Rapport de stage individuel

4ème année

Hydraulics properties of Peatlands

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1) Introduction

1.1) Presentation of the host organisation

I completed a 12-week internship in the Department of Ecoscience at Aarhus University, Denmark.

The Department of Ecoscience comprises approximately 275 employees, with 100 based in Roskilde and the remainder in Aarhus. Of the 275 employees, around 200 are permanent staff, with approximately 15 doctoral students, 20 postdoctoral researchers, and 40 fixed-term contract employees. An inspiring work environment is fostered, and collaborations are established with Danish and international institutions.

Four main research themes emerge:

- The Arctic: Arctic, and particularly Greenland, is studied in collaboration with its government. All trophic levels (microbes, plants, animals) are studied at all scales (individuals, populations, ecosystems).
- Marine ecology: The structure and function of marine ecosystems are studied in this department, from coastal areas to open sea, from the Arctic to tropical regions. Distinguishing human-induced changes from those caused by natural variations is an important theme in the department's research.
- Terrestrial ecology: Here, strategies are developed for green transition and sustainable production in agriculture and forestry, including focusing on nature-based solutions. This section is home to the topic centre « Dry nature and species » under the national monitoring programme NOVANA.
- Freshwater ecology: Freshwater research at Aarhus University is internationally recognized and covers rivers, lakes, ponds, and watersheds.

Within the Department of Ecoscience I was part of the Catchment section (Freshwater ecology). In this section, research is conducted to understand how to respond to the various pressures exerted on aquatic environments such as lakes, rivers, and fjords. This knowledge can then be used by authorities to better manage aquatic ecosystems.

Research and consultancy activities can be divided into three core areas:

- Nutrient dynamics and hydrology
- Tools for reducing nutrient loss to the aquatic environment
- Wetlands and greenhouse gases

During the internship, I worked with the wetland group. This group primarily focuses on the restoration of wetlands. In Denmark, the second environmental plan in 1998 marked the beginning of numerous restorations of lowland wetlands that were previously cultivated areas. Major areas of study therefore concern the pre- and post-restoration conditions of wetlands.

More generally, Research into environmental and climate conditions in wetlands combined with a description of the hydrological processes that take place in interaction with the biogeochemical processes are what they are studying. Currently, a dozen people work in this group. (*Department of Ecoscience*, 2024)

1.2) Presentation of the mission

1.2.1) The mission

In the current context of climate change due to a rapid increase in the quantity of human-induced greenhouse gases in the atmosphere, particularly CO_2, the preservation of carbon sinks is essential. In Denmark, 170,000 hectares of peat soils were under cultivation in 2018. This accounted for 7 % of the cultivated land, yet it was responsible for more than half of the agricultural carbon emissions, totalling 4.8 million tonnes of CO2e out of 9 million (*Carbon rich peat soils | Klimarådet*, 2024). The annual emissions from these peat soils are equivalent to the annual emissions from 1.8 million petrol cars, which corresponds to 70% of the Danish car fleet (*Carbon rich peat soils | Klimarådet*, 2024). Indeed, « Peatlands are terrestrial wetlands ecosystems in which waterlogged conditions prevent plant material from fully decomposing. Consequently, the production of organic matter exceeds its decomposition, which result in an accumulation of peat. » (*IPS - International Peatland Society*, 2024). Therefore, peatlands represent a considerable carbon stock, covering only 3% of the earth's surface (Leifeld et Menichetti, 2018) but accounting for 30% of the carbon present in soils (Gorham, 1991). Therefore, it is crucial to rewet these cultivated soils because, when peatlands are no longer saturated with water, the organic carbon decomposes, releasing greenhouse gases. The Danish Green Deal aims to restore 100,000 hectares of peatland by 2030, representing more than half of Denmark's peatlands (Koch et al., 2023).

The tasks related to this internship are part of the NIFA project. The aim of this project is to study the environmental effects of rewetting peatlands. As part of this project, a study of the hydrological and biogeochemical conditions before and after rewetting is being carried out (*Department of Ecoscience*, 2024). The objective is to gain a comprehensive understanding of the processes occurring in peatlands following restoration efforts. Several peatlands are being studied and restored with this project, as illustrated on Figure 1.

Peatlands can form in a variety of climatic conditions and therefore have different types. However, most peatlands are found in the northern hemisphere, where they form under conditions of high precipitations and low temperatures. Denmark's climate is favourable to the formation of peatlands dominated by *Sphagnum* mosses, sedges and shrubs (*IPS - International Peatland Society*, 2024).

Considering all this, the objective of my internship is to enhance our understanding of peatland hydrology, specifically through the use of slug tests to determine hydraulic conductivity (K, in m/day). Hydraulic conductivity indicates the soil's ability to let water pass through. Understanding the hydrological dynamics of peatlands is crucial. For instance, by measuring the water fluxes in and out of a peatland, we can assess nutrient quantity at various points, revealing the peatland's capacity to absorb nutrients, often from agricultural sources. This knowledge also aids in determining the water retention capacity of peatlands. Slug tests, however, are time-consuming to set up. It is therefore of interest to be able to determine hydraulic conductivity without having to carry out these tests. To do this, we need to be able to identify the factors that determine hydraulic conductivity.

The problematic will therefore be: what factors influence hydraulic conductivity in a peatland and how do they influence it? The specific objectives developed in this report to address the problem will be as follows:

1- Use soil property data to determine which parameters influence hydraulic conductivity and, if possible, find an equation for determining these conductivities without having to carry out a slug test.

2- Do the same thing with soil data obtained using a new method called Borehole Nuclear Magnetic Resonance (BNMR).

3- Determine the impact of piezometer screens on the conductivity results obtained.

4- Make a practical application of what hydraulic conductivity can be used for by modelling certain groundwater flows in a peatland.

The main objective is therefore to provide a better understanding of the factors influencing hydraulic conductivity in peatlands.

1.2.2) Task realised during the internship

During the work placement, Solène Moreau and I conducted the slug tests, some of which were performed with the guidance of our project tutor, Rasmus Jes Petersen. Subsequent data processing and coding operations were executed independently by each of us.

All slug test data from the Vosborg and Ringfenner sites were obtained from the tests conducted by us. However, the data from the Vejrumbro site were acquired by other people. All the open cavity slug tests were carried out by Solène Moreau and me on the field.

For the practical application involving flow modeling, it was agreed that I would focus on the Vosborg site, while Solène Moreau would concentrate on the Ringfenner site.

2) Materials and methods

2.1) Presentation of the study sites

Figure 1 : Sites studied during the course

The three peatlands studied were Ringfenner, Vosborg, and Vejrumbro (Figure 1). These three sites are included in the project and are being studied collectively due to their relatively similar environmental contexts. Each site features peaty soils formed under conditions of water saturation. Historically, all three sites have been drained for agricultural purposes, leading to surface soils containing varying degrees of decomposed peat. Currently, efforts are underway to re-wet all of these sites. As shown in the aerial photos (in annex 7.1), the Vejrumbro and Vosborg sites are located on the banks of a river, whereas the Ringfenner site is in the middle of fields. But dykes are present on the Vosborg site, so only the Vejrumbro site is completely connected to a river. In this report, data from all three sites will be used in the analysis of soil properties and the use of BNMR data. In the last part, the focus will be on the Vosborg site to carry out flow modeling.

2.2) Slug test

2.2.1) Presentation

A slug test « essentially consists of measuring the recovery of head (water level) in a well after a near-instantaneous change in head at that well » (Butler et Jr, 2019). So, for a slug test, you need to add or remove water and see how quickly it returns to the reference situation. In practice, pumping was carried out as often as possible, and water was added when there was insufficient water to pump above the screens.

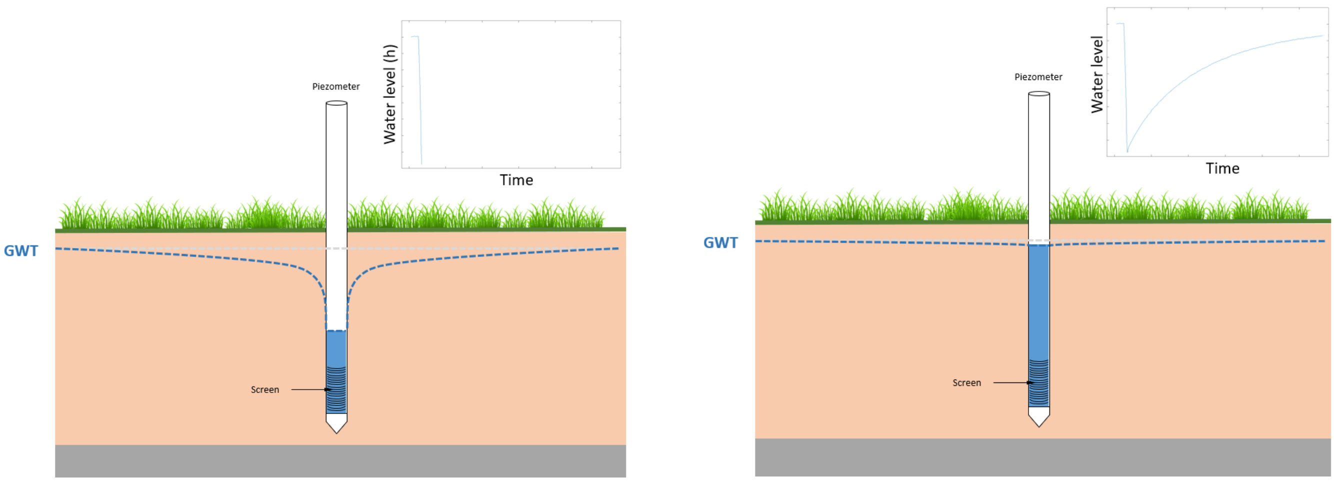

Figure 2 : Representation of a slug test where water water is pumped (author: Rasmus Jes Petersen)

As shown in Figure 2, the water level returns to its initial level after pumping. Various techniques are used for slug tests, depending on the type of aquifer. The Hvorslev method is used for confined aquifers, while the Zlotnik method is used for unconfined aquifers. Both methods start with a slug test to measure the water level over time when water is added or pumped. Ideally, slug tests are conducted three times in each piezometer, with different quantities of water added or removed each time to reduce uncertainty in the results and to evaluate if K is independent of the water level, which is a basic assumption in slug test analyses. The general formula for calculating hydraulic conductivity can be seen in Equation 1. Firstly, Rc and L values are obtained using the information from the piezometer. To determine the slope (Figure 3), plot the logarithm of the water level change (current water level displacement H divided by the initial head water displacement H_0) against time.

$$\text{slope} = \frac{-2L}{r_c^2 \times F} \times K$$

Equation 1 : calculation of hydraulic conductivity (L = screen length ; Rc : casing radius (inner) ; F = shape factor)

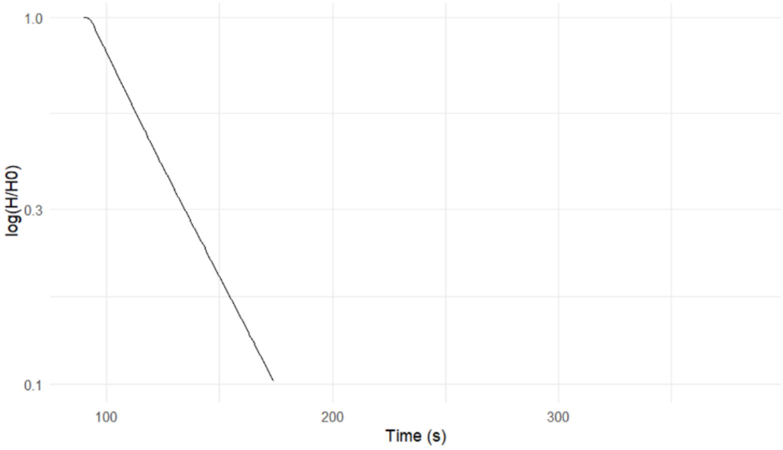

Figure 3 : Straight line for change in water level after pumping depending on the time

This allows the slope to be obtained. However, the line is not always straight. It is shown by Butler that « the best approach for tests in partially penetrating wells is to fit a straight line to normalized response data in the range of 0.15–0.25 » (Butler Jr. et al., 1996).

Then F (the shape factor) needs to be obtained to have K. The Hvorslev (confined aquifer) or Zlotnik (unconfined aquifer) methods are used at this point. In order to determine if a confined or unconfined aquifer is being examined, the borehole profile, where the correspondent piezometer is located, is observed. If the layer of soil where the piezometers well screens are present is fully saturated and is topped by a layer of impermeable soil such as gyttja or clay, then the aquifer in question is considered confined. Otherwise, it is considered unconfined. With Hvorslev method, it consists of using the formula on Equation 2:

$$F_{Hvorslev} = \sin^{-1}\left(\frac{\mathrm{L}}{2\, r_w}\right)$$

Equation 2 : Hvorslev shape factor (L = screen length; Rw : outer radius)

With Zlotnik, the formula in Equation 3 has to be used:

$$F_{Zlotnik} = \frac{\sum_{n=1}^{\infty}\left\{\cos\left(\beta_n \times \frac{H}{D}\right) - \cos\left[\frac{\beta_n (H-L)}{D}\right]\right\}^2 \times \frac{K_0\left(\beta_n \times \frac{r_W}{D}\right)}{\beta_n^3 \times K_1\left(\beta_n \times \frac{r_W}{D}\right)}}{\frac{L \times r_W}{2D^2}}$$

Equation 3 : Zlotnik shape factor (L = screen length; r_w = screen radius (outer); H= saturated thickness above screen bottom; D= aquifer thickness; A, B, C = Look-up values from type-curves; β_n=π(n-0.5) ; K_0= modified zero order Bessel function of the second k

All the calculations have been automated on R programming (See 7.2).

2.3) Use of slug test results

2.3.1) Comparison of K with soil properties

The aim of obtaining these hydraulic conductivities was especially to enable their comparison with the properties of the soil, as mentioned in the introduction. To do this, all the parameters to be studied and for which data are available have been grouped together:

- soil type: peat, sand, gyttja, gyttja with shells, mix (minority soil types such as clay or gravel). Different layers of soil at the Vejrumbro site contain gyttja with shells, which modifies the hydraulic properties and makes the gyttja much more permeable. This is why there is a separate category for gyttja with shells. In view of the amount of corresponding data, this category is not illustrated in most of the graphs.
  The very different properties of these soils will undoubtedly reveal important differences.
- AirDryBD : bulk density without water (g/cm^3).
- LOI (loss of ignition) : this test consists of heating the soil at 550°C during 3 hours to remove combustable and volatile materials. It gives an idea of the amount of organic matter in the soil (« Loss on Ignition Testing », 2022).
- TOC (total organic carbon), in percentage of weight.
- Peat decomposition: level of decomposition of the peat. It is estimated using the Von post scale. This scale is numbered from level 1 to 10 and provides keys for assessing this level in the field (Figure 22). For example, if the peat is squeezed and comes all the way out of the hand between the fingers, it is indicated by the scale that it is completely decomposed.
- Depth (middle of the piezometer screens)

One objective of this method would be to arrive at an equation that allows K to be calculated without having to carry out a slug test, simply using the properties of the soil (With an equation like log(K) = a + b*airdryBD + c*Loi....). At the very least, the results will reveal which parameters have a greater or lesser influence on hydraulic conductivity.

The linear relationships between the different variables will be tested by creating a scatter plot matrix which will create linear regressions between hydraulic conductivity and each variable, this will allow us to see the strength of the relationship between them.

The Pearson coefficient is an index reflecting a linear relationship between variables. It will also be used to explore the links between the different variables. This is a different representation, but the results should be identical to those of the scatter plot matrix in terms of correlation. The assumptions concerning the relationship between the various variables and hydraulic conductivity will be :

- H0: the two variables are independent
- H1: the two variables are related

The significance threshold will be 0.05.

This Pearson heatmap will also be used to separate the data according to soil texture, to see if for the same texture, soil properties can determine the K value. The Pearson heatmaps can also be used to assess the strength of the correlation. Here is Table 1 summarising this (*datatab.fr*, 2024):

Table 1 : Table of the strength of correlation between two variables, Pearson heatmap

p-value	correlation strength	Sign on Pearson heatmap
p > 0.1	Non-significant correlation	-
0.05 < p <0.1	Low significance correlations	*
0.01 < p < 0.05	Significant correlations	**
p < 0.01	Highly significant correlations	***

In an attempt to obtain an equation for the hydraulic conductivity using the different soil properties, multiple linear regression analyses are carried out. The relationships are tested with a log transformation on the K which is often the case in studies using hydraulic conductivity.

2.3.2) Comparison of K obtained with BNMR method

In the same way as for the soil properties from the soil samples, the hydraulic conductivities will be compared with the data obtained using the BNMR method (Reza Mashhadi et al., 2024), which provides various information on the peatland soil:

- totalf (total porosity): the total void space (%)
- clayf (clay-bound porosity): the water content does not move when there is a fluid flowing through the soil (%)
- capf (capillary-bound porosity): where immobile water is held by capillary forces
- freef (free porosity): in percentage.
- mlT2 (geometric mean of relaxation times): return to equilibrium after excitation of a water particle (sec)
- soe (summation of echoes)

After that, the same methods will be used in order to identify any correlation.

2.3.3) Comparison of K between open and closed cavity piezometer

Piezometers were installed without screens at the bottom but instead with an open cavity to observe the impact of screens on measurements. The difference between the two methods can be summarized as follows (Figure 4):

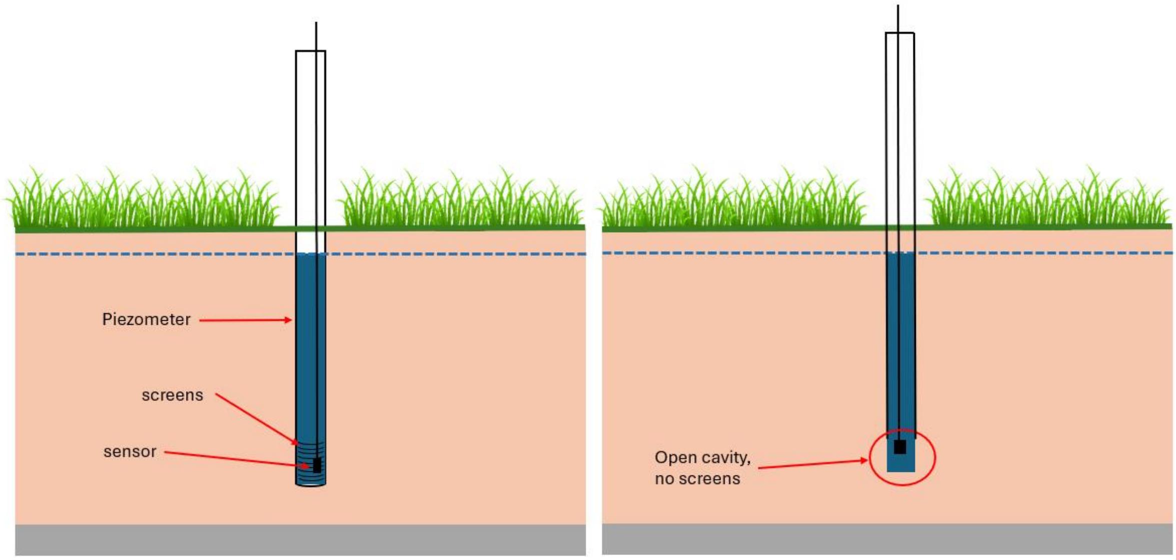

Figure 4 : Difference between open and close cavity piezometer

This method could only be used on a limited number of piezometers, and the difficulty lies in the fact that it has to be done in soil that will not collapse. Consequently, the tests were performed in peat soils. Nonetheless, an initial assessment of the impact that the screens could have on the results will be provided. As the tests were carried out in peat at shallow depths, the zlotnik method was used (unconfined aquifers). As a reminder, the formula for obtaining the Zlotnik (Equation 3) form factor takes into account the internal and external diameters of the piezometer. In this case, there is no screen. In the calculation, the same value (external diameter of the piezometer, here 0.0205m) is used for these two parameters because it is an open cavity.

2.4) Modelling of groundwater flowrates at Vosborg Enge

Figure 5 : aerial photography of the study site, Vosborg

This peatland is located close to a river (Figure 5). Re-wetting by filling in the ditches was in progress during the internship. This part contains two objectives:

- To model the quantity of water passing through some layers of soil at a certain time using the results of the hydraulic conductivities.
- See whether the peatland is fed by the river or vice versa, using probes that continuously measure the water level at various points.

In order to calculate the flow rate through the different layers of the peatland from the hydraulic conductivities, Darcy's law must be applied (Devlin, 2020), as show in Figure 6. Using this law, the aim will be to quantify, with the available data, the flows passing through an aquifer.

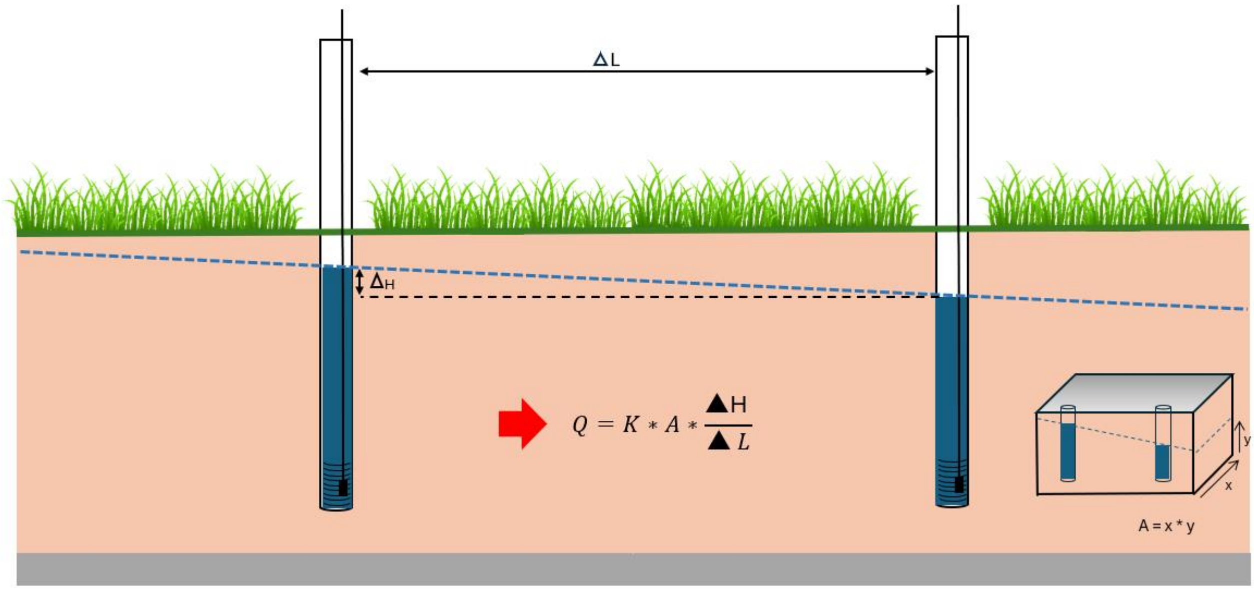

Figure 6 : Calculating water flow using darcy's law (Author: Sacha Gaduel)

On this site, an aquifer of interest is a sandy sheet, shown in red in the figure. Sandy soils typically exhibit higher resistivity due to their lower content of organic matter and clay, as well as their reduced water retention capacity. However, a large quantity of water can pass through it due to its high hydraulic conductivity. The aim will be to determine the flow passing through the area specified in the figure at the time the test was carried out, which is an area where we have data (red in Figure 7).

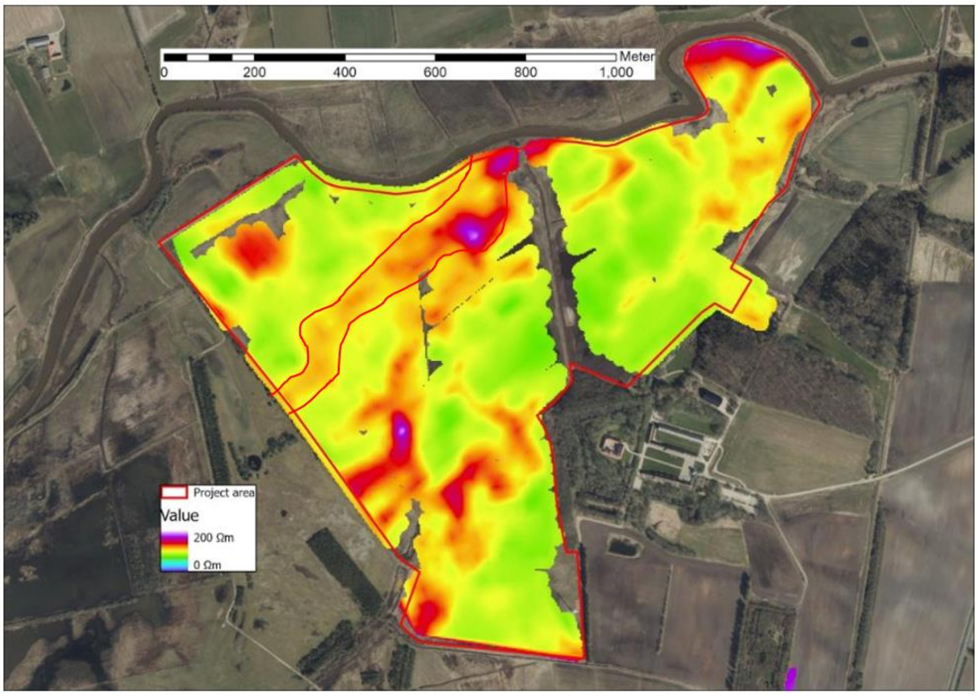

Figure 7 : Resistivity map in Vosborg (source : Rasmus Jes Petersen)

To determine the direction of flow in the peatland, the continuous water levels in 2 piezometers (OC1-10 and OC1-09, visible on Figure 5) will be compared over the past month. This will show whether and when the river is fed by groundwater from the peatland or vice versa.

3) Results

3.1) Hydraulic conductivity

3.1.1) Hydraulic conductivity

Box plots were made to obtain an overview of the hydraulic conductivity values (Figure 8):

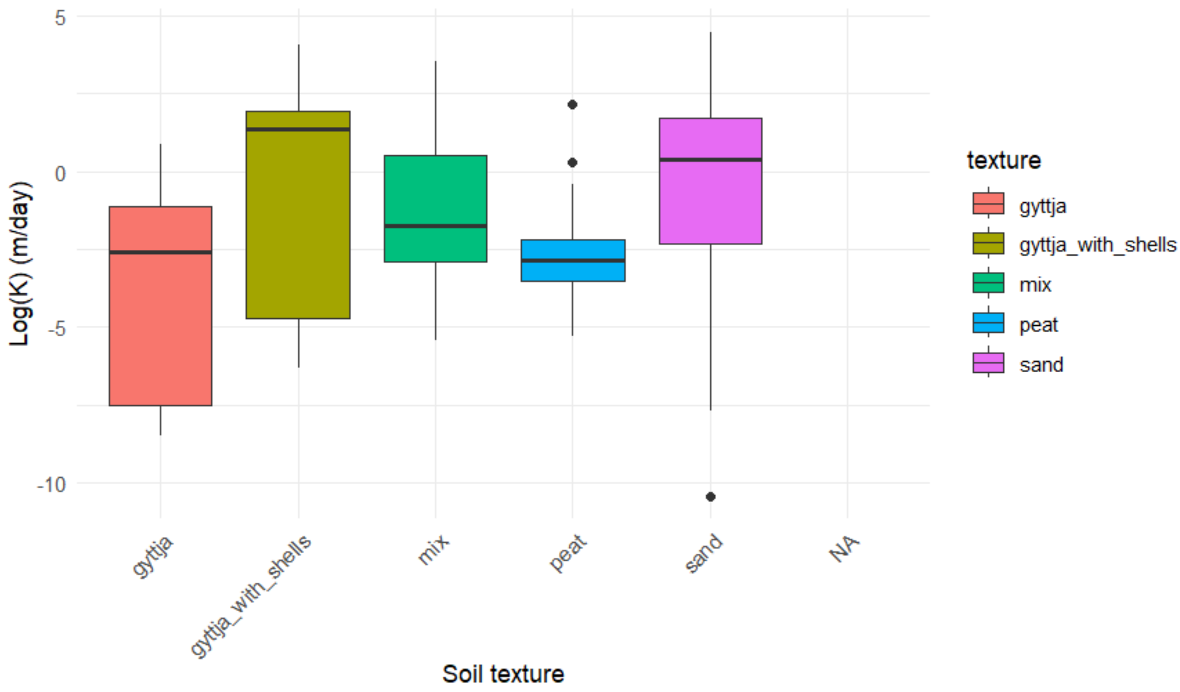

Figure 8 : Box plot of K values recovered in the field, in log scale

The use of the logarithm of the values in the statistical processing reduce the impact of extreme values in the representation of the data. Boxplot with the raw data is shown in annex (7.4) to get an idea of the value in m/day without the logarithm.

3.1.2) Comparison with the different soil properties

Firstly, this table (Table 2) enumerates all the data available for performing correlations. Specifically, there are a total of 170 hydraulic conductivity data sets or 128 from AirdryBD. Mix corresponds to different types of very different layers present in very small numbers (clay, gravel...).

Table 2 : Summary table of available soil data

Texture	K	AirDryBD	Loi	TOC	Depth	Peat_dec
Gyttja	11	10	11	10	11	0
Mix	31	16	15	13	31	0
Peat	71	70	66	58	71	58
Sand	57	32	42	5	57	0
Total	170	128	134	86	170	58

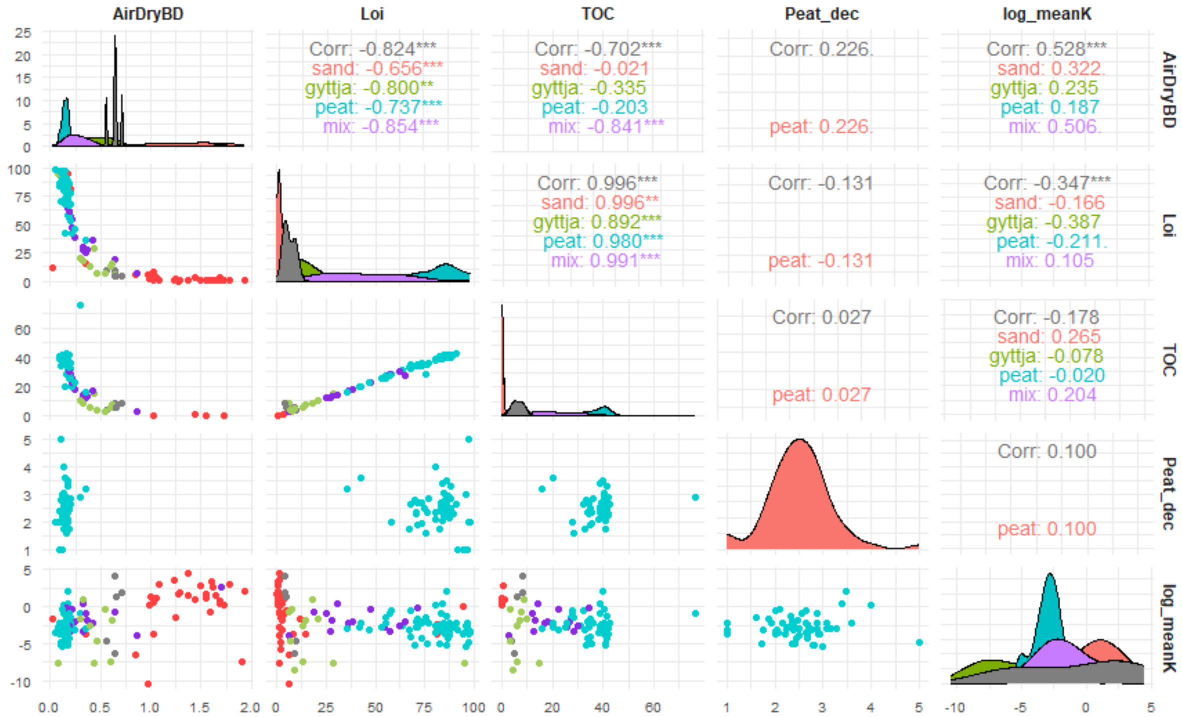

Figure 9 : Scatter plot matrix of hydraulic conductivity and soil properties

The results of this graph (Figure 9) show the distribution of the different parameters, the scatterplots of each variable as a function of each variable and the correlation coefficient between them. Firstly, this figure shows that there is a strong correlation between the TOC and Loi variables. The coefficient of 0.996 suggests that 99.6 % of the variation in TOC can be explained by the variation in Loi. AirDryBD as a function of Loss on ignition but also AirDryBD as a function of TOC follows the form of an inverse function. There does not appear to be any relationship between the various soil parameters (AirDryBD, Loi, TOC) and the level of peat decomposition. As regards the relationship between K and soil properties, a positive correlation seems to be visible between K and AirDryBD. On the contrary there appears to be a negative relationship between hydraulic conductivity values and Loi. The overall correlation is highly significant between hydraulic conductivity and AirDryBD and Loi. The correlation between hydraulic conductivity and TOC is negative (-0.178) but not significant and positive but not significant with peat decomposition (0.100). Correlation levels within same soil type vary widely.

Regarding the histograms, the AirDryBD values are lower for peat, while AirDryBD values are higher but also more dispersed when it comes to sand. The Loi and TOC values are extremely low for sand, whereas they are higher for peat. The peat decomposition level shows a distribution that follows a normal distribution.

Correlations between variables can also be represented using Pearson's heat map (Figure 10) :

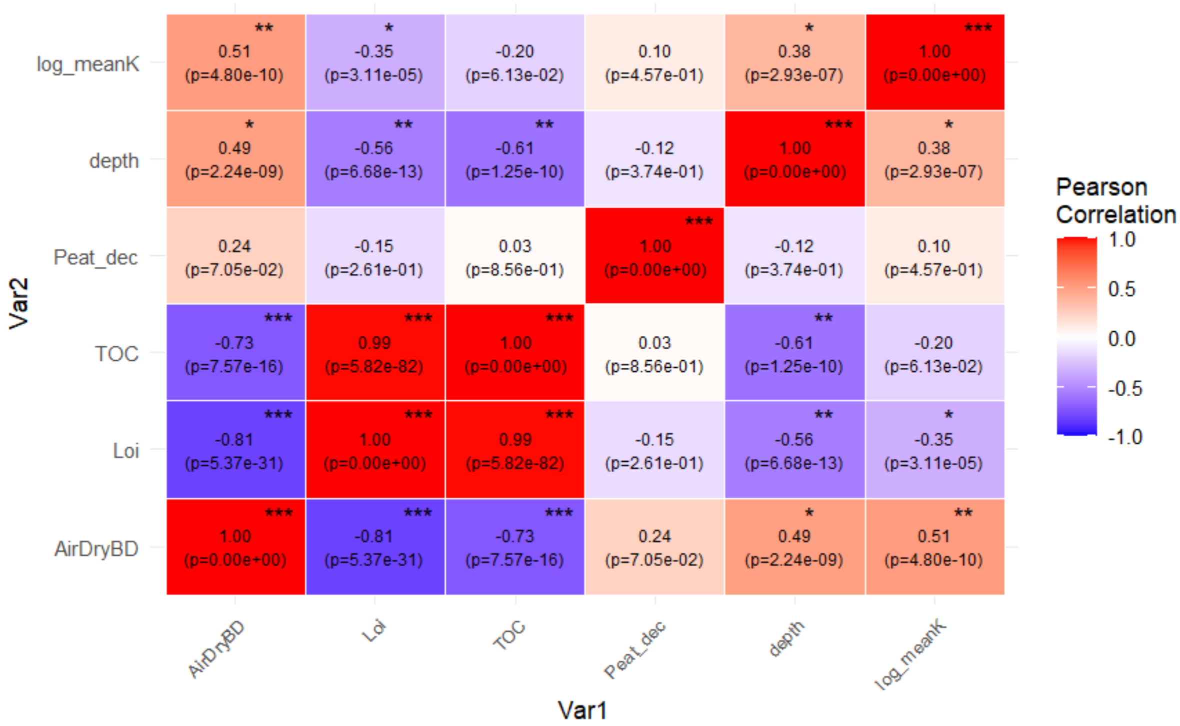

Figure 10 : Pearson heat map, correlation between hydraulic conductivity K and various soil properties

This representation shows that the correlation between hydraulic conductivity values and AirDryBD, Loi and depth can be considered significant, with p-values of less than 0.05. But the correlations are not significant between the hydraulic conductivities and TOC as well as peat decomposition. By separating the data by soil type, the following Pearson heatmaps are obtained (Figure 11) :

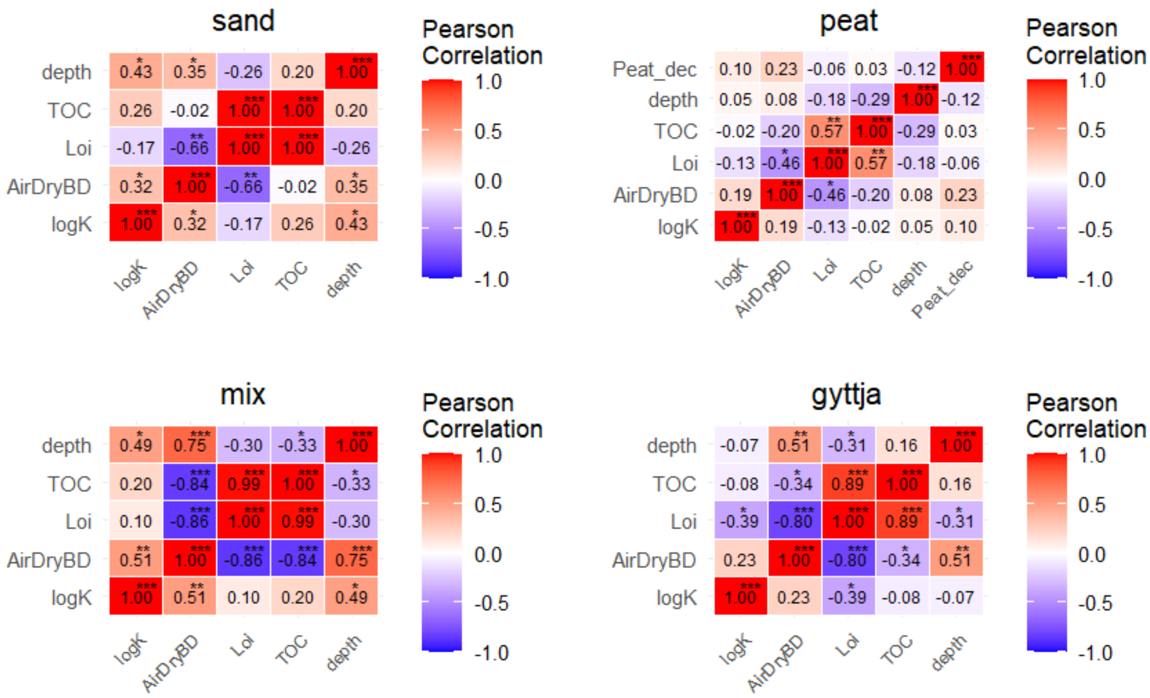

Figure 11 : Pearson heatmaps for each soil texture

Correlations are generally much weaker when soil textures are taken one by one than when all hydraulic conductivities are mixed. It can be seen that only 5 properties have a value greater than 0.3 : AirDryBD and depth for sandy soils and mix soils, Loi for gyttja soils.

Table 3 : Pedotransfer function using multiple linear regression

Variables tested	Pedotransfer function	R^2	p-value
AirDryBD + Loi	$Log(k) = -3.2239877 + 2.8213803 * AirDryBD - 0.0001295 * Loi$	0.3	P < 0.001

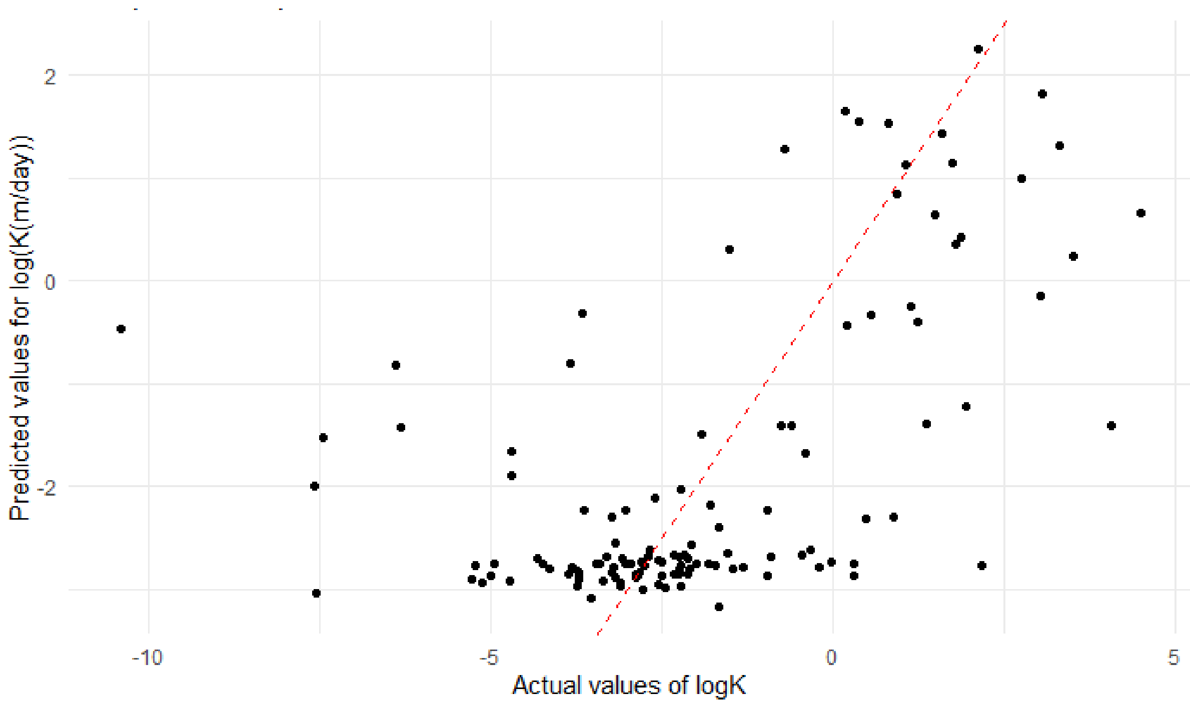

Figure 12 : Comparison of predicted values with actual values using multiple linear regression

Figure 12 shows that the dispersion of the values around the line is quite large, hence the relatively low R^2. In particular, the values that the model predicts to be low have a very high error rate. Adding TOC to the model makes it much less effective. the equation obtained in Table 3 therefore gives an idea of the impact of each variable but cannot be used operationally.

The following Table 4 shows the results of the equations, taking the different types of soil one by one. The p-value is less than 0.05 only for sand. Therefore the correlation is significant only for sand when the soil types are taken independently.

Table 4 : Pedotransfer function using multiple linear regression by soil type

Soil type	Variables tested	Pedotransfer function	R^2	p-value
sand	AirDryBD + Loi	$\text{Log (k)} = 3.15271 - 9.13537 \cdot \text{AirDryBD} - 0.11203 \cdot \text{Loi}$	0.23	$P < 0.05$
peat	AirDryBD + Loi	$\text{Log (k)} = -1.51570 + 0.94833 \cdot \text{AirDryBD} - 0.01743 \cdot \text{Loi}$	0.045	$P > 0.05$
gyttja	AirDryBD + Loi	$\text{Log (k)} = 3.15271 - 9.13537 \cdot \text{AirDryBD} - 0.11203 \cdot \text{Loi}$	0.36	$P > 0.05$

3.1.1) Comparison of hydraulic conductivity with bNMR method

The following figures shows the correlations between hydraulic conductivity and the various parameters obtained using the BNMR method, for the different types of soil :

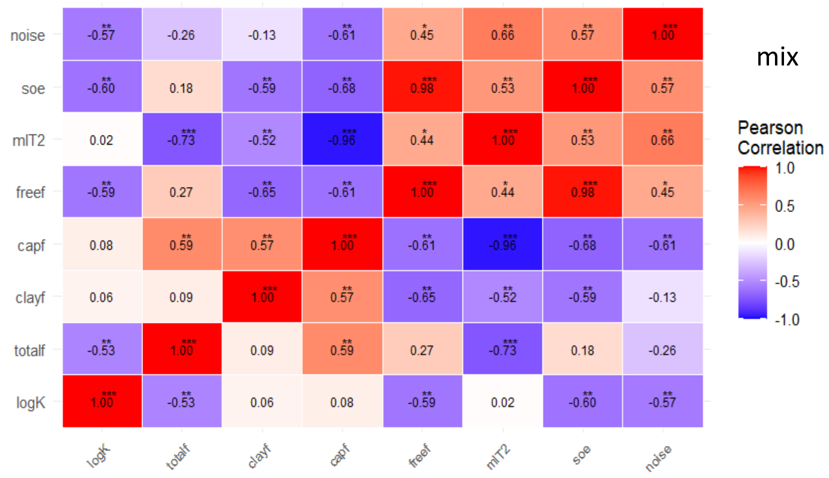

Figure 13 : Pearson heat map, correlation between hydraulic conductivity K and various soil properties for mix soil

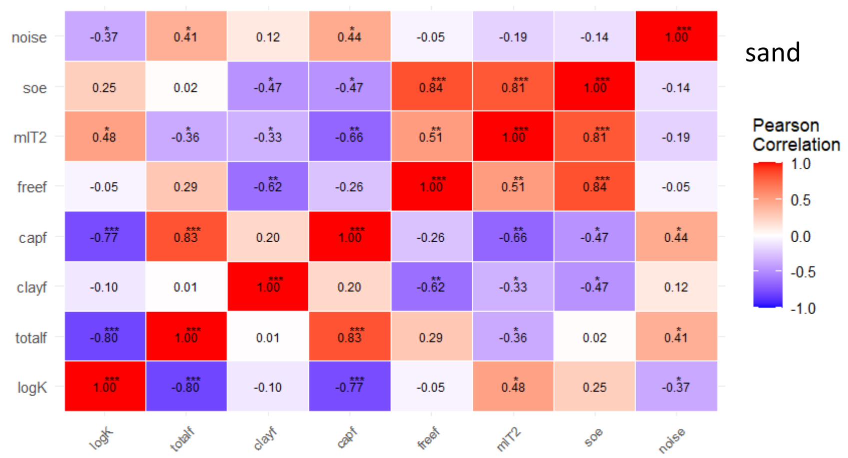

Figure 14 : Pearson heat map, correlation between hydraulic conductivity K and various soil properties for sandy soil

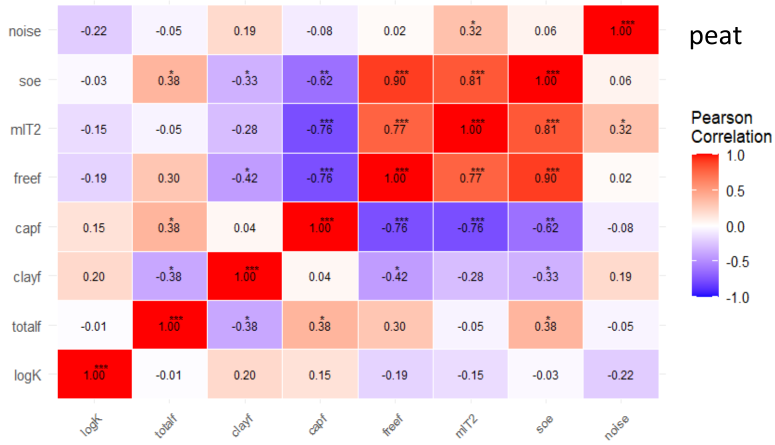

Figure 15 : Pearson heat map, correlation between hydraulic conductivity K and various soil properties for peaty soil

This allows us to see that there are very significant correlations visible between hydraulic conductivity and totalf and capf for sandy soils, whereas the correlations are again weaker for peaty soils.

Table 5 : pedotrasnfer function for sandy soil and peaty soil using parameter from the BNMR method

Variables tested	Soil type	Pedotransfer function	R^2	p-value
All BNMR variables	sand	$Log(k) = 10.5 - 15.0 * totalf + 14.7 * clayf + 14.8 * capf + 14.6 * freef - 7.5 * mlT2 + 104.0 * soe$	0.66	$P < 1*10^{-5}$
All BNMR variables	peat	$Log(k) = 43.4 + 21.0 * totalf - 21.0 * clayf - 21.0 * capf - 21.1 * freef - 23.4 * mlT2 + 43.1 * soe - 0.035 * noise$	0.13	$P < 0.05$

In Table 5, the R-squared value of the equation for sandy soils begins to be relatively high (0.66) and applicable in the field to get an idea of hydraulic conductivity at different sites. The R-squared value for peaty soils is very low (0.13).

if peat is separated between sites for processing results, the results are better on the Ringfenner site, but remain inconclusive for the Vejrumbro site (there are not enough results on peaty soils at Vosborg), as shown on Figure 16 :

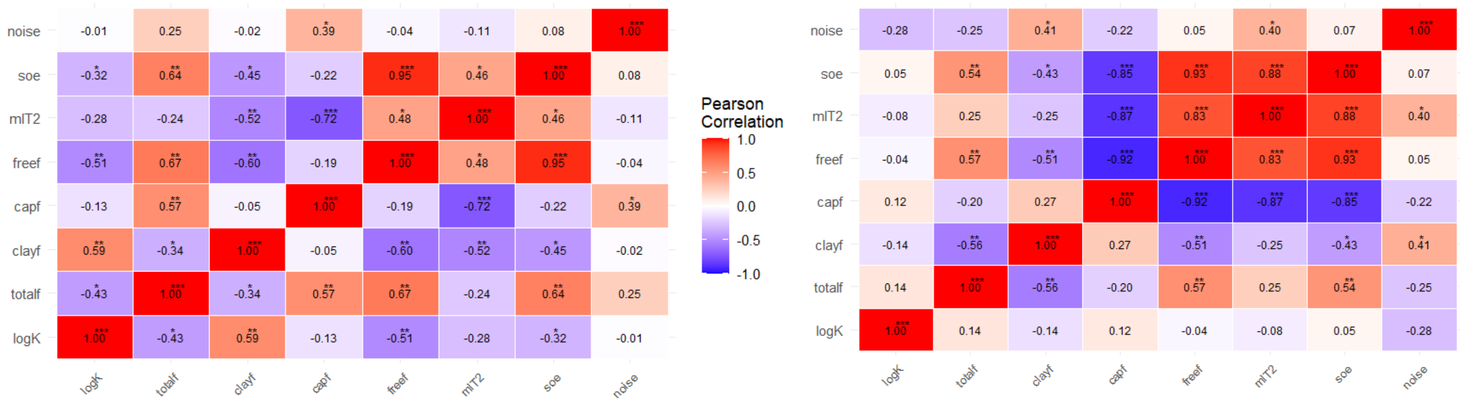

Figure 16 : correlation between hydraulic conductivity and peaty soil parameters for Ringfenner (left) and Vejrumbro (right)

3.1.2) Comparison between open and closed cavity piezometer

Table 6 : Table of hydraulic conductivity results for normal and open-cavity piezometers

Piezometer	K (m/day)	SD (%)	K open cavity	SD (%)	% differences
Ri2-NS3-02-2	0.00513	16.8	0.0140	11.6	63
Ri2-NS3-03-2	0.00900	16.3	0.0094	25.4	5
Ri2-NS3-05-3	0.0350	41.4	0.0677	59.4	48

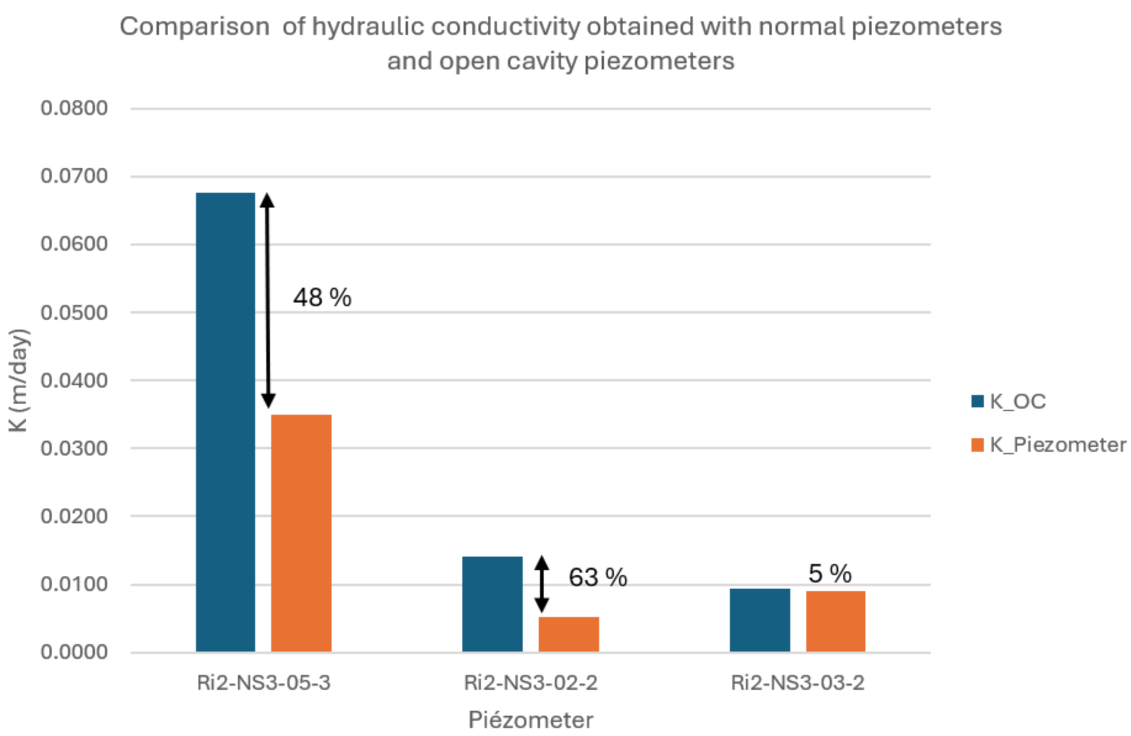

Figure 17 : Comparison of hydraulic conductivity obtained with normal piezometer and open cavity piezometer (OC)

Hydraulic conductivity results are higher for open-cavity piezometers than for conventional piezometers. The difference varies between 5 and 63% (Figure 17). As the values are very low, the orders of magnitude remain the same at the same point, between an open-cavity piezometer and a normal piezometer. The orders of magnitude of the standard deviation are relatively close (Table 6).

3.2) Flowrates at Vosborg

3.2.1) Water flow calculations

Here is the piezometer information table (Table 7) as well as details of the parameters used to calculate Q (Table 8) with the explanation for the aquifer thickness (Figure 18). This figure is a geophysical profile of the soil, it allows us to determine the thickness of the aquifer with the resistivity values. The same range of values corresponds to the same aquifer. Table 9 summarises the results obtained on the transect studied:

Table 7 : Information on piezometers (elevation = altitude; hat = height above ground level of the piezometer; sounding: depth at which the water was measured)

Piezometers	Elevation (m)	Hat (m)	Sounding (m)	H
VE-OC1-01	1.163	1.5	2.206	0.457
VE-OC1-02	0.617	1.5	1.706	0.411

Table 8 : Table for calculating the daily flow through the study area

dH (m)	Aquifer thickness (m)	aquifer width (m)	A (m2)	L (m)	K (m/day)	Q (m3/day)
0.046	5	50	250	53.4	3.32	0.71

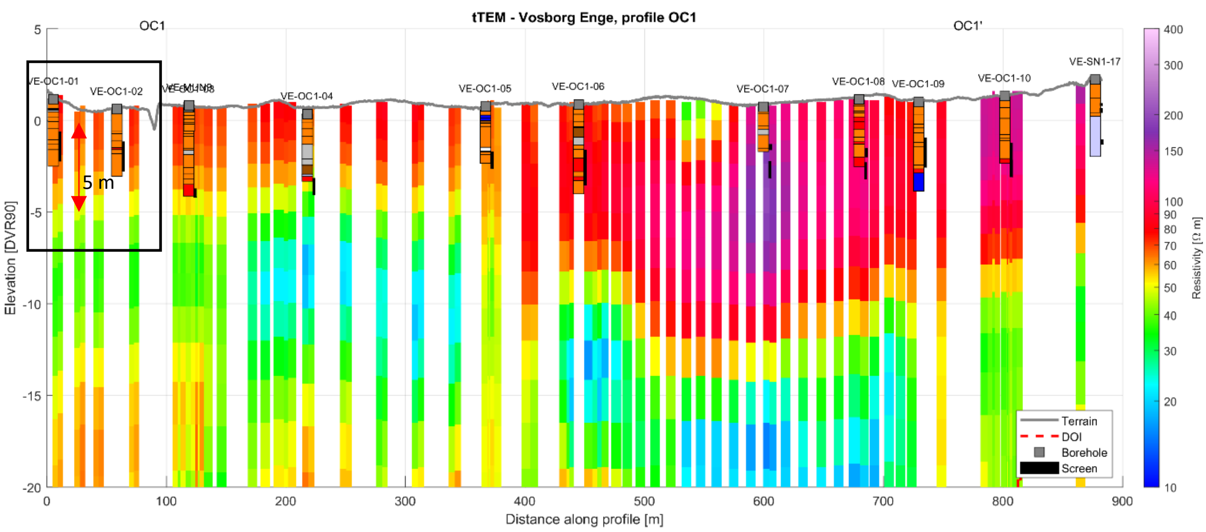

Figure 18 : Obtaining the thickness of the aquifer

Table 9 : Results of reconstructed flows on transect OC1 at Vosborg, 24 May 2024

Piezometers	Q (m3/day)	Depth
01-1 - 02-1	0.7	2.5825
03-1 - 04-1	6.1	4.325
05-1 - 06-1	0.5	3.1825
06-1 - 07-1	8.5	3.4325
07-1 - 08-1	11.9	3.6575
08-2 - 09-1	1.5	2.82225

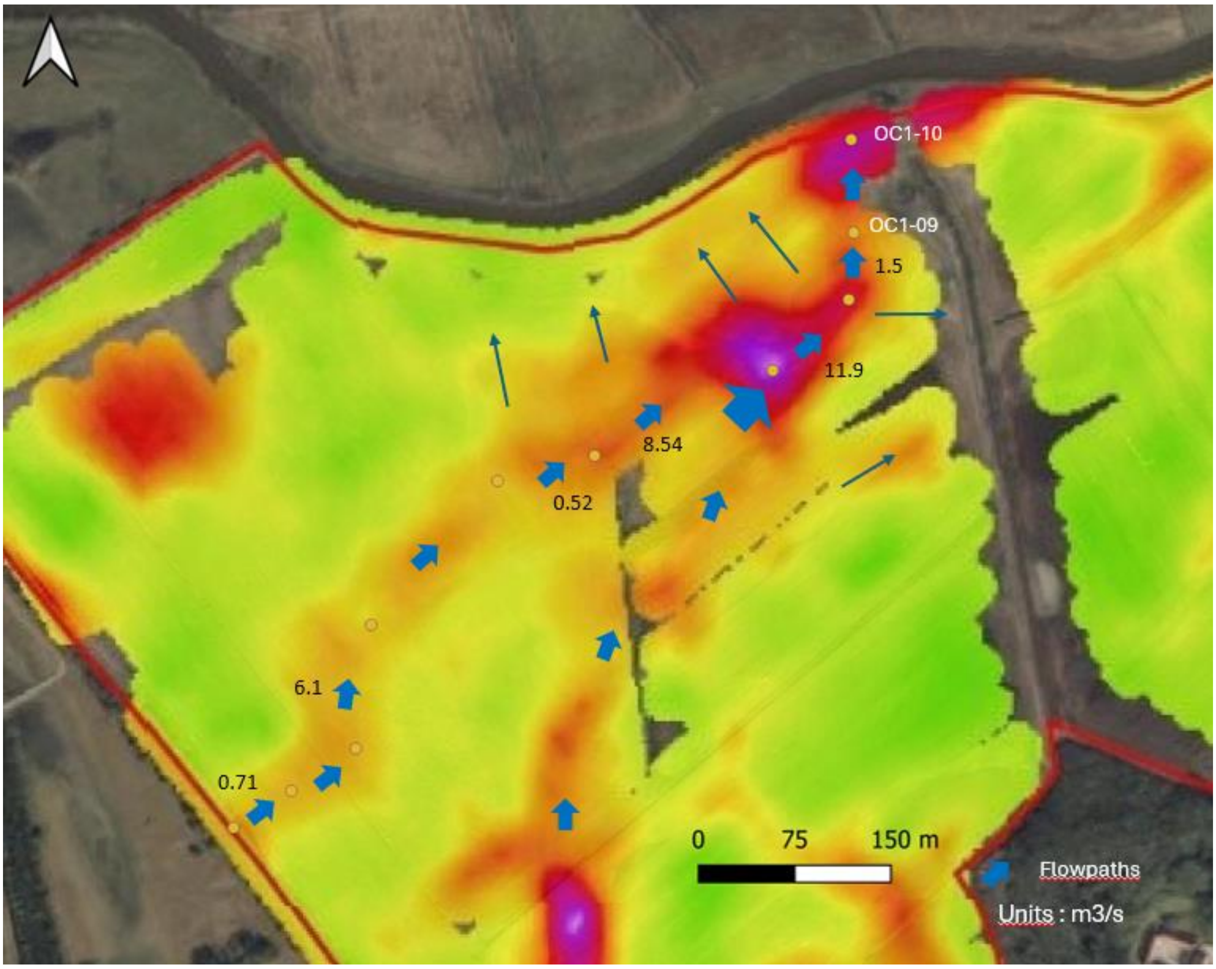

Figure 19: flow map for 24 May 2024 on transect OC1 at the Vosborg site, in the sandy aquifer

This Figure 19 shows that the water flows increase when the two aquifers converge. The area with the highest flow rates allows, according to the results obtained, 11.9 m³ per day, or 11,900 liters of water per day.

3.2.2) direction of flow over time

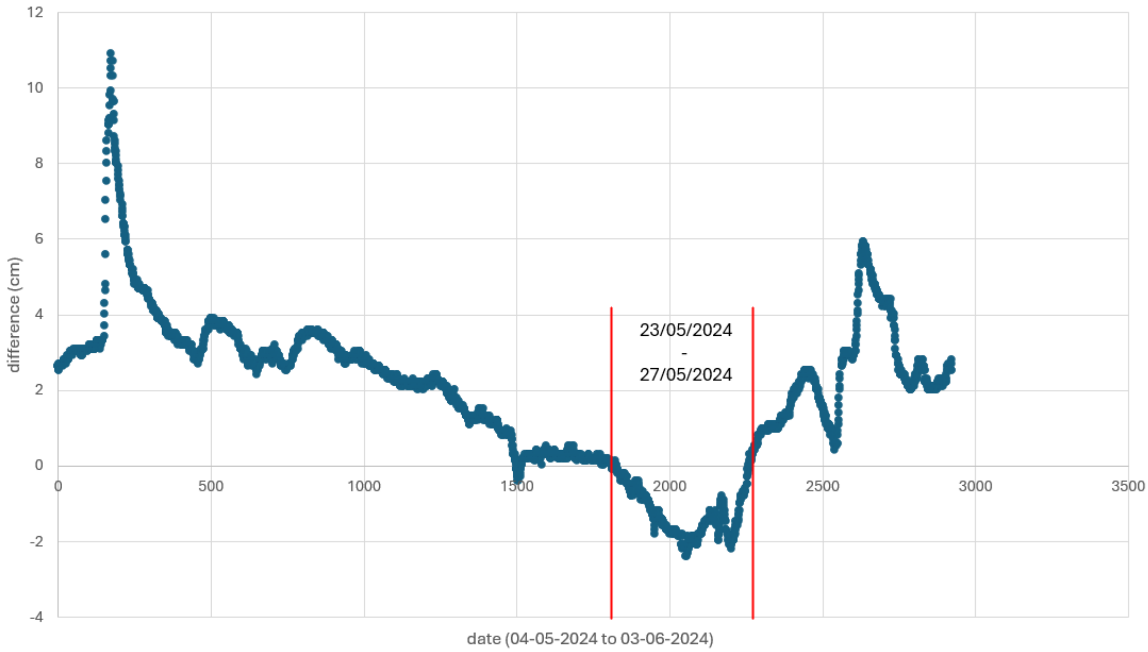

Figure 20 : Difference in water level between piezometers OC1-09 and OC1-10 between 04/05/2024 and 03/06/2024.

The two points of interest OC1-09 and OC1-10 are visible in Figure 19 in white. The results (Figure 20) show that over a period of 1 month, only 5 days show negative results, therefore a direction of flow from the river to the peatland, since the calculation made is the piezometers on the peatland side minus the piezometer on the river side. The rest of the time, the peatland feeds the river.

4) Discussion

4.1) Comparison with the different soil properties

Initially, correlations were observed, indicating that soil characteristics significantly influence hydraulic conductivity, confirming findings from previous studies. Additionally, these correlations validate the accuracy of the field-conducted slug tests and subsequent data processing. If we take the results as a whole, singular correlations are observed between hydraulic conductivity and airdryBD as well as hydraulic conductivity and Loi and hydraulic conductivity and depth. As far as bulk density is concerned, it's quite logical: when it increases, it means that the soil is less rich in organic matter and sandier. On the other hand, sandier soils do not have a high water retention capacity, so this may explain why hydraulic conductivity tends to increase with bulk density (« Bulk Density - Natural Resources Conservation Service », 2008). Conversely, loss on ignition (Loi) decreases while hydraulic conductivity increases. An increase in the amount of organic matter increases Loi, since this parameter corresponds to the percentage of the sample weight that volatilises at high temperature. An increase in the amount of organic matter would therefore reduce the capacity of water to pass through the soil, according to our results, which can also be confirmed in the literature (W.J. Rawls et al., 2004). Following this logic, TOC should also be negatively correlated with hydraulic conductivity. This is the case in the results, but the correlation is not significant according to the Pearson test. However, this can be explained by the fact that the number of samples with values for this parameter was lower, particularly in sandy soils. This lack of data is undoubtedly a cause of the lack of significance in the test.

When separated by texture, correlations are present but are also not highly significant. But as the total amount of data is small, it is even smaller if the data is separated by texture. A larger number of data points could perhaps provide better data. However, the soil category where the most data was obtained, the peat soils, showed no significant correlation between hydraulic conductivity and the soil properties tested. The obtained equation with all types of soil shows significant limitations in predicting K values with an R-squared of only 0.3. The general trend is respected; however, the precision is far from sufficient. Once again, a larger dataset could have potentially led to better results, but this is not certain. The poor prediction could also be attributed to the omission of an important soil parameter (such as pore size, pore distribution…). The reduced efficiency of the model when implementing TOC values is probably due to the fact that its implementation removes a lot of data, particularly on sandy soils where TOC have not been measured. so even if TOC is strongly linked to Loi, the lack of data would make the results less significant between hydraulic conductivity and TOC than between hydraulic conductivity and Loi.

When the equations are made taking the soil types one by one, the results are no more significant. The p-value is less than 0.05 for sand, but greater for peat and gyttja. There is no significance for gyttja, but this can certainly be explained by the small size of the sample, since the R-squared is 0.36. The peat may be different from one site to another, which could explain the results obtained. The same operations would then have to be carried out, with the data separated by site, in order for this to be verified.

4.2) BNMR results

The results for the BNMR method seem very promising, with higher correlations and better pedotransfer functions than with soil parameters obtained by sampling, particularly on sandy soils. However, on peaty soils, the results are very different from one site to another, which confirms the hypothesis that peat can vary greatly from one site to another. As the study of these parameters was the last task to be completed during the internship and was not a priority, the analysis could not be carried out deeply, but these initial results invite further research into the use of this method to obtain more accurate hydraulic conductivities. Indeed, the various porosity parameters (totalf, clayf, capf, freef) showed very high correlations with the hydraulic conductivities, and therefore seem very promising for studying hydraulic conductivity if they can be obtained quickly using the BNMR method. These parameters, combined with the soil parameters used in the previous section, could also lead to better pedotransfer functions.

4.3) Open / closed cavity piezometer

The open cavity tests conducted at the first site (Vejrumbro, Figure 1) did not proceed well, with ground collapse occurring at times and the results obtained by the probe not appearing very usable. At the Ringfenner site (**Erreur ! Source du renvoi introuvable.**), a second day in the field resulted in much better ground conditions, allowing satisfactory and usable results to be obtained for 3 boreholes, because the peat held together better and didn't collapse.

The aim of applying slug tests with open cavity piezometers was to observe the impact of screens on conductivity results. The results obtained suggest that screens reduce hydraulic conductivity. However, other factors need consideration. The results obtained with the open cavity method sometimes closely looks like conventional results and sometimes differ significantly, knowing that the depth was quite similar between the normal and open cavity slug test (Table 10) :

Table 10 : depth of the conducted slug tests in open and closed cavity (m)

Piezometer	Depth normal Piezometer	Depth open cavity
Ri2-NS3-05-3	0.19 - 0.49	0.3 - 0.45
Ri2-NS3-02-2	0.33 - 0.83	0.3 - 0.6
Ri2-NS3-03-2	0.4 - 0.7	0.3

Therefore, it is challenging to determine whether some results were biased during the experiment. Nevertheless, a hypothesis can be proposed that screens reduce hydraulic conductivity in peat soils, despite the inclusion of screens in the zlotnik and Hvorslev methods with data from piezometers in equations. These findings would require confirmation with a much larger dataset than the three tests conducted. Comparing these results across the entire Ringfenner site could provide valuable insights but would take substantial time investment. Such an approach might facilitate the application of a correction factor to results obtained with standard piezometers.

4.4) Flow calculations

4.4.1) Water flow calculations

The flow results obtained provide an idea of the flow in the sand aquifer. However, several factors must be considered in the interpretation of the data:

- The period when the data was collected was particularly dry (May 24, one of the rare times when water seemed to enter the peatland from the river in the lowest area of the peatland between piezometers OC1-09 and OC1-10).
- The results are obtained at different depths, each with specific soil characteristics. Deeper soils often have coarser sands, which may explain the differences in conductivity observed from one area to another in certain cases.
- It would be beneficial to have data on the other transects on the same day to provide a basis for comparison.

4.4.2) Direction of flow over time

The direction of flow in the peatland over the past month has been studied, revealing that the water flows from the peatland to the river Storå. However, the reverse was true over some day during the period. It is therefore of interest to understand the factors that caused this shift in flow regime. One hypothesis is that weather conditions, which influence the levels of the water table and the river, are responsible for these variations. To study this accurately, precise information about how the sand aquifer is supplied would be necessary. Previous results have shown a close connection between the ditches and the sand aquifer, so perhaps during rainy periods, the water collected in the drains gradually migrates into the aquifer, which would create a gradient with the river. Notably, the period when the flow ratio was reversed coincides with almost two weeks without rain, according to historical weather data for the area (Timeanddate.com, 2024). Such dry periods are relatively rare in this geographic region, especially in winter (Vemb Climate By Month, 2024). It is thus likely that the phenomenon, where the river feeds the sand aquifer due to insufficient precipitation, is infrequent over the course of a year. This hypothesis assumes that the lack of precipitation had a more significant impact on the aquifer than on the river, resulting in the reversal of water flow direction.

5) Conclusion

5.1) Report conclusion

The main objective of this report was, by obtaining hydraulic conductivities and comparing them with certain soil parameters for which data was available on the sites in question, to find an equation that would enable hydraulic conductivity to be determined without the need for time-consuming slug tests. In a broader sense, the aim was to see what correlations exist between these different soil parameters and hydraulic conductivity. With regard to this objective, the equation obtained with the multiple linear regressions has a low R-squared (0.3), and therefore does not allow the hydraulic conductivities with the soil parameters in question (depth, AirDryBD and Loi) to be determined accurately. However, certain correlations were observed, the most convincing being between the AirDryBD values and hydraulic conductivity, with a correlation of 0.5. The correlations when separating the data by type are lower than when all the samples are mixed. However, with the parameters of the BNMR method, promising results were obtained, whether with all types of soil mixed together, or by separating the soils by texture.

Slug tests using open-cavity piezometers showed an increase in hydraulic conductivity compared with traditional methods. However, the number of slug tests carried out was very limited. In view of the differences for two of the three piezometers where the tests were carried out, some of the difference in results is certainly caused by the screens themselves, which could therefore slightly underestimate the results obtained. More in-depth studies and larger datasets would therefore be required to confirm this hypothesis. However, this type of manipulation is very time-consuming for the number of tests that can be carried out.

The practical study of flow modelling at Vosborg has enabled us to determine the quantities of water passing through a sandy aquifer in the peatland on a given day. The study of water flows entering and/or exiting the peatland over a month has highlighted that this peatland more often supplies the river than the reverse. An analysis of data over a year would confirm this hypothesis, or even strengthen it. Indeed, a comparison here showed that the period when the river fed the aquifer was a time with no precipitation over a long period. Such a phenomenon is rather rare in Denmark, and even more so during other times of the year. It would be interesting to see if this type of phenomenon recurs during a dry period. This would mean that the lack of precipitation affects the aquifer in question more significantly than the river.

More broadly, other types of applications could have been conducted to study the peatland using hydraulic conductivities. For example, a significant study could have been undertaken to examine nutrient concentrations in the peatland at various points. This could have provided insights into the amount of nutrients retained in the peatland and the quantity that is released into the river, as the peatland feeds into it.

5.2) Critical reflection on professional experience

Regarding the personal experience of this internship, I had the opportunity to work in the field of research for the first time, after having had various more traditional professional experiences. This allowed me to discover new ways of working, especially in a new country. The various tasks I had to complete allowed me to acquire skills mainly in data processing, as I had the opportunity to work extensively with RStudio, which will be an asset in my future professional projects. Having had the opportunity to conduct the fieldwork related to the data I later used also allowed me to thoroughly understand what I was working on afterward in the office.

Overall, this internship allowed me to discover the different aspects of working in the research world, both positive (flexibility and freedom in how to conduct one's work and research to meet set objectives) and negative (results obtained are not always what one would like to achieve, which is certainly even more true in research within the field of the natural environment). I believe that this professional experience as a whole will be an asset for my future projects in France.

6) Bibliography

Bulk Density - Natural Resources Conservation Service. (2008). https://www.nrcs.usda.gov/sites/default/files/2022-10/nrcs142p2_051591.pdf

Butler, J. J. et Jr. (2019). *The Design, Performance, and Analysis of Slug Tests* (2e éd.). CRC Press. https://doi.org/10.1201/9780367815509

Carbon rich peat soils | Klimarådet. (2024, 28 juin). https://klimaraadet.dk/en/analyser/kulstofrige-lavbundsjorder

datatab.fr. (2024). https://datatab.fr/tutorial/pearson-correlation

Department of Ecoscience. (2024, 23 mai). https://ecos.au.dk/en/

Devlin, J. F. (2020). 2 Darcy's Law as a basis for measuring groundwater velocity. https://books.gw-project.org/groundwater-velocity/part/darcys-law-as-a-basis-for-measuring-groundwater-velocity/

Gorham, E. (1991). Northern Peatlands: Role in the Carbon Cycle and Probable Responses to Climatic Warming. *Ecological Applications*, *1*(2), 182-195. https://doi.org/10.2307/1941811

IPS - International Peatland Society. (2024). https://peatlands.org/

Leifeld, J. et Menichetti, L. (2018). The underappreciated potential of peatlands in global climate change mitigation strategies. *Nature Communications*, *9*(1), 1-7. https://doi.org/10.1038/s41467-018-03406-6

Loss on Ignition Testing. (2022, 28 janvier). *Membrane Works*. https://membraneworks.com.au/loss-on-ignition-testing/

Reza Mashhadi, S., Grombacher, D., Zak, D., Erik Lærke, P., Estrup Andersen, H., Christian Hoffmann, C. et Jes Petersen, R. (2024). Borehole nuclear magnetic resonance as a promising 3D mapping tool in peatland studies. *Geoderma*, *443*, 116814. https://doi.org/10.1016/j.geoderma.2024.116814 von Post, L. (1922). Sveriges Geologiska Undersöknings torvinventering och några av dess hittills vunna resultat. *Svenska mosskulturföreningens tidskrift*, (37). https://res.slu.se/id/publ/124005

W.J. Rawls, A. Nemes, et Ya. Pachepsky. (2004). Effect of soil organic carbon on soil hydraulic properties. https://www.sciencedirect.com/science/article/pii/S0166248104300061

Wong, L. S., Hashim, R. et Ali, F. H. (2009). A Review on Hydraulic Conductivity and Compressibility of Peat. *Journal of Applied Sciences*, *9*(18), 3207-3218. https://doi.org/10.3923/jas.2009.3207.3218

7) Annex

7.1) Aerial photographs of the study sites

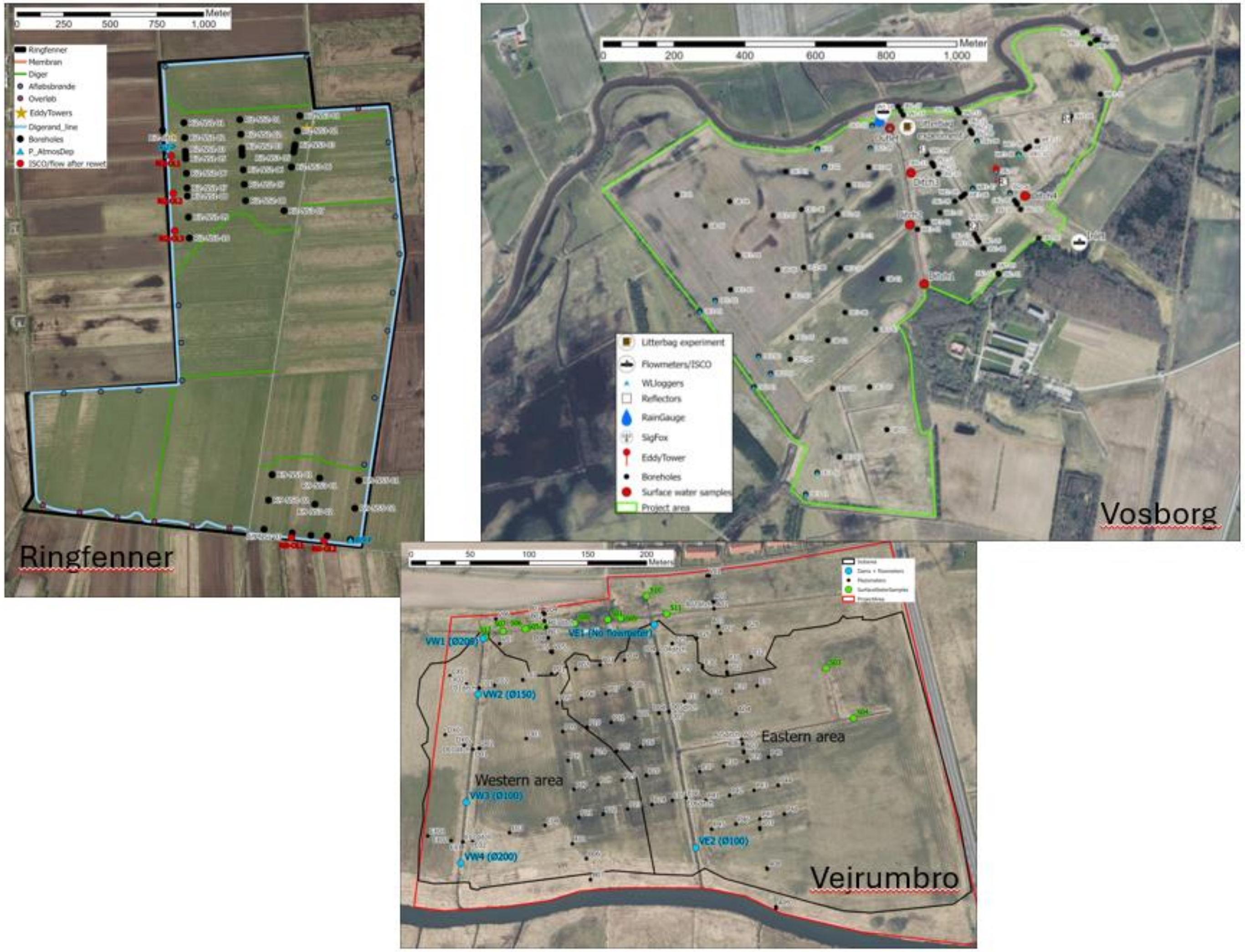

Figure 21 : Aerial photographs of the study sites

7.2) R program for the calculation of the hydraulic conductivity

```
library(ggplot2)

chemin_fichier <- "C:/Users/SachaG/Documents/DAE/danemark/travail/travail/slug
test/open_cavity/tri/Ri2-NS3-02-2_5.csv"

data <- read.csv(chemin_fichier)
data$Time <- seq(1, length.out = nrow(data))

nom_fichier <- basename(chemin_fichier)
nom_piezometre <- sub("^(.*?)_.*", "\\1", nom_fichier)

chemin_parametres <- "C:/Users/SachaG/Documents/DAE/danemark/travail/travail/slug
test/data_piezo.csv"
parametres <- read.csv(chemin_parametres)

# Utilisation de grep pour une correspondance partielle
indices <- grep(nom_piezometre, parametres$Piezometre, ignore.case = TRUE, fixed = FALSE)

# Définition des données relatives aux piézomètres à partir des paramètres lus
parametres_piezometre <- parametres[indices, , drop = FALSE]
L <- as.numeric(parametres_piezometre$L)
Rw <- as.numeric(parametres_piezometre$Rw)
Rc <- as.numeric(parametres_piezometre$Rc)
H <- as.numeric(parametres_piezometre$H)
D <- as.numeric(parametres_piezometre$D)
nmax <- 1000

# Initialiser la somme
Psum <- 0

# Boucle pour calculer la somme des termes
for (n in 1:nmax) {
  betan <- pi * (n - 0.5)
  term <- (cos(betan * H / D) - cos(betan * (H - L) / D))^2
  bessel_term <- Bessel::BesselK(betan * Rw / D, 0) / (betan^3 * Bessel::BesselK(betan * Rw / D, 1))
  Psum <- Psum + term * bessel_term
}

# Calculer le facteur de forme de Zlotnik ou Hvorslev
F <- L * Rw / (2 * D^2 * Psum) #Zlotnik
#F <- asinh(L / (2 * Rw))# Hvorslev
print(F)

max_value <- max(data$LEVEL)
min_value <- min(data$LEVEL)
first_value <- head(data$LEVEL, 1)

# Calculer le rapport pour chaque valeur de l'altitude
#data$Ratio <- (max_value - data$LEVEL) / (max_value - min_value) # pompage
```

```r
data$Ratio <- (data$LEVEL - first_value) / (max_value - first_value) #ajout

# Trouver le premier index où Ratio est calculé
first_ratio_index <- which(data$Ratio == 1)[1]

# Filtrer les données à partir du premier calcul de Ratio
data_filtered <- data[first_ratio_index:nrow(data), ]

datasub <- subset(data_filtered, Ratio >= 0.15 & Ratio <= 0.25) # on garde que les lignes dans
l'intervalle

# Effectuer la régression linéaire sur les données filtrées
fit <- lm(log(Ratio) ~ Time, data = datasub)
slope <- coef(fit)[2]
summary(fit)

K <- ((slope * Rc^2 * F) / (-2 * L)) * 86400
K <- paste("K_Zlotnik (m/day):", round(K, 5))
print(K)

y_milieu <- median(data_filtered$Ratio)

ggplot(data_filtered, aes(x = Time, y = Ratio)) +
  geom_line() +
  scale_y_log10(limits = c(0.1, NA)) +
  labs(x = "Time (s)", y = "log(H/H0)", title = paste("Recovery head -", nom_fichier)) +
  theme_minimal() +
  theme(plot.title = element_text(hjust = 0.5)) +
  annotate("text", x = max(data_filtered$Time), y = y_milieu, label = K, hjust = 1, vjust = 1, size = 4,
color = "blue") +
  geom_smooth(data = datasub, method = "lm", se = FALSE, fullrange = TRUE, color = "red")
```

7.3) Von post scale

Scale number	Description	Amorphous material	Plant structure	Expressed fluid	Peat lost from hand	Peat retained in the hand	
						consistency	colour
H1	completely unhumified	none	obvious	colourless, clear	none	not porridgey	less dark
H2	virtually unhumified	none	obvious	yellow-brown, clear	none	not porridgey	less dark
H3	little humified	small	obvious	noticeably turbid	none	not porridgey	less dark
H4	poorly humified	modest	obvious	very turbid	none	somewhat porridgey	less dark
H5	fairly humified, structure distinct	fair amount	plain, but somewhat obscured	strongly turbid	some	very porridgey	less dark
H6	fairly humified, structure less distinct	fair amount	indistinct, but still clear	strongly turbid	up to 1/3	very porridgey	less dark
H7	quite well-humified	considerable	much still visible	strongly turbid	about 1/2	gruel-like	very dark
H8	well-humified	large	vague	strongly turbid	2/3	only fibrous matter and roots remain	very dark
H9	almost completely humified	most	almost none visible	strongly turbid	almost all	homogeneous	very dark
H10	completely humified	all	none visible	strongly turbid	all	porridge	very dark

Figure 22 : Von post Scale (von Post, 1922)

7.4) Annex 4 : Boxplot of raw hydraulic conductivities

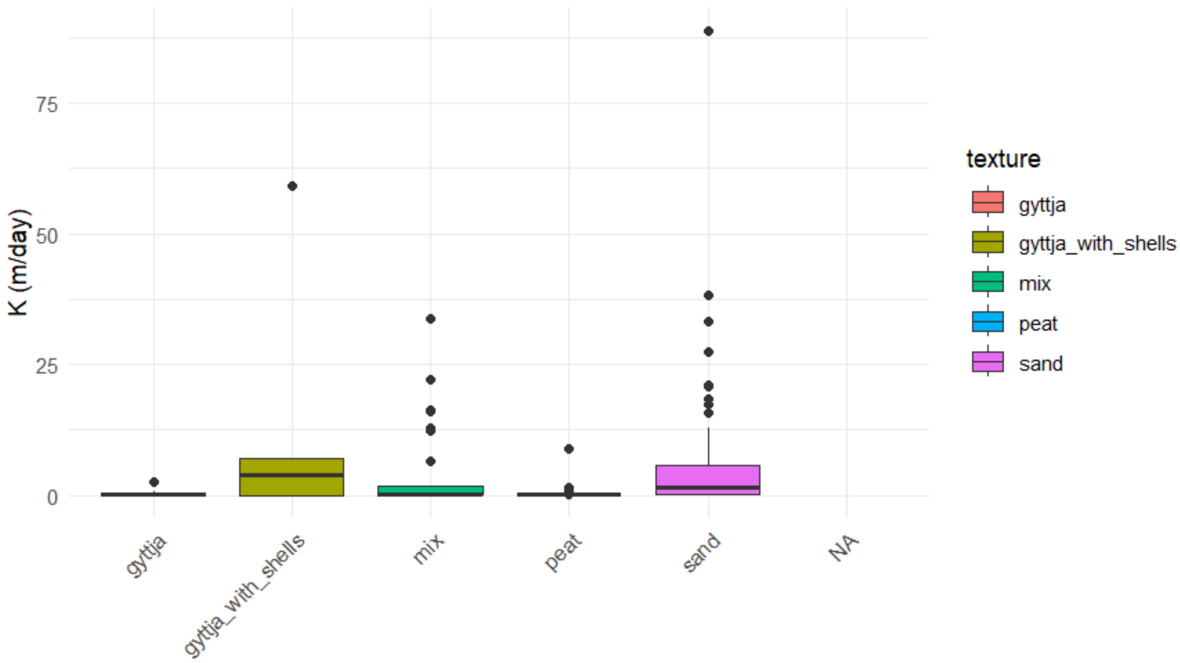

Figure 23 : box plot of K values recovered in the field

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Hydraulic Properties of Peatlands

Résumé :

This 12-week placement in the Ecoscience Department at the University of Aarhus focused on the study of hydraulic conductivity in peatlands. Studying these peatlands allows for better protection and restoration, which is an important goal in Denmark's environmental policies, as they are significant carbon sinks.
The missions carried out have expanded the available database on hydraulic conductivities across different sites, but most importantly, they have helped understand the parameters influencing these conductivities by searching correlations, or by studying the impact of the screens of the piezometers.
The tasks involved fieldwork, data processing, coding, and bibliographic research.

Mot clés : hydrology, peatlands, hydraulic conductivity, slug test

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