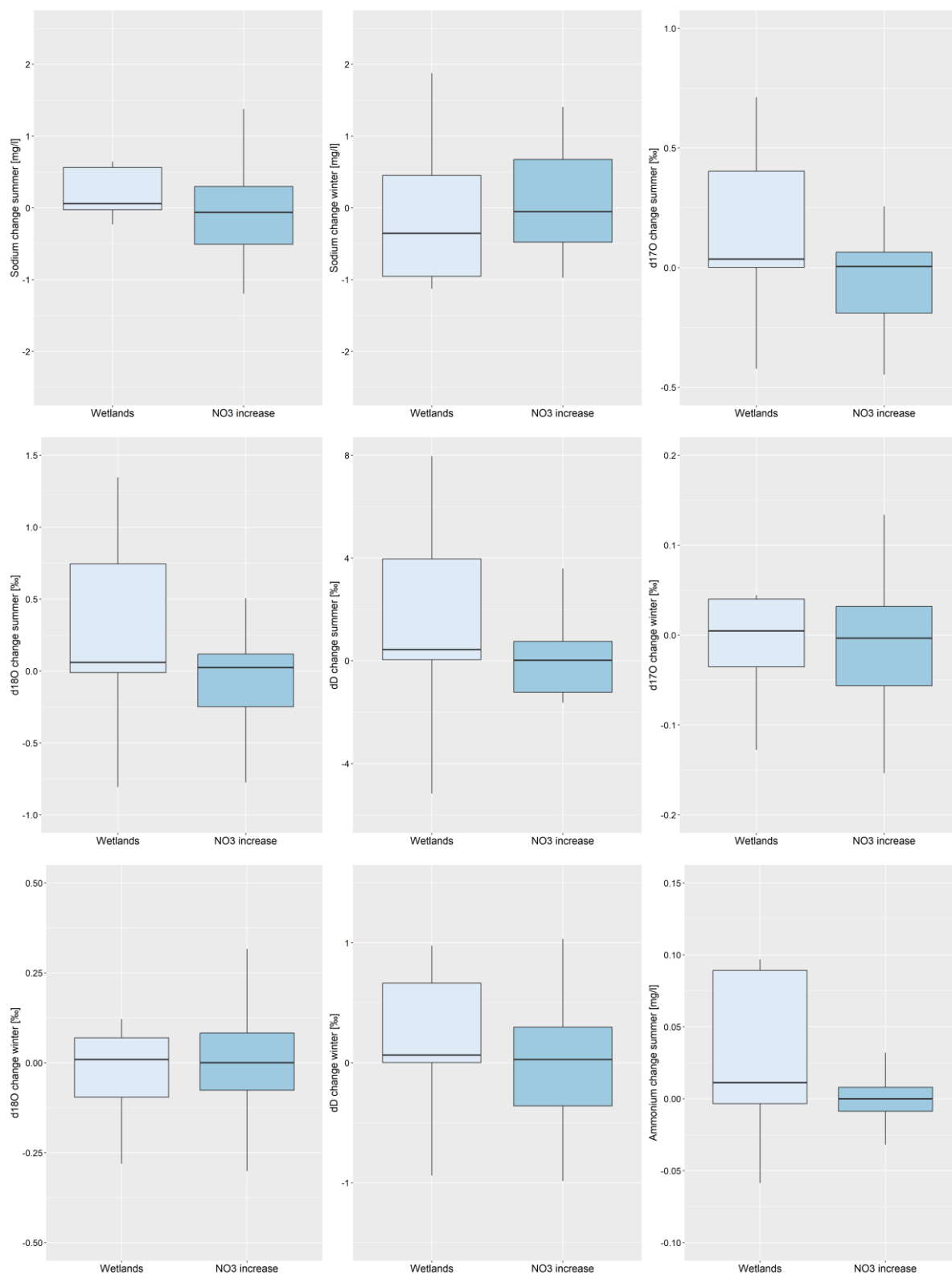
## Appendix T: 14 wetland beaver reaches

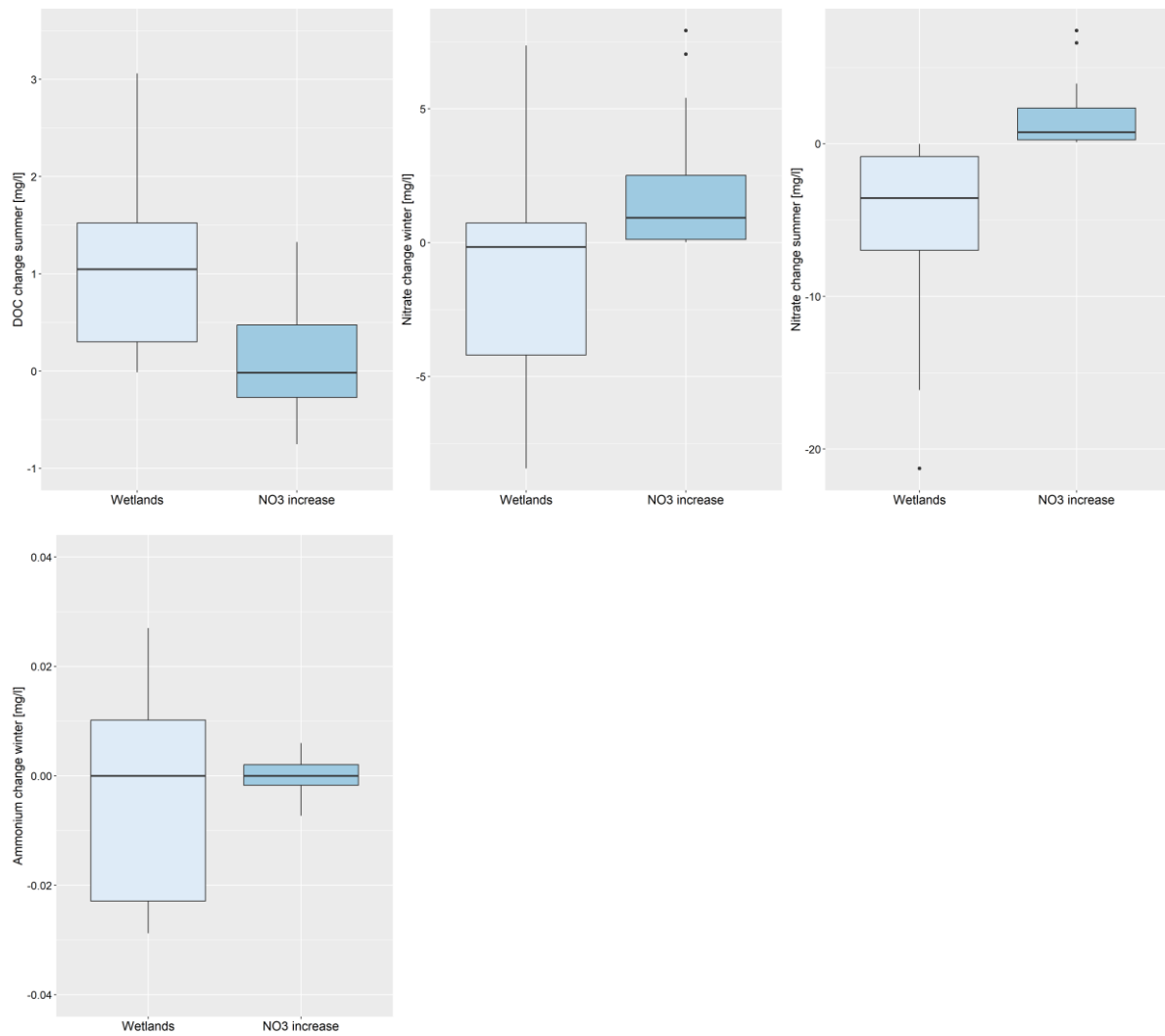
| Beaver reach | Distance [m] | Wetlands [m <sup>2</sup> ] | X_Coord_US | Y_Coord_US | X_Coord_DS | Y_Coord_DS | Created by beavers damming activity                    | Nitrate winter change [mg/l] | Nitrate summer change [mg/l] | DOC winter change [mg/l] | DOC summer change [mg/l] |
|--------------|--------------|----------------------------|------------|------------|------------|------------|--------------------------------------------------------|------------------------------|------------------------------|--------------------------|--------------------------|
| 19           | 606          | 14262                      | 2695582    | 1241577    | 2695945    | 1242032    | No                                                     | -8.43                        | -6.83                        | 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 U: Comparison wetland vs. nitrate source beaver reaches**









## Appendix V: Beaver reach Nr. 67

Table 26: Water quality parameters in beaver reach Nr. 67 compared to the median concentrations in all the other beaver reaches.

| Winter US concentrations [mg/l] |        |           |         |           |          |          |         |         |         |       |          |
|---------------------------------|--------|-----------|---------|-----------|----------|----------|---------|---------|---------|-------|----------|
| Beaver reach 67                 | Sodium | Magnesium | Calcium | Potassium | Fluoride | Chloride | Bromide | Nitrate | Sulfate | DOC   | Ammonium |
| All other                       | 5.22   | 8.50      | 134.70  | 2.21      | 0.10     | 9.03     | 0.05    | 1.35    | 50.38   | 9.91  | 0.19     |
|                                 | 8.20   | 15.96     | 95.33   | 1.91      | 0.08     | 13.36    | 0.05    | 16.24   | 18.67   | 1.95  | 0.02     |
| Winter DS concentrations [mg/l] |        |           |         |           |          |          |         |         |         |       |          |
| Beaver reach 67                 | Sodium | Magnesium | Calcium | Potassium | Fluoride | Chloride | Bromide | Nitrate | Sulfate | DOC   | Ammonium |
| All other                       | 4.62   | 7.62      | 118.90  | 2.55      | 0.12     | 7.88     | 0.05    | 1.03    | 44.27   | 24.31 | 0.21     |
|                                 | 8.43   | 16.08     | 97.07   | 1.91      | 0.08     | 14.86    | 0.05    | 16.42   | 19.94   | 1.97  | 0.02     |
| Summer US concentrations [mg/l] |        |           |         |           |          |          |         |         |         |       |          |
| Beaver reach 67                 | Sodium | Magnesium | Calcium | Potassium | Fluoride | Chloride | Bromide | Nitrate | Sulfate | DOC   | Ammonium |
| All other                       | 6.63   | 8.83      | 145.88  | 5.62      | 0.14     | 10.35    | 0.05    | 5.74    | 52.55   | 10.13 | 0.12     |
|                                 | 8.78   | 15.97     | 88.72   | 2.44      | 0.09     | 12.99    | 0.05    | 12.70   | 19.28   | 2.66  | 0.03     |
| Summer DS concentrations [mg/l] |        |           |         |           |          |          |         |         |         |       |          |
| Beaver reach 67                 | Sodium | Magnesium | Calcium | Potassium | Fluoride | Chloride | Bromide | Nitrate | Sulfate | DOC   | Ammonium |
| All other                       | 6.40   | 7.40      | 103.40  | 4.19      | 0.27     | 8.59     | 0.05    | 0.40    | 7.07    | 55.50 | 2.00     |
|                                 | 8.95   | 16.12     | 88.36   | 2.51      | 0.10     | 13.76    | 0.05    | 12.05   | 19.82   | 3.18  | 0.03     |

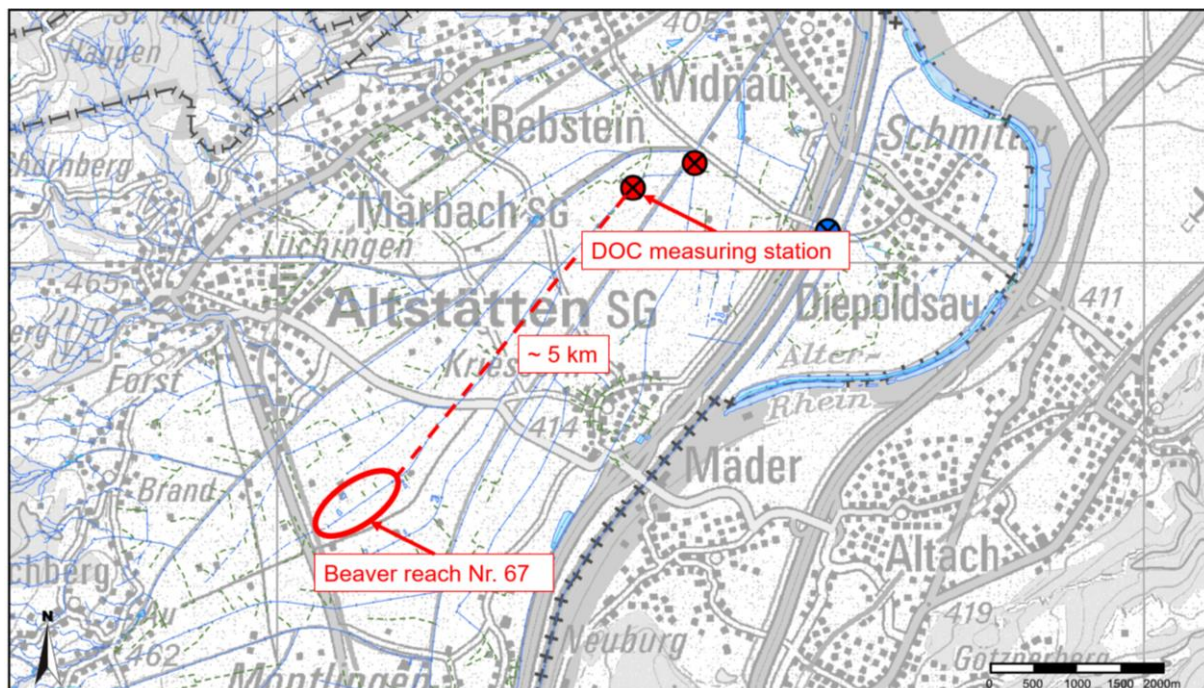


Figure 110: Beaver reach Nr 67 and DOC measuring station ~5 km downstream (Geoportal Kanton St. Gallen, 2023).

**Kanton St.Gallen**  
**Amt für Wasser und Energie**

**Mittlerer Seegraben (Balgacher Riet)**


|                                      |                     |                               |
|--------------------------------------|---------------------|-------------------------------|
| Gemeinde:                            | Balgach             | Landnutzung im Einzugsgebiet: |
| Messstelle:                          | OGB252              | Fläche total: 10 km²          |
| Meereshöhe:                          | 407 m.ü.M.          | Wald: —                       |
| Koordinaten:                         | 2764'109 / 1250'860 | Siedlung: —                   |
| Abflussregimetyp:                    | —                   | Landwirtschaft: —             |
| Abfluss (Q <sub>347</sub> ):         | —                   | Gewässer: —                   |
| Abwasseranteil am Q <sub>347</sub> : | 0. %                | Übriges: —                    |
| Natürlichkeitsgrad:                  | —                   |                               |

**Beurteilung der Wasser- und Gewässerqualität**

| Kenngrossen | Ammonium<br>(mg/L NH <sub>4</sub> -N) | Nitrit<br>(mg/L NO <sub>2</sub> -N) | Nitrat<br>(mg/L NO <sub>3</sub> -N) | Phosphat<br>(mg/L PO <sub>4</sub> -P) | Gesamtphosphor<br>(mg/L P) | DOC<br>(mg/L C) | Makrozoobenthos<br>(IBCH) | Kieselalgen<br>(DI-CH) |
|-------------|---------------------------------------|-------------------------------------|-------------------------------------|---------------------------------------|----------------------------|-----------------|---------------------------|------------------------|
| 2018 / 2019 | 1.291                                 | 0.049                               | 2.2                                 | 0.003                                 | 0.040                      | 13.9            |                           |                        |
| 2020 / 2021 | 1.352                                 | 0.045                               | 3.3                                 | 0.007                                 | 0.089                      | 18.0            | 5                         |                        |

**Beurteilungsklassen**

|             |          |     |               |                |          |
|-------------|----------|-----|---------------|----------------|----------|
| Zustand     | sehr gut | gut | mässig        | unbefriedigend | schlecht |
| Zielvorgabe | erfüllt  |     | nicht erfüllt |                |          |

 Weitere Details: [www.modul-stylen-konzept.ch](http://www.modul-stylen-konzept.ch)

 Detaillierte Informationen zu den Beurteilungskriterien Chemie und Biologie finden Sie auf unserer Homepage: [www.sg.ch/umwelt-natur/wasser/fluesse--baeche/gewaesserqualitaet/messnetz--messprogramm.html](http://www.sg.ch/umwelt-natur/wasser/fluesse--baeche/gewaesserqualitaet/messnetz--messprogramm.html)

Erstellt im August 2022

 Weitere Informationen: [www.sg.ch/umwelt-natur/wasser.html](http://www.sg.ch/umwelt-natur/wasser.html)

Figure 111: DOC measuring station from the office for water and energy, Canton St. Gallen (Amt für Wasser und Energie, 2022).

## **Declaration of consent**

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

Name/First Name: Berger/Kaspar

Registration Number: 17-109-315

Study program: Geography Master Mono

Bachelor ☐ Master ☒ Dissertation ☐

Title of the thesis: Modification and spatial variation of riverine water quality due to beaver damming across Switzerland

Supervisor: Prof. Dr. Bettina Schaeffli  
Dr. Annegret Larsen

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

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

Bern / 30.05.2023

Place/Date

Signature

