Rapport de stage individuel

4ème année

Wetlands rewetting and consequences on nitrogen cycle

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1- Host structure

Aarhus university was founded in 1928 and is now a well-known public research university. It counts about 38 000 students and 26 departments of research. This large number of departments allow the university to cover all major fields of research. The University is ranked 78 in the world, 13 Europe and 2 in Denmark according to Shanghai ranking in 2023.

Among them, the department of Ecoscience, where this internship took place, is counting about 270 employees and 170 of them are in Aarhus. It is divided into four areas: Terrestrial ecosystems, Freshwater ecosystems, Marine ecosystems and the Arctic.

Artic area: the focus is on the study of Arctic nature and the environment, particularly in Greenland, where knowledge transfer is facilitated through collaboration and consultancy with Greenland's self-government, including the Greenland Institute of Natural Resources. The geographical focus spans across trophic levels, from microbes to plants to animals and birds, encompassing marine, fresh, and terrestrial ecosystems at individual, population, and ecosystem levels.

Marine ecology area: the structure and function of marine ecosystems across different systems, from the coastal zone to the open marine areas, are the focus of the work carried out. The distinction between changes caused by natural variations and those caused by human activity is a special emphasis. Tools and methods are developed to assess the state of the marine environment, analyse the factors affecting ocean dynamics and health.

Terrestrial ecology area: the research conducted contributes to the development of strategies for green transition and sustainable production in agriculture and forestry, including a focus on nature-based solutions. Tools for effective and cost-efficient nature conservation are developed, and methods for resolving conflicts between nature and disturbances are explored, such as hunting and outdoor recreation. The institution hosts the topic centre 'Dry nature and species' under the national monitoring programme NOVANA and is responsible for methodological development, data analysis, and annual reporting on the state of nature.

Freshwater ecosystems area: at the highest international level, a unique research environment exists within aquatic freshwater biology and ecology. It encompasses streams, lakes, ponds, and the surrounding rural areas (catchments) that direct water to freshwater areas, including both natural and constructed wetlands. The research is characterized by the retrieval of unique long time series through field studies and the department's test facilities in Lemming, where controlled and manipulated conditions allow the study of pelagic abiotic and biotic dynamics.

The internship subject is part of Freshwater ecosystems and more specifically the wetland group. This group is a team of interdisciplinary scientists engaged in freshwater wetland research. The field of wetland research encompasses ecology, hydrology, biogeochemistry, and modeling. Several large Danish, Nordic, and European projects are being undertaken, with a focus on the restoration of riparian wetlands, the restoration of low-lying organic soils, and the development of mitigation measures to address nutrient loads from agricultural catchments (including constructed wetlands, integrated buffer zones, and saturated buffer zones).

2- Introduction

In the last 200 years, the area of wetlands in Denmark and across Europe has significantly decreased(Fluet-Chouinard et al., 2023). These areas have been drained with ditches and drains for agricultural purposes, resulting in dry meadows with low-water level (Hoffmann & Baattrup-Pedersen, 2007). Agricultural activities introduce a large amount of nutrients, particularly nitrogen (N) and phosphorus (P), into the environment. This excessive nutrient load leads to an increase of eutrophication and the proliferation of invasive species, that disrupts natural biodiversity.

To mitigate these significant nutrient inputs, several action plans have been implemented. At the European level, the Water Framework Directive mandates achieving a good ecological state of water bodies in all member states, initially by 2015 and currently by 2027. At the national level, Denmark established the Danish Action Plan on the Aquatic Environment II in 1998, aiming to restore between 60,000 and 100,000 hectares of wetlands over a 20-year period. This plan has successfully restored approximately 20,000 hectares of wetlands.(Audet et al., 2020)

Re-establishing wetlands through rewetting is an effective method for nutrient capture, particularly nitrate (NO_3^-), as wetlands often create anoxic conditions that facilitate denitrification. Denitrification is the process by which NO_3^- in the soil is transformed into N_2 gas. This process occurs in oxygen-poor, anoxic environments. Since oxygen diffusion is about 10000 times slower in water than in air, rewetting wetlands can create these beneficial anoxic conditions. (Walton et al., 2020)

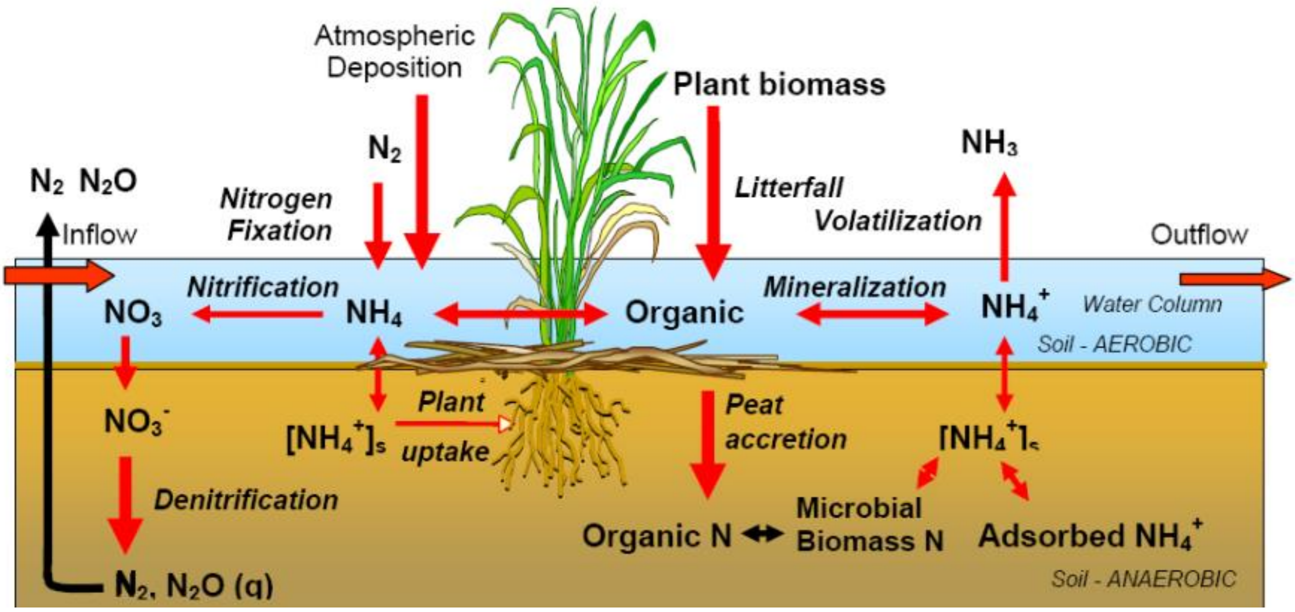

Figure 1: Nitrogen cycle in a wetland (Reddy & DeLaune, 2008)

Without any human activity, natural N (on the form of ammonium NH_4^+) is utilised by plants to grow and then go back to the soil when the plant dies. The NH_4^+ may then be transformed into NO_3^-, which may be transformed into N_2 or N_2O with the denitrification process. This process occurs under anoxic conditions and is therefore facilitated when the water level is high (figure 1).

With the human activity the NO_3^- inputs are very high, and the denitrification process must be very efficient to reduce the impact of these inputs on the natural environment.

However, the monitoring of various rewetting projects remains inadequate. There is a lack of knowledge about how the restoration affect the wetland and that can be a problem when planning new projects because there is a lack of data before rewetting. Rewetting a wetland is a good solution to increase the N retention, but it can also have some side effect such as a release of dissolved P (reductive dissolution of Fe^{3+} to Fe^{2+} leads to release of P adsorbed to Fe^{3+} minerals).

or the deterioration of habitat conditions as the environment change (Hoffmann et al., 2011). The monitoring of the current projects could permit to reduce those side effect for future projects. The NIFA project, conducted by the University of Aarhus and funded by the Ministry of Environment of Denmark, aims to monitor the impact of wetland restoration on different factors, particularly N removal, and potential P release.

The objective is to understand and quantify the N removal resulting from wetland restoration. This necessitates conducting measurements before and after restoration to evaluate the difference in N input and output.

The aim of the internship is to study the hydrology and N cycle in a recently rewetted area known as " Lobæk" (55.133448, 8.947468) (figure 2). This will involve measuring flow rates and water levels using stations set up on the site, taking water samples to analyse nutrients and finally to calculate water and N balances for the area before and after rewetting.

Figure 2: Rewetting projects in Denmark included in NIFA project

3- Materials and Methods

The Lobæk project encompasses an area of 238.7 hectares and primarily consists of freshwater formations, morainic clays, and meltwater sand and gravel. The annual mean temperature is 12°C which is above the annual mean temperature of the country (8.8°C).

The main activities of the project involved raising ditches, closing drains and wells, and installing new viaducts.

The expected results following the rewetting efforts are a removal of 15.7 tons of CO_2 per hectare per year, a removal of 65.9 kg of N per hectare per year, and a release of 7.52 kg of P per hectare per year.

The rewetting of Lobæk took place on April 26, 2022, and a monitoring program has been in place since May 2021. This allows for data collection both before and after the rewetting process.

Six surface water measurement stations were installed, with four corresponding to the project area's inlet, one at the outlet, and one serving as a middle station (figure 3). Each station is equipped with a water level logger that measures the water level every 15 minutes since April 2022 (figure 4).

A time-proportional automatic sampler (ISCO, Teledyne ISCO) is also present at each station, collecting water samples every 3 hours, which are then combined into weekly samples. Additionally, manual water samples and discharge measurements were taken every 3 weeks (figure 4).

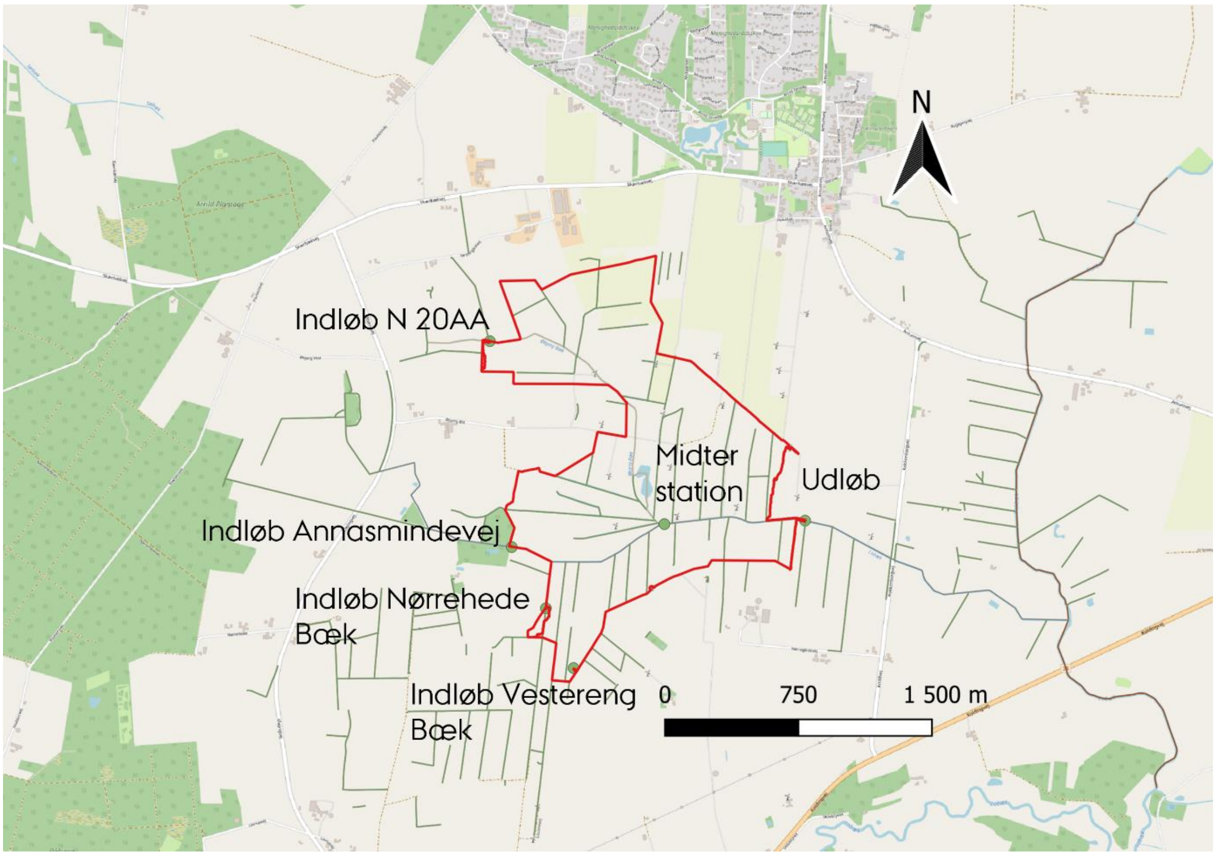

Figure 3: Lobaek area and position of the stations

Figure 4: ISCO sampler and water level logger

A nearby downstream reference station (40000165, Figure 3) with daily measurements of water level and discharge was utilized to assist gap filling during periods of missing water level or flow data

Climate data, including precipitation and evapotranspiration, were obtained from the Danish Meteorological Institute from May 2021 to May 2023.

This data was then used to calculate the water balance of the project. The water balance can be written as:

$$Q_{Annasmindevej} + Q_{Vestereng} + Q_{N20AA} + Q_{Norrehede} + P + Residual = Q_{Udlob} + ET$$

where P is Precipitation and ET is evapotranspiration.

The residual here corresponds to groundwater or other missing inputs. The site is located in a very flat area so groundwater inputs are not expected to be major.

To obtain a continuous discharge at every station, relations were made either with the continuous water level (h) or with a continuous discharge from another station.

A Q-h relation is this type of relation: $Q = k_1 * (h - h0)^{k_2}$

This relation links the water level of the station with the discharge of the same station. When a robust relation can be found, this relation will be used to calculate discharge since it is the most direct measurement.

The Q-Q relation is a linear relation between discharges from two different station. It is used when the Q-h relation cannot be used.

The collected data was subsequently analysed using Python with a Jupyter notebook.

4- Personal work and internship aim

The main task of my internship in the department was to calculate the water balance and nitrogen balance before and after the implementation of the Lobaek rewetting project.

To do this, I was given the data collected in the field (samples and measurements of water levels, discharge, or nutrients) as well as the rainfall data for the area. I then used python with a jupyter notebook to process the data.

First, I had to match the dates between all the measurements, fill in the gaps, convert the units and separate the data before and after restoration.

I then found relations between a point discharge and a water level (measured continuously) or another continuous discharge to calculate a continuous discharge for each station.

I was then able to add up the different flows, precipitation, or evapotranspiration to establish the water balance and obtain several graphs showing the impact of the different inputs on the output discharge.

I also did some field work. I was able to go to the Lobaek site twice to collect the water samples taken by the ISCO samplers and to measure the discharge, temperature, and oxygen concentrations at each station.

I also went several times to another site (Ringfenner) to clean the piezometers installed and measure the temperature and oxygen levels in these piezometers. This site is a raised bog and Lobaek is a fen, that’s the two major mire types in Denmark.

5- Results

Prior to the rewetting, continuous water level measurements were unavailable (point measurements of discharge were available), but continuous discharge measurements were taken at the downstream station. Q-Q relations were established to calculate the continuous discharge at all stations within the project area (figure 5)

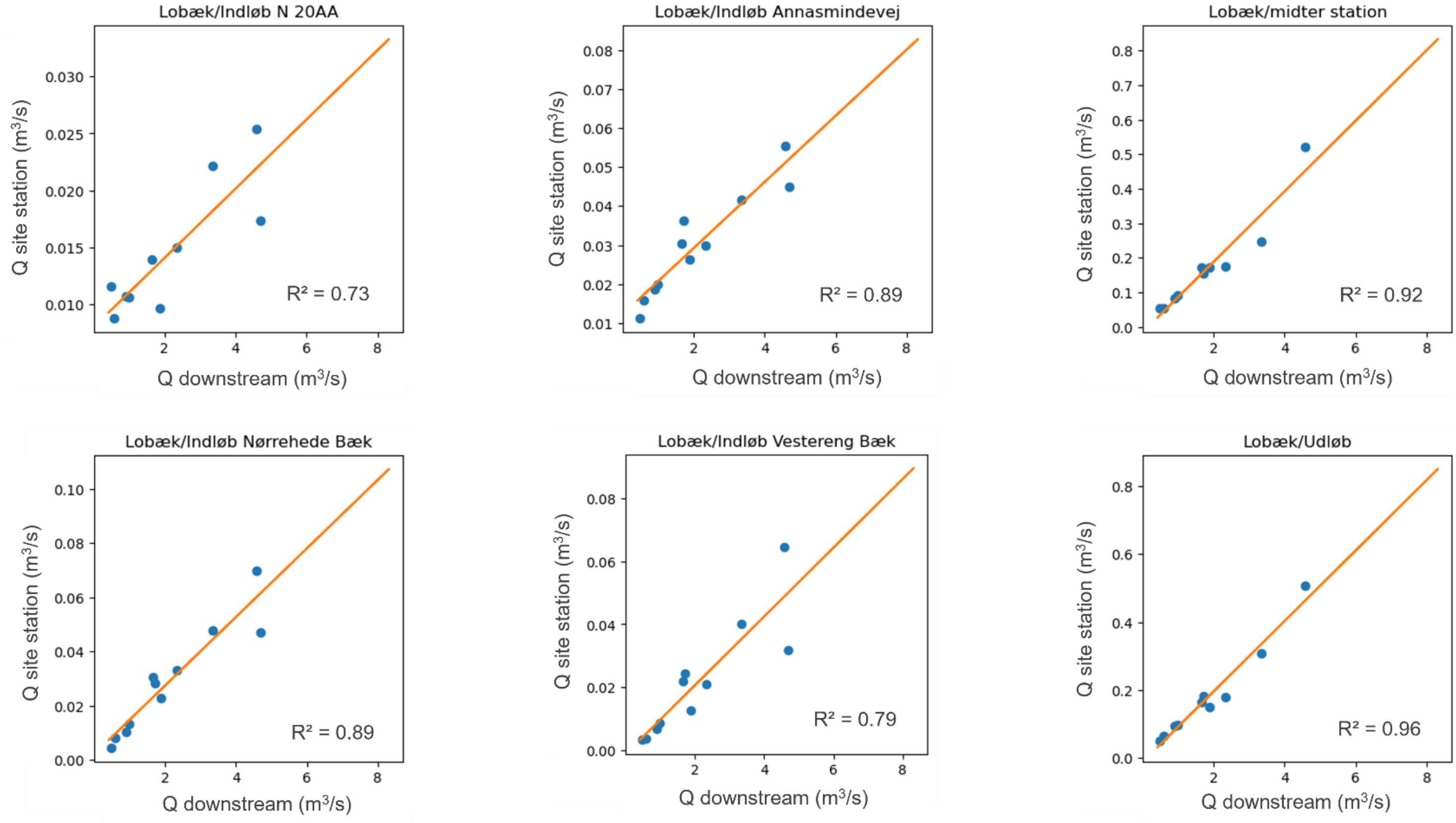

Figure 5: Q-Q relations with the downstream station before rewetting. The blue dots correspond to the discharge measurements made at the station and the orange line is the linear regression

The linear relations found are quite robust since the minimum coefficient of determination is 0.73 for N20AA inlet station.

After the rewetting, continuous water level data became available for each station. Attempts were made to determine Q-h relations at each station, but only the middle station and the outlet Q-h relation proved to be robust (figure 6). Consequently, Q-Q relations were established between them and the other stations to calculate the continuous discharge at each respective station (figure 7).

Furthermore, there was gaps in the water level data for the middle station and the outlet station. Those gaps were due to broken water loggers and were not exceeding 2 consecutive weeks. To fill the gaps a Q-Q relation between the middle station and the outlet was used, allowing to fill the gaps at both sites. There was only one day where both water loggers in middle station and outlet were broken so linear interpolations were made for this day.

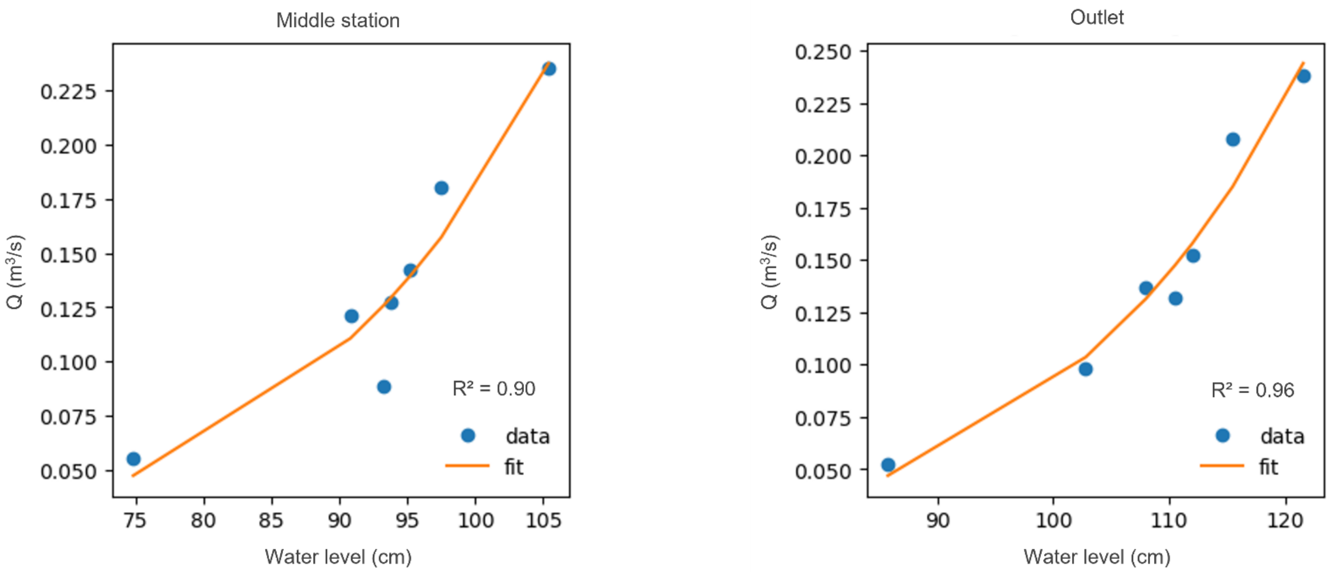

Figure 6: Q-h relations at the middle and the outlet stations

These Q-h relations (figure 6) are very reliable, the coefficient of determination is above 0.90 but uncertainties remain due to a little number of points.

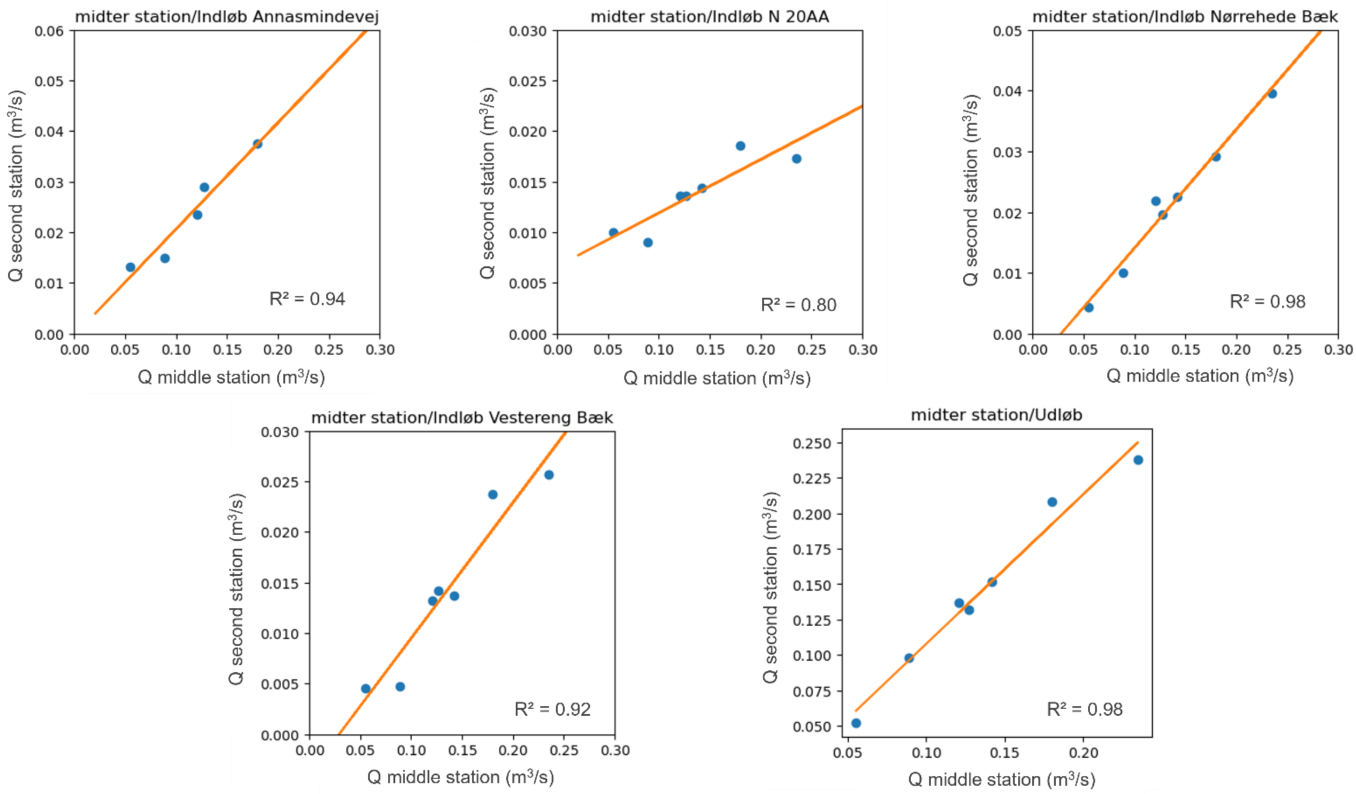

Figure 7: Q-Q relations with the middle station

These Q-Q relations (figure 7) are reliable, the coefficients of determination are high and especially the one for the relation between the middle station and the outlet (R^2 = 0.98). This allows to fill the gaps in the water level data with this Q-Q relation.

All these relations allow to calculate a continuous discharge for all the stations. With these discharges, the precipitation, and the evapotranspiration (figure 8 and 9), it ispossible to calculate the residual part (figure 10 and 11).

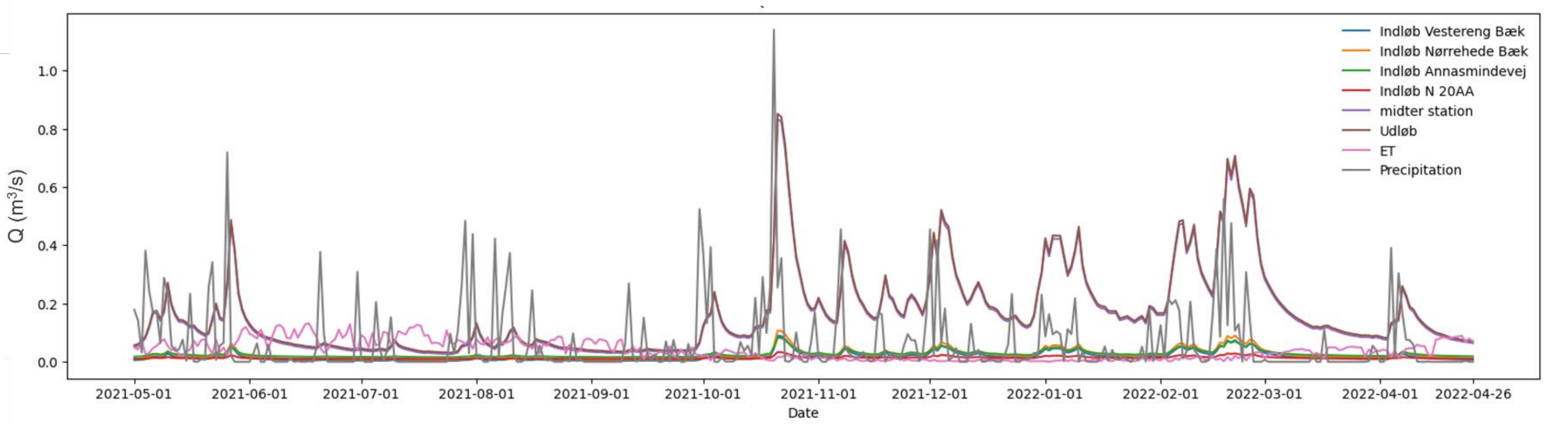

Figure 8: Daily discharges, precipitation, and evapotranspiration before rewetting

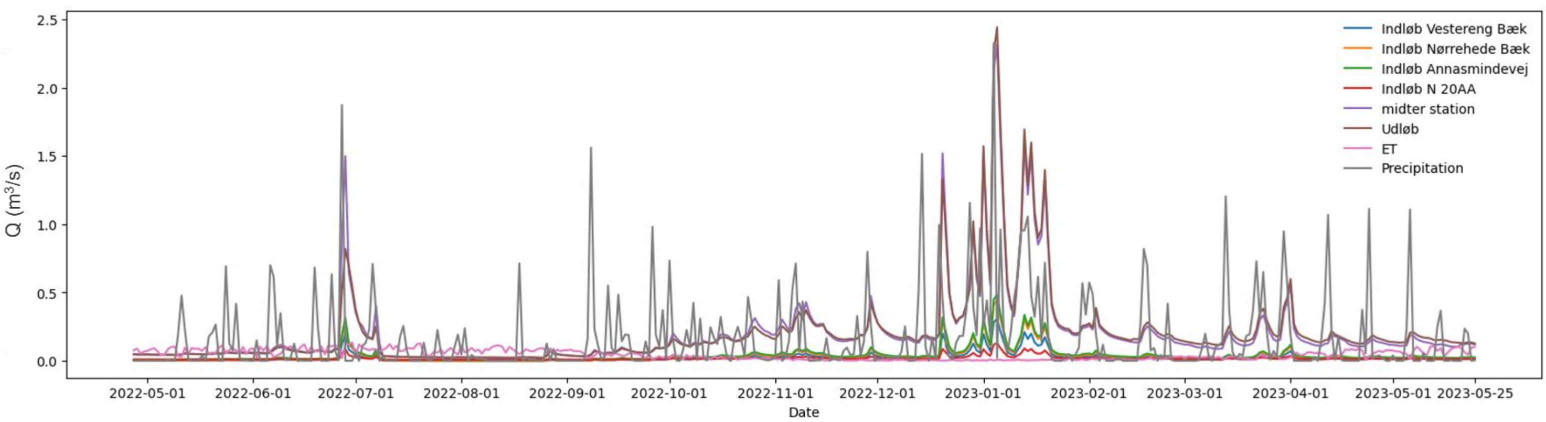

Figure 9: Daily discharges, precipitation, and evapotranspiration after rewetting

There is more water leaving the area after rewetting as the maximum discharge at the outlet before is about 0.8 m^3/s and after it is about 2.5 m^3/s. The difference is easier to see in winter.

To compare more easily the data before and after, monthly discharge been calculated and the residual part too with this equation (figure 10 and 11):

$$Q_{Annasmindevej} + Q_{Vestereng} + Q_{N20AA} + Q_{Norrehede} + P + Residual = Q_{Udlob} + ET$$

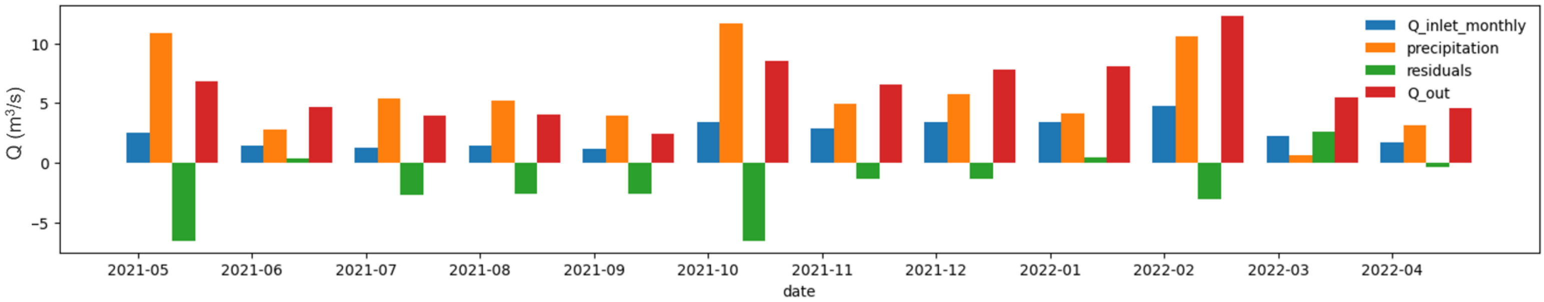

Figure 10: Monthly discharges, precipitation, and residual part before rewetting

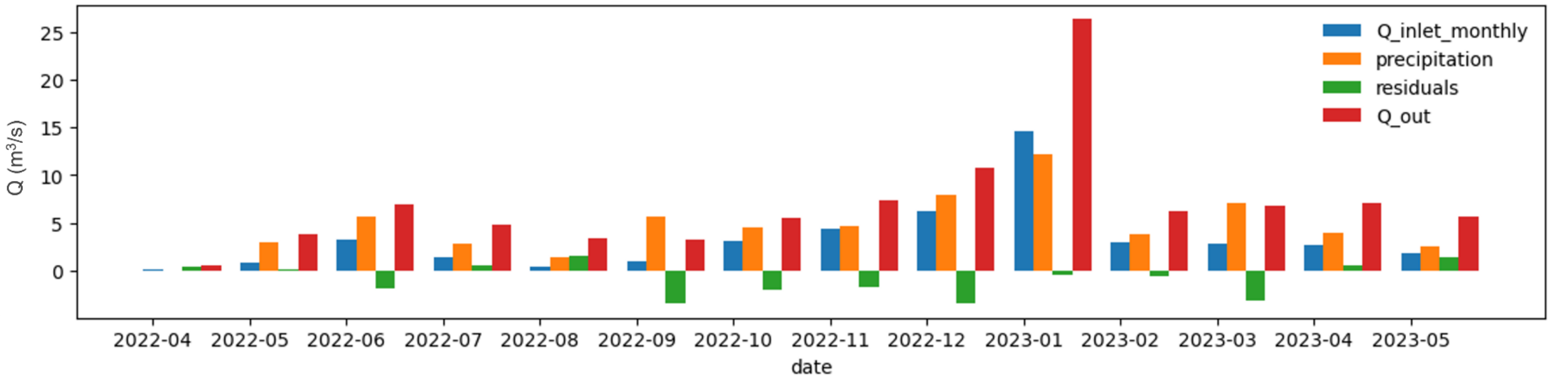

Figure 11: Monthly discharges, precipitation, and residual part after rewetting

In those graphs (figure 10 and 11), the term "Q_out" is a sum of the discharge at the outlet and ET.

Here again the main difference is the maximum discharge during winter, reaching 25 m^3/s in January after rewetting and only 12 m^3/s in February before rewetting. The difference could not be a result of the rewetting, it could be due to a difference in precipitations between the two periods.

The difference is not that important over all year, as the monthly mean discharge at the outlet before rewetting is 6.27 m^3/s and 7.02 m^3/s after rewetting.

The residual part decreased after the rewetting. The annual residual part represents 23.7% of the outlet before rewetting whereas it is 14.5% after rewetting (table 1). Part of this difference could be because of the difference in the relation used to find the discharges but the most part must be explained thanks to the rewetting. The rewetting raised the water level in the area, the water being higher in the zone decrease the groundwater gradient with the outside of the zone, bringing less groundwater in the Lobaek site.

Table 1 : Water balance before and after rewetting

Data	Total Q before rewetting (average m3 per day)	Total Q after rewetting (average m3 per day)	Catchment area (ha)
Indløb Vestereng Bæk	1535	1978	84
Indløb Nørrehede Bæk	2077	2901	565
Indløb Annasmindevej	2332	3597	224
Indløb N 20AA	1150	1485	63
Sum of the inlets	7093	9960	936
midter station	13977	17273	1381
Udløb	14597	17716	1509
Precipitation at the middle station	12821	11097	445
Precipitation at the outlet	16509	14290	573
ET at the middle station	2431	2735	445
ET at the outlet	3403	3829	573
Residuals at the middle station	-3506	-1050	445
Residuals at the outlet	-5603	-2705	573

The measured and calculated water discharge were multiplied by daily values of total nitrogen (TN) concentrations at each station (interpolated from weekly data) resulting in a TN balance for each station both daily (figure 12) and monthly (figure 13).

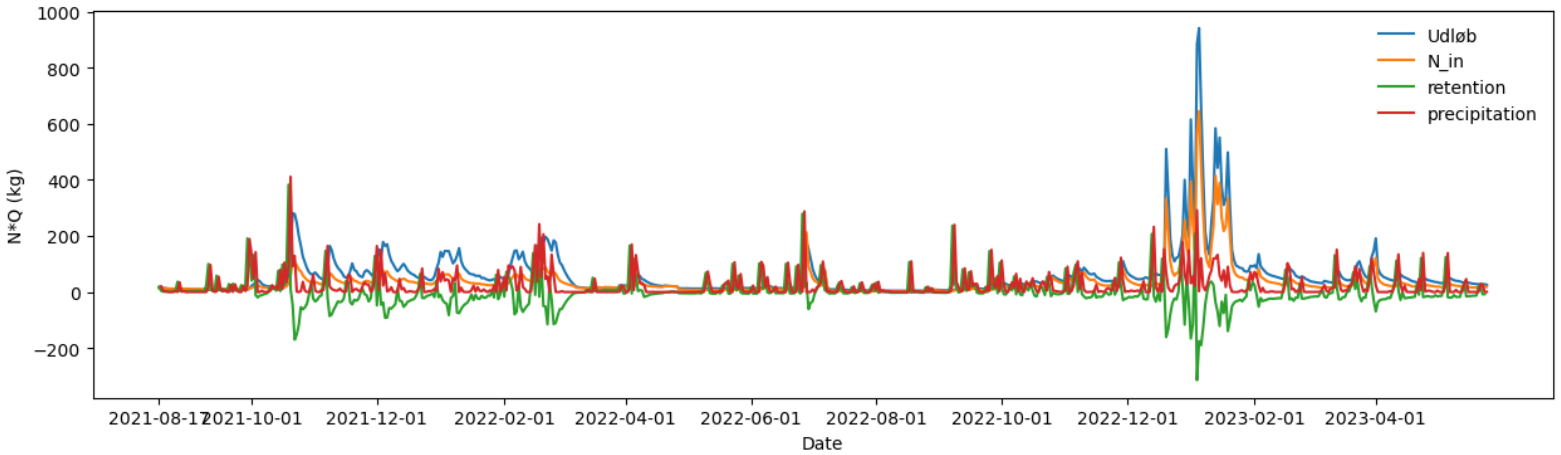

Figure 12: Daily TN balance

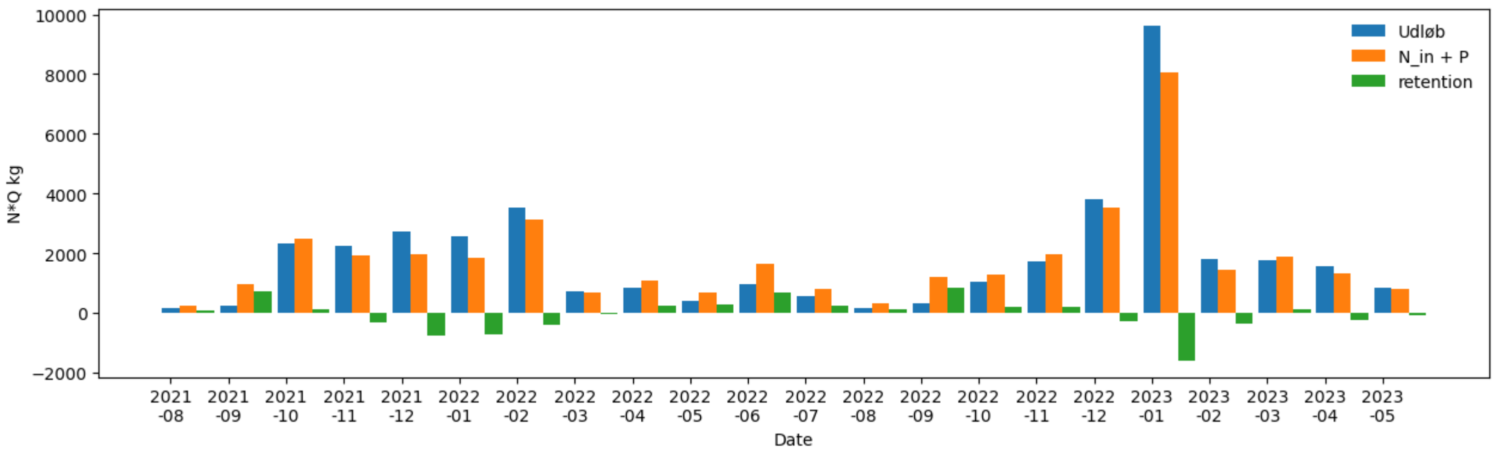

Figure 13: Monthly TN balance

Here the retention corresponds to the difference between TN at the inlets and in the precipitation and TN at the outlet.

On those graphs it seems to have less months with N released after rewetting but the difference beteween before and after is not very clear (Table 2 and 3).

Table 2: TN balance before rewetting

Date	N_in (kg)	N_out (kg)	N_retetion (kg)	N_retention (%)	N_retention (kg/ha)
2021-08	258	166	91	35	0
2021-09	952	226	726	76	4
2021-10	2468	2332	136	6	1
2021-11	1927	2241	-314	-16	-2
2021-12	1954	2714	-760	-39	-4
2022-01	1864	2570	-706	-38	-3
2022-02	3121	3536	-415	-13	-2
2022-03	679	730	-51	-7	0
2022-04	1078	828	249	23	1
Over 9 months	14300	15343	-1043	-7	-5

Table 3: TN balance after rewetting

Date	N_in (kg)	N_out (kg)	N_retetion (kg)	N_retention (%)	N_retention (kg/ha)
2022-05	693	405	289	42	1
2022-06	1648	973	675	41	3
2022-07	813	558	255	31	1
2022-08	305	169	136	45	1
2022-09	1197	337	860	72	4
2022-10	1275	1057	218	17	1
2022-11	1948	1733	215	11	1
2022-12	3546	3812	-266	-8	-1
2023-01	8057	9640	-1583	-20	-8
2023-02	1454	1820	-366	-25	-2
2023-03	1869	1752	117	6	1
2023-04	1323	1547	-224	-17	-1
2023-05	791	860	-70	-9	0
Over 13 months	24918	24663	256	1	1

Before rewetting the site was a source of nitrogen, it released about 5 kg of N per ha per year and after rewetting the site is retaining 1.25 kg of N per kg per year. This corresponds of a retention of 1% of the TN incoming into the site.

6- Discussion

The results obtained here indicate that the rewetting of this site shifted the N balance from a net release to a net retention of N. However, the N retention was not very efficient (1.25 kg/N/year) and was lower than that of other rewetted study sites (Audet et al., 2020), with a measured range of N retention between 42 and 308 kg ha^{-1} $year^{-1}$.

This low retention could be attributed to the site's very flat terrain, which leads to groundwater flows. The project itself was not very ambitious either; only a few ditches and drains were closed, and the water level was raised without making any changes to the land use in the surrounding areas. Knowing that the mean export of N leached from agricultural areas to Danish streams is estimated as 4–14 kg N ha^{-1} agricultural land $year^{-1}$ (Blicher-Mathiesen et al., s. d.) the agricultural activities on Lobaek site could explain this low removal of nitrogen as the inputs of the agricultural field are not included in this work.

A major source of errors likely stems from the delineation of catchment areas used to calculate precipitation on the site and N from atmospheric deposition. This delineation was based on a relatively fine digital elevation model (0.4 x 0.4 m), which poses challenges in flat areas where small topographical and subsurface features can influence flow directions. Moreover, unmapped drains and culverts might not have been considered in the analysis, potentially leading to significant errors.

To a lesser extent, the differences between pre-rewetting and post-rewetting conditions could also be explained by calculation errors. Different inlets were used to calculate daily discharge before and after rewetting, and a downstream station was used before rewetting. Although the station was near the site, assuming similarity in soil properties might not have been accurate without proper investigation.

Overall, this restoration project did not yield significant results. The flat terrain is a significant factor; achieving notable outcomes becomes challenging due to the low and dispersed flow patterns. Additionally, integrating agricultural practices into the project and monitoring process could have enhanced its effectiveness. Incorporating the agricultural field into the project might have encouraged farmers to reduce N inputs, enabling more precise monitoring and assessment of the project's impact.

Selecting the appropriate area for a rewetting project is crucial for achieving better results. Simply raising the water level is insufficient; an effective project should encompass the agricultural field to make a meaningful impact on N inputs.

Acknowledgments

I want to thank my internship supervisor, Joachim Audet and my project supervisor Rasmus Jes Petersen for their inclusion, explanations and help for this work. I also want to thank the staff of the Ecoscience department for their help during my internship.

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2022-2023

Titre: Wetlands rewetting and consequences on nitrogen cycle

Résumé: Le travail effectué durant ce stage a été d'analyser les données récoltées dans une zone humide qui a récemment été remise en eau. Mon travail portait sur le la retention de l'azote suite à cette restauration. J'ai effectué un bilan hydrique de la zone qui m'a ensuite permis d'effectué un bilan azoté avant et après restauration.

Mots Clés : Bilan azoté, zone humide

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