Rapport de stage individuel

4ème année

Measurements and application of hydraulic conductivity and groundwater flows in wetlands

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Summary

1. Introduction

1.1. The host institution, the Ecoscience departement

The University of Aarhus is one of Denmark's leading universities, ranking in the top 150 universities worldwide and in the top 25 universities in the European Union. The university is divided into five faculties including Technical Sciences. Within this faculty there are several departments, such as Ecosciences, the host organization for this internship (Aarhus University, s. d.). The Department of Ecoscience has a staff of around 275, of whom around 200 are permanent employees, 15 are PhD students, 20 are post-docs and around 40 are employees on fixed-term contracts (Aarhus University, 2024).

The department's domains of research cover a wide range of aspects of biology and ecology, from the genetic level, physiological processes, individuals, species and populations to ecosystems. The Ecoscience department is organized into several sections, themselves divided into various research domains:

- **Arctic:** Studies in the Arctic help to better understand the nature and environment specific to this habitat, particularly in Greenland. Research covers a wide range of trophic levels, from micro-organisms, plants and animals to individuals, populations and ecosystems. The department is particularly involved in advising on the use of raw materials as well as in mining operations. Another research topic studies the effects of climate change on Arctic ecosystems and their environment.
- **Marine ecology:** Studies seek to understand the structure and function of marine ecosystems from the coastal zone to open marine areas. A distinction is also made between changes caused by natural variations and changes caused by human activity. The department aims to develop tools and methods to assess the state of marine areas, and sustainable solutions to promote carbon retention and biodiversity restoration.
- **Terrestrial ecology:** Research is aimed at developing strategies for more sustainable production in the fields of agriculture and agroforestry, through the development of nature-based solutions. The emphasis is on developing tools to restore a balance between nature and the things that impact it, such as recreational activities.
- **Freshwater ecology:** This field covers the biology and ecology of streams, lakes, ponds, natural and artificial wetlands, particularly in rural areas where pressure on water resources can be significant. Biological and chemical processes are studied, as are ecosystem relations with nutrients and hazardous substances. Other topics include lake and river restoration, greenhouse gas monitoring and interactions between catchments and freshwater zones.

In these four areas, the Ecoscience department is setting up research, monitoring and advisory services for various authorities, enabling more sustainable management of these habitats by proposing solutions for preserving and enhancing ecosystem biodiversity. Major national environmental databases are managed, providing information on freshwater, marine and terrestrial areas.

1.2 - The catchment science section

In order to deal with the previous research domains, the Department of Ecoscience is organized into sections, such as marine ecology, freshwater ecology which focuses on lakes, and the catchment science and environmental management section. As part of this internship, tasks and missions will be supervised by this third section. It focuses on numerous aquatic areas such as lakes, streams and fjords, ecosystems altered by high inputs of nutrients and hazardous substances, human activities (in urban and agricultural zones) and climate change. The main areas of focus are hydrology and nutrient dynamics at the catchment section, the creation of tools to reduce nutrient loss to the aquatic environment and relation between greenhouse gases and wetlands. This knowledge is used to provide advice to authorities to ensure better management at catchment scale.

1.3 - The internship subject

1.3.1 - Context

The riparian zone is an important transition zone between terrestrial ecosystems such as upstream hills and freshwater ecosystems such as rivers. It is a strip of land that separates these two systems, and can be referred to as a buffer zone, vegetated riparian strip or floodplain and wetland when their width is greater[1]. Because of their position, they play an important role in the movement of runoff and groundwater, which can be loaded with nutrients and chemicals from the uplands to the outlet (Hill, 1996).

Inorganic nitrogen is present in aquatic environments naturally (atmospheric deposition, dissolution of geological deposits, N_2^- fixation by prokaryotes, degradation of organic matter) and is found in the form of ammonium ions ammonium NH_4^+, nitrites NO_2^- et nitrates NO_3^- (Camargo et al., 2005b). However, anthropogenic activities have considerably altered the natural nitrogen cycle. Agricultural activities (livestock breeding, crop fertilization), agricultural and urban runoff, industrial waste and wastewater effluents are major new sources of nitrogen. Due to oxidation processes, most nitrogen is found in the form of nitrates. As a source of nutrients, large quantities of nitrates (and phosphates) lead to excessive enrichment of the environment, as well as to increased growth and development of algae and aquatic plants. Eutrophication degrades water quality and can lead to various secondary effects, such as a drop in ecosystem biodiversity. (Smith, 2003; V. Smith et al., 1999)

In recent decades, a great deal of research has been carried out into the ability of wetlands to remove nitrates. Indeed, due to their significant buffering effect, they help reduce diffuse pollution from agriculture and other human activities (Hill, 2019). In order to understand nitrate elimination processes, groundwater hydrology and flow paths are recognized as essential. (Petersen et al., 2020)

Within wetlands, hydrology and groundwater flow paths are rather complex. Firstly, peatlands are categorized according to the source of their water supply. A peatland with a water supply via rainwater alone will be ombrotrophic, while a supply via adjacent sources will correspond to a minerotrophic peatland. Furthermore, the degree of decomposition of peat and decomposing vegetation may differ from one site to another. The combination of hydrological and morphological parameters of a wetland controls flow directions, ecology, water quantity and the type and quantity of dissolved minerals and nutrients. These complex environments are considered efficient for storing nitrogenous inputs, which can be eliminated or transformed by various processes. Nitrogen components can be taken up by plants, which is a temporary storage of nitrogen, which will return to the system when the plant dies. Nitrogen can also simply be stored in the soil and groundwater. Denitrification, on the other hand, is a microbial transformation of nitrogen (NO_3^-- into N_2^-, the gaseous phase of nitrogen), with the advantage of completely eliminating nitrogen from the system (Mayer et al., 2007).

1.3.2 - Purpose of the internship

In the context of a better understanding of hydrology for effective nitrate removal, the aim of the internship will be to determine how much water runs through these wetlands.

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[1] For better understanding in this report, we will use the terms "wetland" and "peatland".

To this end, it is advisable to analyze hydraulic conductivity, which represents soil permeability, and which can be measured on the field in units of distance per unit of time. This parameter varies according to soil composition so it will be possible to determine correlations with soil parameters. It also allows us to calculate flow which comes in and comes out in wetland soil using Darcy's law. Finally, an alternative method to the original slug test will be tested as a solution to a bias brought about by the original technique.

1.3.2 - Tasks carried out during the internship

In order to successfully complete this internship, several tasks will be carried out. Sessions at several study sites will enable us to carry out various measurements of hydraulic conductivity (using the slug test method that will be presented later in this report), as well as adding new data to the existing database. A considerable amount of data sorting will be required before the data can be processed. To this end, a code will be developed using R software, enabling hydraulic conductivities to be automatically calculated from the slug tests. The results obtained will be analyzed and correlated with other factors, such as soil composition. Additional analyses can be carried out, such as the open cavity slug test, the alternative method which will be explained later. The aim of this report will be to use hydraulic conductivity in Darcy's law and model flow in the various soil layers.

Some tasks were carried out with Sacha Gaduel, who had a similar internship subject. Fieldwork and data collection and sorting were carried out in collaboration. The following tasks were carried out individually: data analysis, processing and visualization with R, interpretation and reporting. This work will be carried out on a set of data from three study sites. Only the modeling will be carried out on Ringfenner, different from Sacha's.

2. Material and methods

2.1 - Presentation of study sites

In order to gain an overall view of hydraulic conductivity, several study sites will be taken into account, namely Vosborg, Ringfenner, and Vejrumbro where slug tests have already been carried out (figure 1).

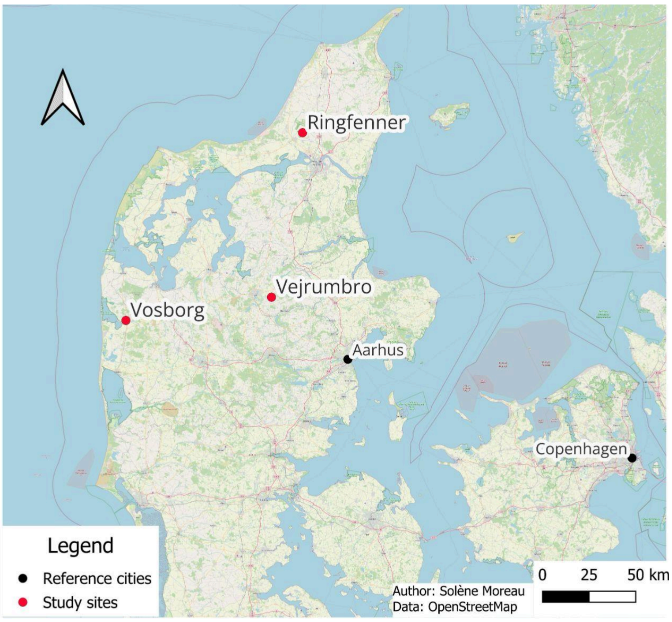

Figure 1: Map of study site locations (author : Solène Moreau). Study sites are represented in red. Aarhus and Copenhagen are shown on the map as geographic landmarks.

Vosborg is located in central western Denmark. The site, formerly occupied by crops, has recently been restored to its original peatland function. It is bordered by the Storå river and is about ten kilometers from the ocean. The site is occupied by numerous piezometers organized in transects or groups which allow to study hydrology of the site (Figure 2). It is a minerotrophic peatland, which means that it is fed by groundwater, but also by adjacent waters such as the river.

Figure 2: Map of Vosborg study site (author: Ecosciences departement)

Vejrumbro is also a minerotrophic peatland located in the center of Denmark (figure 3). The measurements carried out on this site are used in the rest of this report and were not carried out as part of this course but were previously carried out by employees of the Ecosciences department.

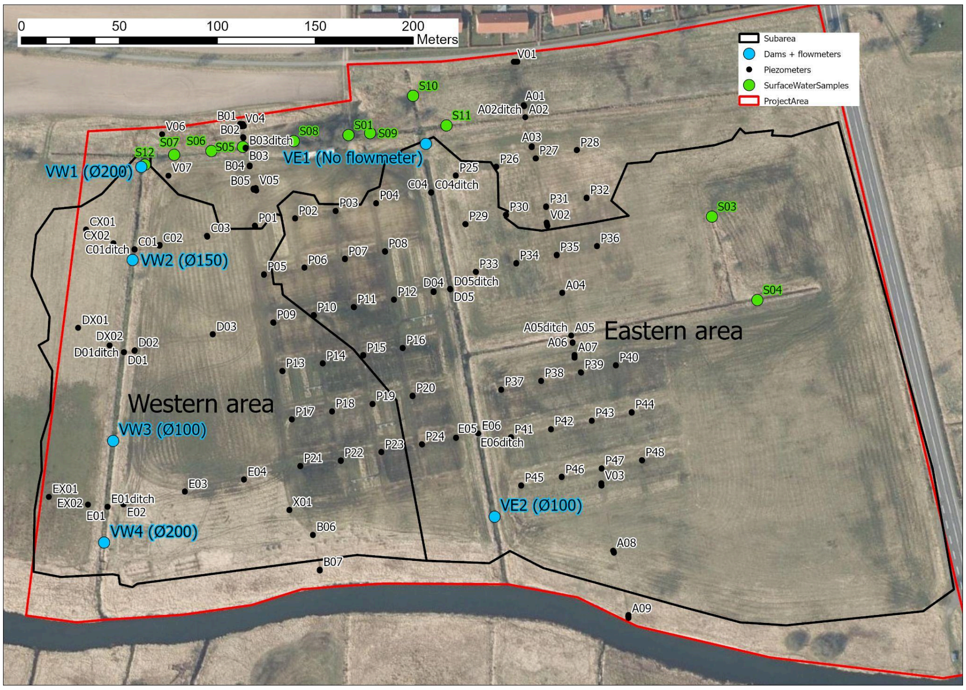

Figure 3: Map of Vejrumbro study site (author: Ecosciences departement)

Ringfenner is an ombrotrophic peatland located in northern Denmark. The land has also been restored to its former state of cultivation. However, restoration is more advanced here than at Vosborg. The piezometers are installed along transects and in two zones to the north-west and south-east (figure 4). For the purposes of this course, only the northern zone was studied. Its ombrotrophic nature means that this peatland is supplied only by rainwater. The peatland was restored in such a way as to isolate it hydrologically from adjacent areas. As a result, the peatland is lined with impermeable material.

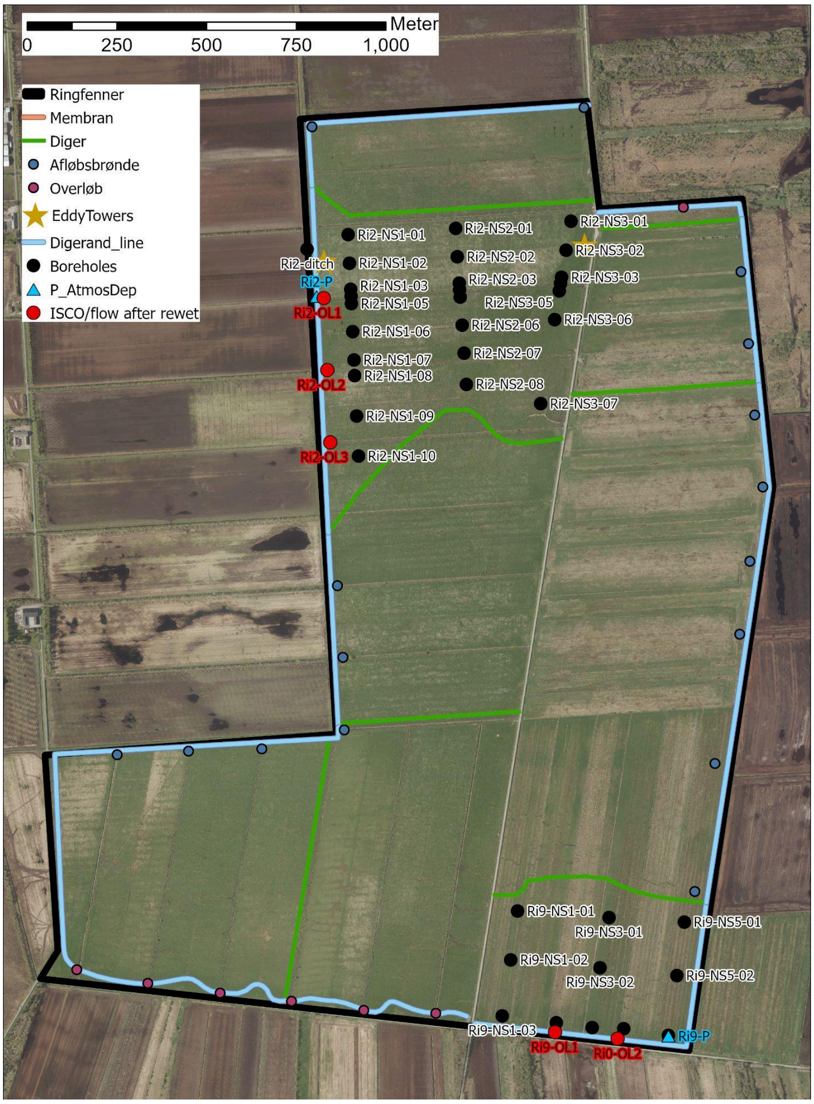

Figure 4: Map of Ringfenner site (author: Ecosciences departement)

For the hydraulic modeling part, the Ringfenner site will be studied. Six piezometers near a ditch will be used to estimate the amount of water entering and leaving the ditch (figure 5).

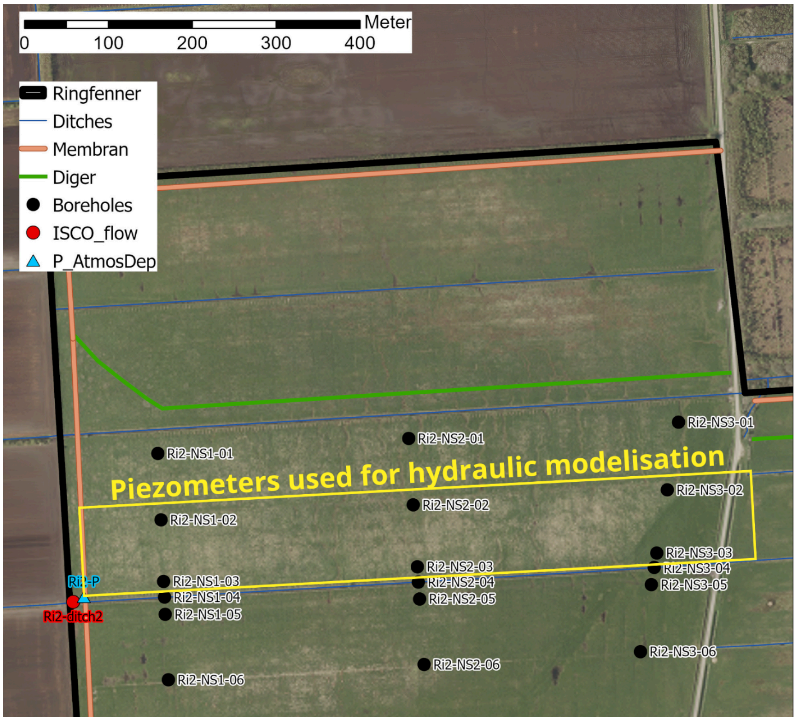

Figure 5: Close-up of the Ringfenner map on the piezometers used for hydraulic modelling

2.2 - Hydraulic conductivity measurements and calculations

2.2.1 - Slug test method

Hydraulic conductivity can be measured in situ using the slug test method. In this method, the water level in a piezometer is suddenly lowered into an aquifer, and the change in water level is measured until it returns to its initial state (Butler, 2019).

The piezometers consist of the components shown in figure 6. A screen is located at the bottom of the tube, allowing water to infiltrate. HAT represents the distance between the ground and the top of the piezometer, while TOP represents the distance between the ground and the bottom of the piezometer. Max H0 represents the maximum height of water that can be withdrawn, and is calculated as HAT + TOP - Sounding. The sounding is measured on the field before the slug test.

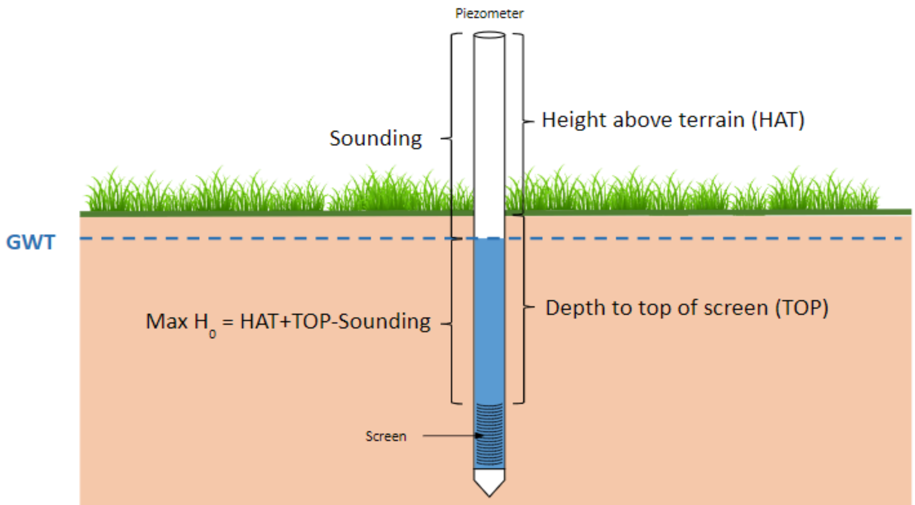

Figure 6: Cross-section of a piezometer (author: Rasmus Jes Petersen)

First, the water level in the piezometer (Sounding) is measured using a water level detector. This is used to determine Max H0. A data logger is placed at the bottom of the piezometer to record variations in water level over time during slug tests.

There are several ways to implement this method, depending on the operator and the context[2].

- Here, if the water level is well above the piezometer screen (Max H0 > 1m), the water level is varied by pumping water (figure 7). Three replicates are carried out, pumping three different heights of water, evenly distributed in relation to Max H0. For example, for a Max H0 of 1.8m, the three replicates can be 0.5, 1 and 1.5m of water pumped.
- If Max H0 < 1m, water is added. The quantity is defined randomly. Up to three replicates are performed.

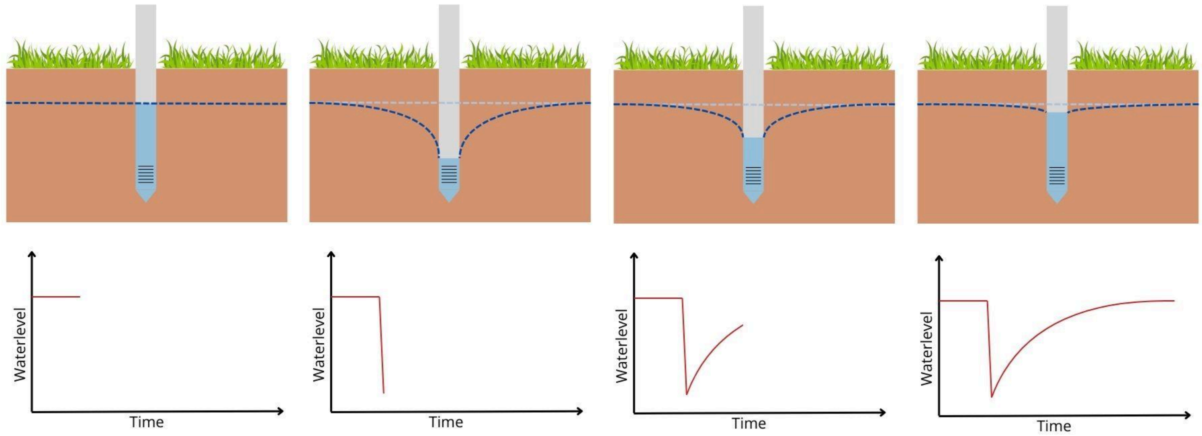

Figure 7: Diagram of a multi-stage piezometer cross-section and water level evolution (author: Solène Moreau). This diagram shows a slug test performed using water pumping.

Throughout the slug test session, a barometer measures atmospheric pressure variations. This data is used to correct the piezometer data, so that only variations within the piezometer are taken into account.

2.2.2 - Open cavity slug test method

The normal slug test technique introduces a bias into the screen. Sediments can become trapped in the screen holes, slowing down the flow of groundwater. To eliminate this bias, it is possible to perform an open cavity slug test. This consists of using a piezometer without a screen (a tube), open on both sides. The principle is to push the tube in at depth, digging out the interior little by little. Once the desired depth has been reached, the tube is raised 15cm, creating a cavity (figure 8). Next, the slug tests are carried out as before, with the addition of water.

[2] If the water level is below the top of the screen, no slug test can be performed.

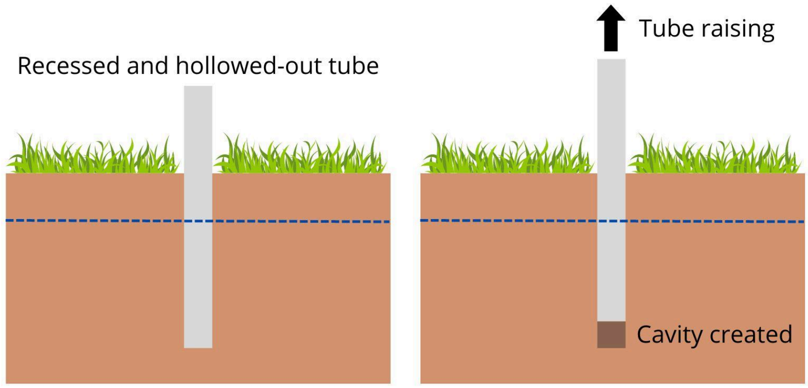

Figure 8: Diagram of the open cavity slug test (author: Solène Moreau)

2.2.3 - Collecting and sorting data

A great deal of data sorting is required before the slug test data can be used in the R code calculating hydraulic conductivities.

For each piezometer, the data loggers are used to obtain a file of data on water level variations with respect to time, including all the replicates carried out. First, each file is corrected with the barometer data. Then, each replicate is isolated to a single CSV file. The data is then cleaned: when the pump is introduced into the piezometer, noise is generated and displayed as a peak on the graph, which must be removed by hand.

On the Ringfenner and Vosborg sites, data collection, sorting and calculation of the hydraulic conductivities of 56 piezometers were carried out as part of the internship. In order to study this parameter on a larger data set, 110 hydraulic conductivity values on the Vejrumbro site collected in 2019 and 2022 were used.

2.2.4 - Calculation of the hydraulic conductivity

Once the data have been sorted and cleaned, a large number of files need to be analyzed to obtain the hydraulic conductivity of each piezometer. A code was created in R to automate this calculation **[Annexe 1]**.

The initial water level, prior to the slug test, is used. From the initial data, a ratio h/h0 is calculated, representing the displacement (the difference between the water level at time t and the initial level), divided by the displacement at time t=0 when it is at its maximum. An exponential trend curve is produced with the curve corresponding to this ratio between 0.15 and 0.25, estimated as the most stable part (Butler, 2019). The slope of this curve is used to obtain an estimate of hydraulic conductivity from the following formula:

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

Where:

L = screen length

r_c = casing radius inner

r_w = screen radius (outer)

F = shape factor

The form factor F takes into account the physical parameters of the piezometer. There are different form factors depending on whether the aquifer is confined or unconfined (Butler, 2019):

- Hvorslev (confined aquifer):

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

- Zlotnik (unconfined aquifer):

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

Where :

L = screen length

r_w = screen radius (outer)

H = saturated thickness above screen bottom

D = aquifer thickness

$\beta_n = \pi(n - 0.5)$

K_0 = modified zero order Bessel function of the second kind

K_1 = modified first order Bessel function of the second kind

Hydraulic conductivities in m/day are then calculated through a code on R **[Annexe 1]**. The code takes as input CSV files that have been previously sorted and cleaned (2.2.3). It produces several output files: a global Excel file showing the hydraulic conductivity for each input file, as well as several graphs for each file: the evolution of water level versus time, the h/h0 ratio and the trend curve for this ratio between 0.15 and 0.25.

2.2.5 - Soil parameters

Hydraulic conductivities will be correlated with various soil parameters to determine whether the latter can have an impact on groundwater flow velocity. When creating each piezometer, information was collected for different depth intervals:

- **Texture** → sand, peat, clay or gyttja. There can be mixes between two textures.. Gyttja is a Swedish term for the eutrophic mud often found at the bottom of aquatic systems. It is a fine-textured material, gelatinous when wet. When it dries, it becomes hard, detracts and cracks horizontally. It is the result of a combination of organic (animal residues, diatoms, algae) and inorganic materials. Gyttja can be found in the soil of peatlands. (Woessner & Poeter, 2020 and Ismail-Meyer et al., 2018)
- **AirDryBD** = Air Dry Bulk Density (g/cm3) → A soil sample is air-dried and its density measured. This parameter assesses the permeability of the sample being measured.
- **DEGDECOMP** → Decomposition degree of the peat: this corresponds to the Von Post scale divided by two for simplicity. The Von Post scale is a field test which determines the degree of decomposition of peat. A sample of peat is squeezed in the hand. Then, according to "the color of the liquid that is expressed between the fingers, the proportion of the original sample that is extruded, and the nature of the plant residues", a decomposition degree is chosen **[Annexe 2]**. It goes from H1 (undecomposed) to H10 (completely decomposed) (Armstrong & Castle, 2015).
- **LOI** = Loss On Ignition (% weight) → This represents the organic matter contained in a sediment sample. This sample is "ignited", heated to a high temperature, allowing the volatile substances present in the sample material to escape. These volatile substances are generally

composed of water and CO2. The before and after weights are compared to obtain the LOI (Sun et al., 2009).

- **TOC** = Total Organic Carbon (% weight) → This corresponds to the organic richness of the sediment. The total quantity of carbon is related to the weight of the initial sample to form the TOC (Mahmoud et al., 2017).

2.3 - Darcy's law and hydraulic modelling

Hydraulic modelling will be carried out on the Ringfenner site using soil parameters and previously calculated hydraulic conductivities. Darcy's law aims to create a relationship between the flow of groundwater in an aquifer and measurable data such as the hydraulic conductivity K, and the hydraulic gradient i. The latter is obtained by dividing the difference between the water level at two points by the distance separating them.

$$q_x\ (specific\ discharge\ m/s) = -Ki = -K\frac{\Delta h}{\Delta x} = -K\frac{h_2 - h_1}{\Delta x}$$

$$Q\ \ (total\ discharge, m^3/s) = -KA\frac{\Delta h}{\Delta x} = q_x A$$

q_x = Water flow (m/s)

K = Hydraulic conductivity (m/s)

h_n = Water level of the first and second piezometers (m)

Δx = Width of the section represented by a pair of piezometers (m)

A = Area (m^2)

As mentioned in section 2.2.1, three pairs of piezometers were used for the modelling. Each pair represents a transect approximately 260m wide (figure 9). From the hydraulic conductivity values found for each piezometer, Darcy's law is applied, making it possible to obtain a flow rate for each transect. In addition, as the soil is made up of two aquifers, we obtain a lower flow rate and an upper flow rate for each transect, which are added together to give a total flow rate for each transect.

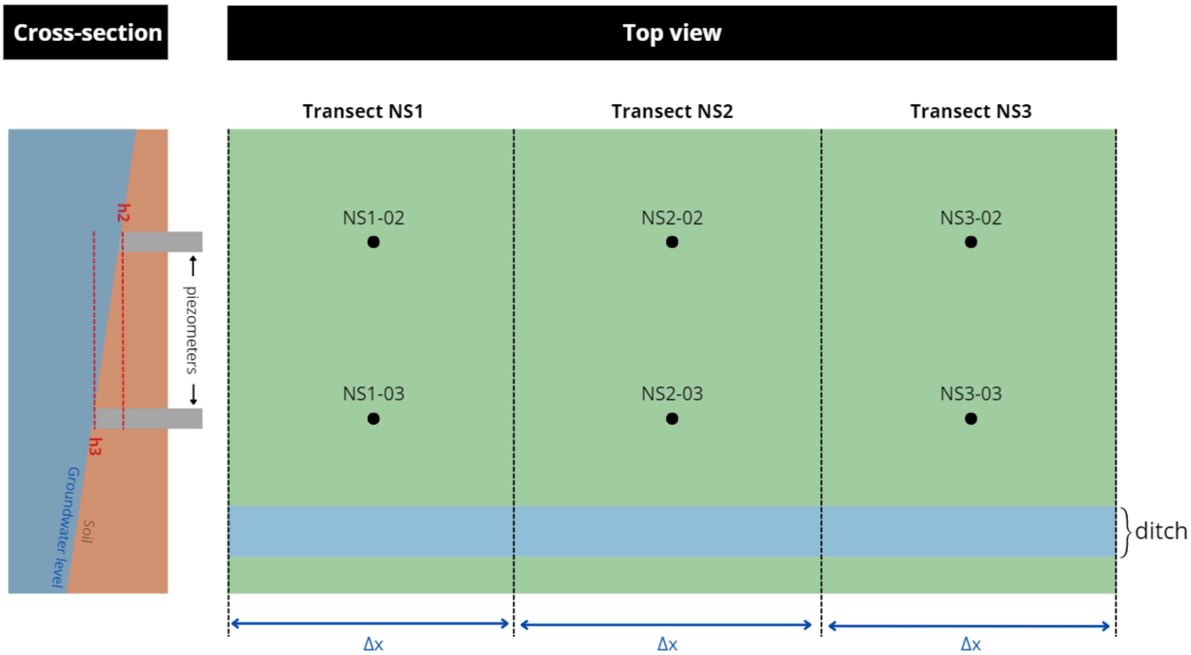

Figure 9: Diagram of the piezometers used for hydraulic modelling. This diagram shows the data involved in Darcy's law: Δx in blue, the width of each transect, and h_n, the waterlevel of the piezometers, detailed in the cross-section on the left.In this diagram, the water flows in the direction from piezometers 2 to 3, towards the ditch.

3. Results and discussion

3.1 - Hydraulic conductivity

3.1.1 - “Raw” results of the hydraulic conductivity

The slugtests carried out on the three study sites provided hydraulic conductivity values for 164 piezometers. In order to compare these values according to their textures, the hydraulic conductivities are related to the major texture from each piezometers (figure 10 and table 1). Of the 164 hydraulic conductivities calculated, 26 could not be related to texture parameters, which corresponds to the “Undefined” category.

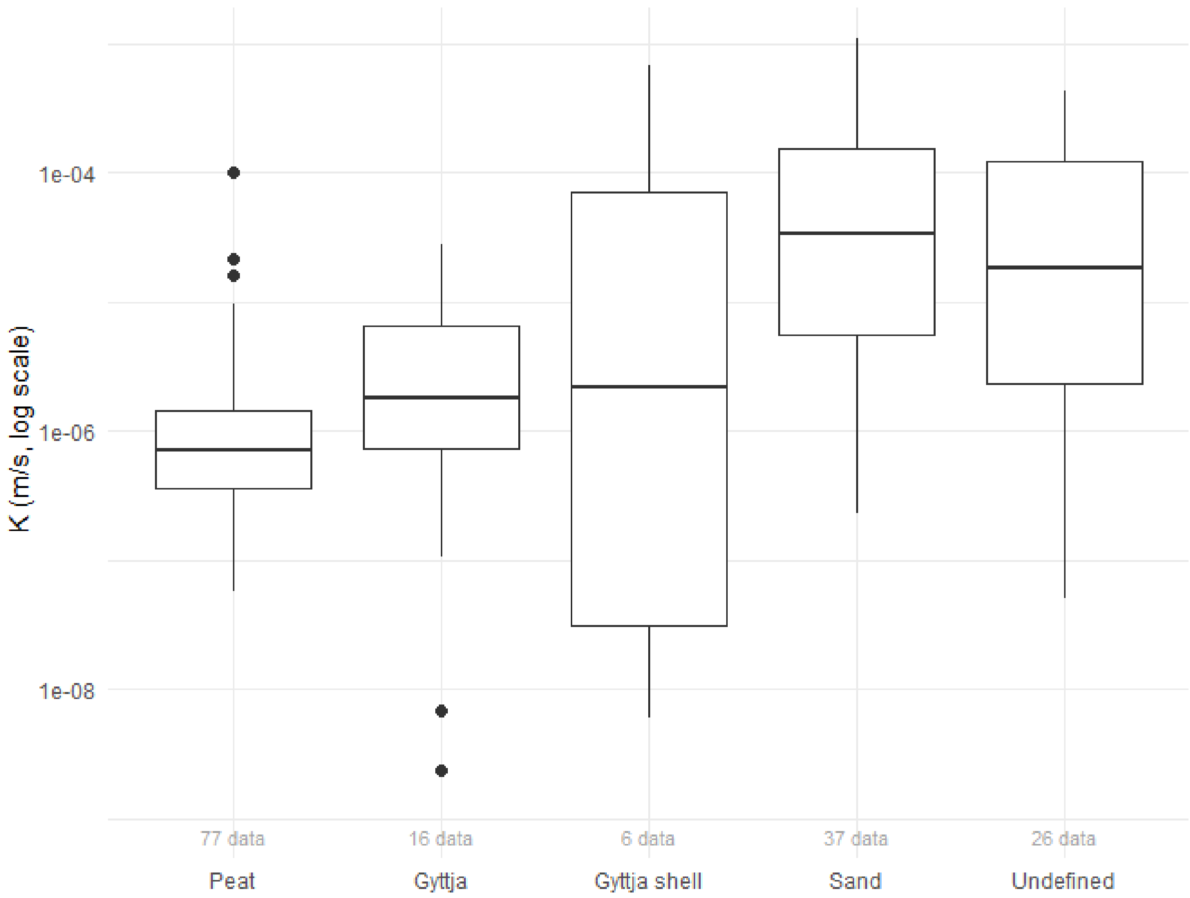

Figure 10: Box plot of hydraulic conductivities according textures. The vertical axis of the box plot is in logarithmic scale. Outliers appear outside the quartiles: Peat = 3 outliers; Gyttja = 2 outliers

Table 1: Statistics of hydraulic conductivities according textures (in m/s)

	Peat	**Gyttja**	**Gyttja shells**	**Sand**	**Undefined**
Number of measures	77	16	6	37	26
Mean	$3.12 . 10^{-6}$	$5.30 . 10^{-6}$	$1.35 . 10^{-4}$	$1.17 . 10^{-4}$	$8.65 . 10^{-5}$
Standard deviation	$1.18 . 10^{-5}$	$7.79 . 10^{-6}$	$2.71 . 10^{-4}$	$2.08 . 10^{-4}$	$1.30 . 10^{-4}$
Median	$7.00 . 10^{-7}$	$1.81 . 10^{-6}$	$2.29 . 10^{-5}$	$3.36 . 10^{-5}$	$1.81 . 10^{-5}$
Minimum	$5.85 . 10^{-8}$	$2.39 . 10^{-9}$	$6.00 . 10^{-9}$	$2.31 . 10^{-7}$	$5.03 . 10^{-8}$
Maximum	$1.01 . 10^{-4}$	$2.81 . 10^{-5}$	$6.83 . 10^{-4}$	$1.01 . 10^{-4}$	$4.34 . 10^{-4}$

Hydraulic conductivity values do not seem to be statistically different according to texture. There are, however, fairly low values, such as $3.12 . 10^{-6}$ m/s for peat, the closest to an impermeable texture. The hydraulic conductivity of peat ranges from 10^{-5} for fibrous peat to 10^{-8} for amorphous peat. The more decomposed the peat, the lower the hydraulic conductivity (towards an impermeable texture). The more fibrous the peat, the higher the hydraulic conductivity (towards a permeable texture) (Wong et al., 2009).

Higher values are found in sand, at 1.17 . 10^{-4} m/s, indicating high permeability. In literature, values for sand are from 10^{-7} m/s for silty sand to 10^{-2} m/s for clean sand (Woessner & Poeter, 2020). The values calculated are therefore fairly close to clean sand.

Gyttja is between these two previous values, at 5.30 . 10^{-6} m/s and 1.35 . 10^{-4} m/s for the gyttja shell texture. A distinction was made between these two textures due to the presence of shells in some piezometers, which increase soil permeability. The hydraulic conductivity of gyttja has been little studied, making it impossible to report values from open-source literature. However, gyttja is similar in texture to clay (Döll & Schneider, 1995). According to Woessner & Poeter, 2020, clay textures include values between 10^{-12} m/s to 10^{-8} m/s, with very low values corresponding to a very low permeability texture. However, the calculated values are far from the literature values for clay. This may be explained by the fact that gyttja remains a less impermeable texture than clay.

3.1.2 - Links between hydraulic conductivity and soil parameters

The aim of this part will be to compare results of hydraulic conductivity with soil parameters in order to determine correlations.

The scatter plot matrix (figure 11) represents the various parameters and hydraulic conductivity in relation to each other (Emerson et al., 2012). This figure does not show any clear correlation between soil parameters and hydraulic conductivity.

However, it is possible to identify correlations between the various parameters. The most obvious correlation is LOI vs TOC. As these parameters both measure the quantity of carbon in the sediment sample, it is normal to find a positive correlation. They also correlate well with AirDryBD. The correlation between bulk density and TOC has been demonstrated several times in the literature, even giving rise to Schmoker's pedotransfer function (Schmoker, 1979). The lower the bulky density, the higher the TOC. This is due to the more porous (and therefore less dense) nature of carbon-rich organic matter. On the contrary, mineral matter (with a low TOC) is dominated by fairly dense minerals (Warren et al., 2012).

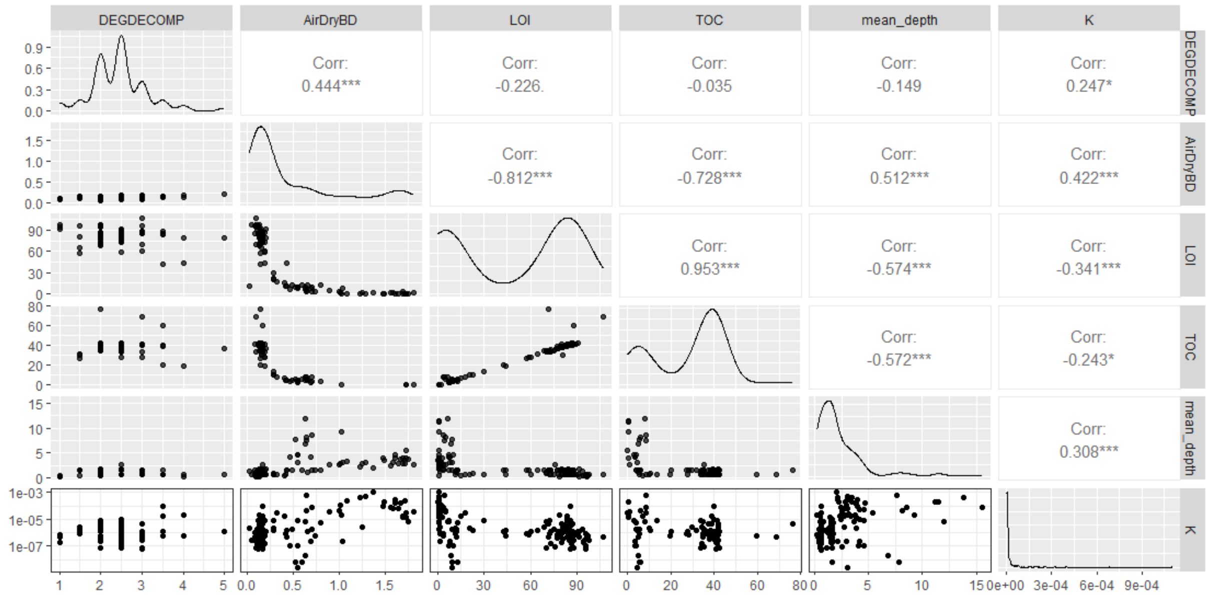

Figure 11: Scatter plot matrix of soil parameters. The graphs on the bottom left are scatter plots. Graphs on the diagonal represent the distribution of data for each parameter. The boxes at top right show the Pearson correlation coefficient of the previous scatter plots. The figure can be read

symmetrically, taking the diagonal distribution of points as the axis of symmetry. Panels with K on the y-axis have a log scale.

To determine relationships with soil texture, figure 12 shows the relationship between hydraulic conductivity and soil parameters as a function of soil texture.

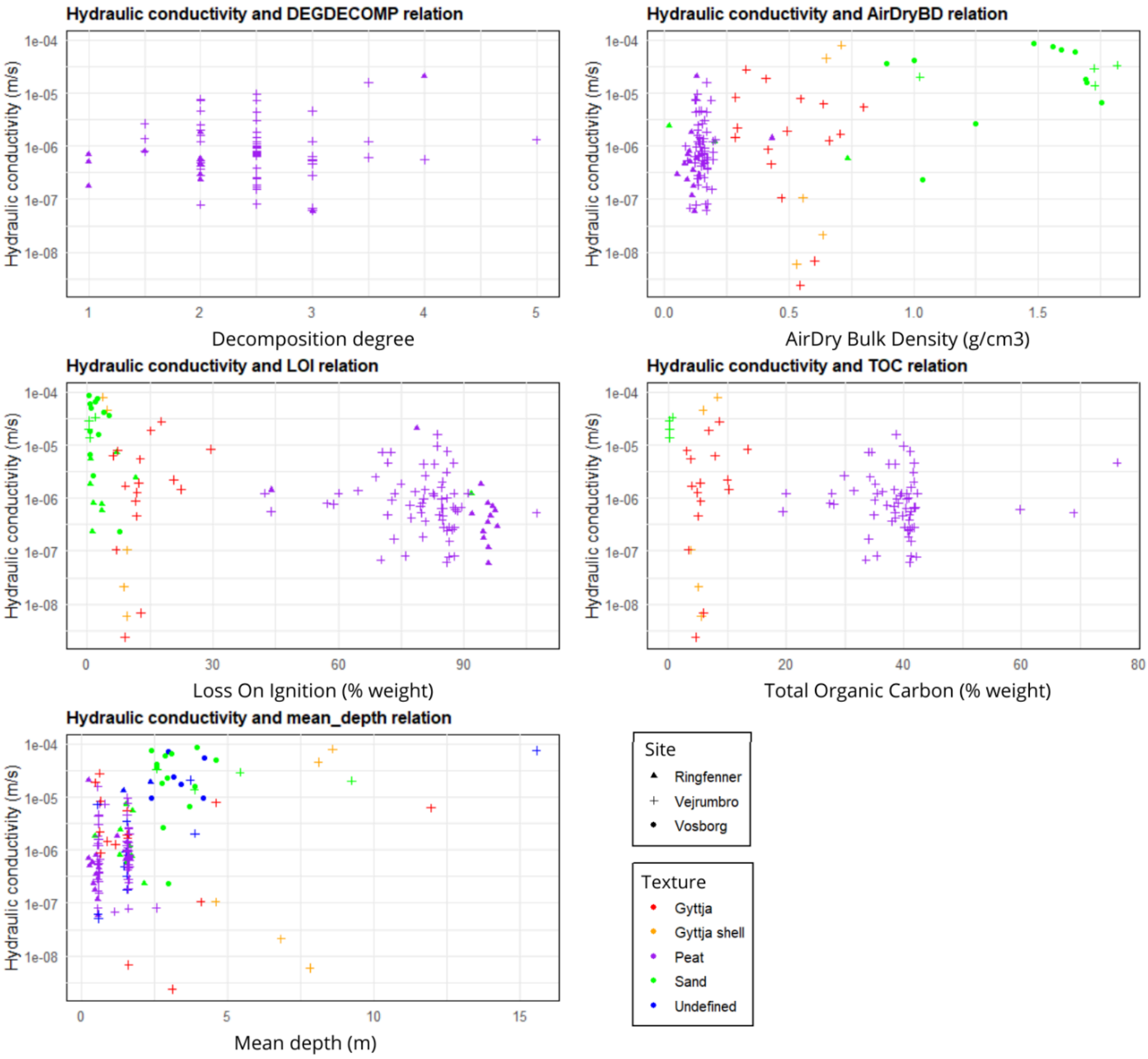

Figure 12: Relations between hydraulic conductivity and soil parameters. 5 soil parameters are represented according to hydraulic conductivity. Each point is differentiated by its color, indicating its texture, and by its shape, indicating the study site concerned.

The degree of decomposition is a parameter of the peat texture. Consequently, the other textures are not represented in this graph. Of the five textures represented, the gyttja shell and the undefined texture have few points to determine a correlation: they will therefore not be analysed further.

Overall, most of the data comes from Vejrumbro, represented by peat, gyttja and sand. The data from Vosborg are sandy or undefined textures.

By representing the points according to their study site, we can see that the values for one location differ from those for another. For example, LOI values in peat are generally lower at Vejrumbro (purple "plus", below 90%) than at Ringfenner (purple triangle, above 90%). In contrast, AirDryBD values appear to be slightly higher at Vejrumbro than at Ringfenner, where values are concentrated around 0.2 g/cm^3. The degree of decomposition and average depth graphs show little correlation. The differences observed could be due to the composition of the peat, which differed between the two study sites. It might be appropriate to carry out this analysis only on peat, classifying the data according to their degree of decomposition, and on more study sites.

The four graphs (all except Decomposition degree vs hydraulic conductivity) show clouds of points concentrated according to texture. The LOI and TOC first show sand with low values (around 2% and 0% respectively), then gyttja (and gyttja shell, although not very well represented) with higher values (around 15% of weight and 8% respectively) and finally peat with much higher values (around 80% and 35% respectively). The opposite is true for AirDryBD, with values of around 0.15 g/cm^3 for peat, 0.5 g/cm^3 for gyttja and over 0.8 g/cm^3 for sand.

By distinguishing textures from others, it is possible to determine some correlations between a parameter and hydraulic conductivity. Sand is particularly interesting for these correlations (figure 13). The results for sand show that the greater the hydraulic conductivity, the greater the density, the lower the quantity of organic matter and the greater the depth.

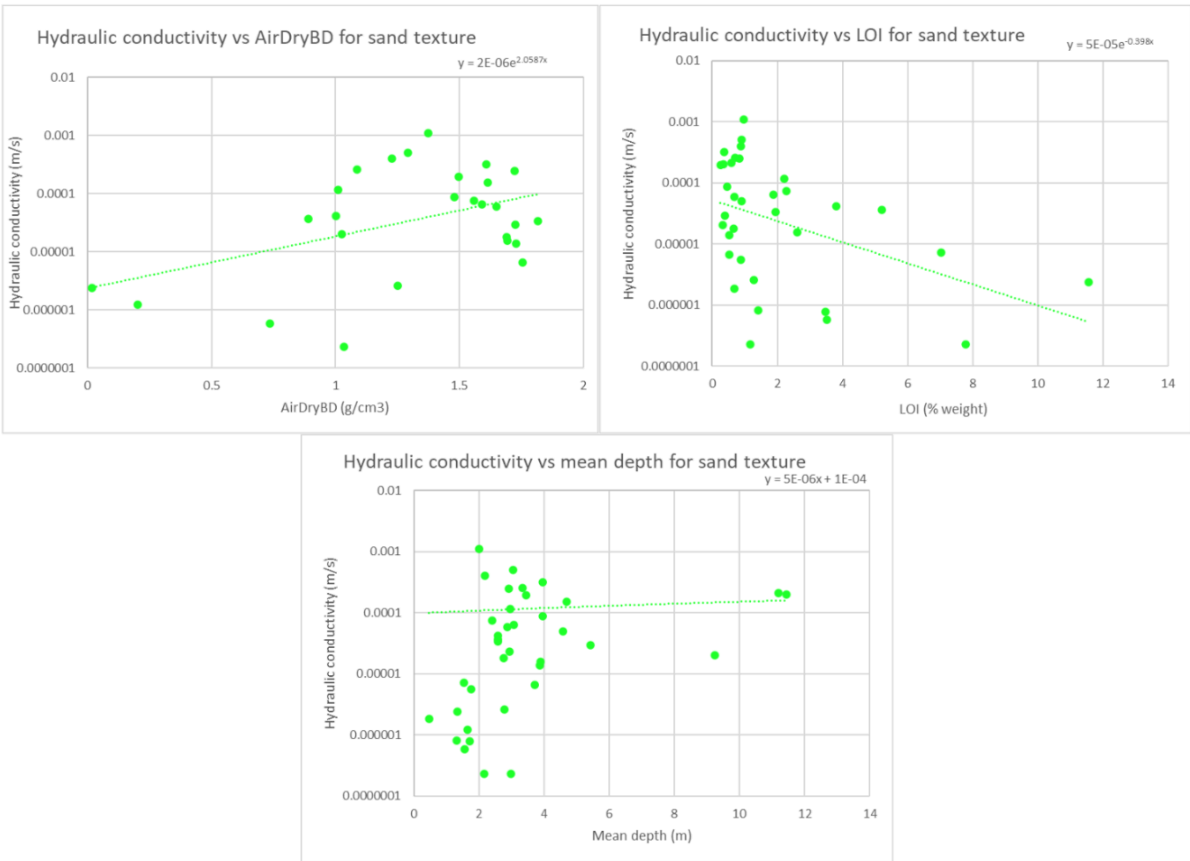

Figure 13: Correlations between hydraulic conductivity and soil parameters for sand texture

There would therefore appear to be some correlation between soil parameters and hydraulic conductivity. However, the results presented here are insufficient to validate this hypothesis for all textures. Only sand seems to show correlations, although additional data would be needed to validate the hypotheses made about AirDryBD, LOI and average depth.

3.1.3 - Hydraulic modelling

Using Darcy's law, these measurements can be used to determine the flow (Devlin, 2020). Hydraulic modelling in Excel can be carried out to show the different flows over several wetland layers.

Water flows from the highest point to the lowest point. Here, the flow is defined as going from piezometers 2 to 3, towards the ditch. So, in these graphs, a positive flow will correspond to water coming from the peatland towards the ditch. In this case, it is the peatland that feeds the ditch.

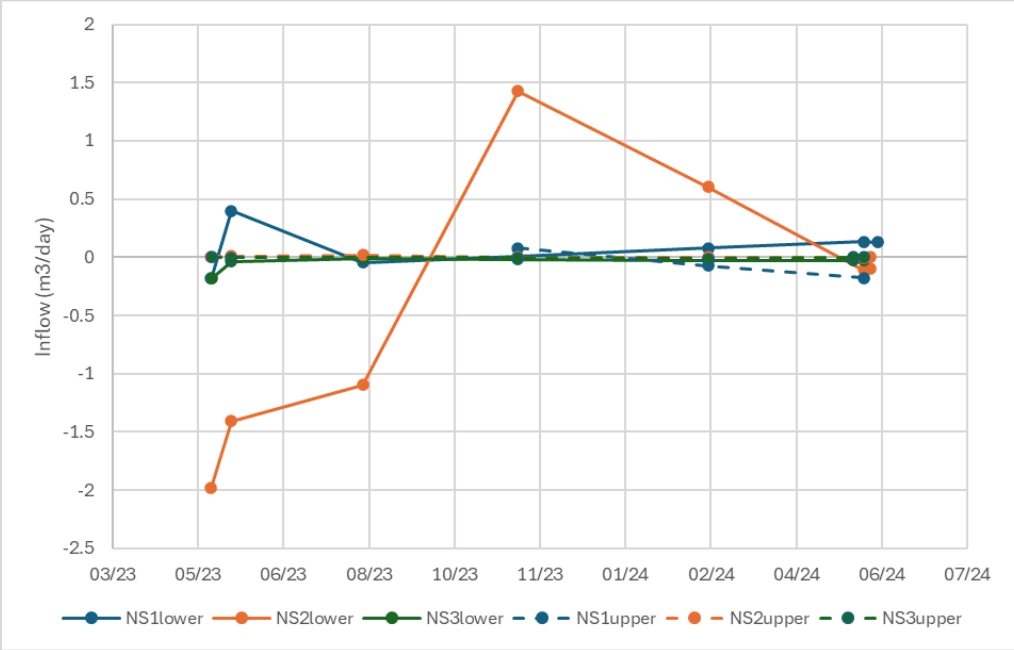

Figure 14: Detailed flows of the studied part in the Ringfenner site. Here, each transect and each aquifer is separated from the others. The full lines represent the lower flows, while the dotted lines represent the upper flows.

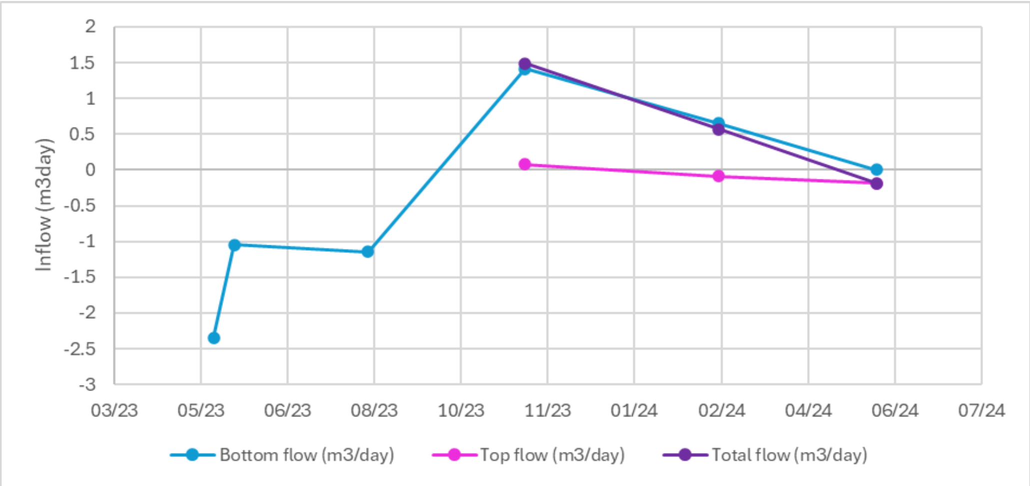

Figure 15: Total flow of the studied part in the Ringfenner site. Top and bottom flow are represented in pink and blue curves. The purple one is the sum of the two.

As explained previously (2.2.1), the Ringfenner site is an ombrotrophic peatland, which is therefore fed only by rainwater. In this modelling, the underground aquifers of the ditch are differentiated, although they all belong to the same hydrological unit that is the peatland.

The figure 14 and figure 15 show variations over more than one year, showing both positive and negative flow. A positive flow corresponds to a flow from the peatland to the ditch. A negative flow indicates that it is the ditch that supplies the peatland with water.

The data for the study area extends from May 2023 to May 2024 for the lower layer, and a shorter period from November 2023 to May 2024 for the upper layer. Figure 14 shows the upper and lower layer fluxes for the three transects. It can be seen that the NS2lower flux is more variable than the others. NS2lower varies between -2m^3/day and 1.5m^3/day, while the others are very close to 0m3/day. This flow has a major impact on the bottom flow and total flow in figure 15. In the summer of 2023, the peatland was humidified. The results therefore seem to indicate that only the deep layer changed its flow pattern.

The small amount of data does not allow an in-depth analysis of the peatland's flows. It would be interesting to follow this trend over the longer term, and to test it on the other side of the ditch to see if the trends are repeated spatially and temporally.

This application of Dracy's law has several biases. First, the bias of this law is that it assumes that the soil composition of the aquifer is homogeneous, which is not necessarily true in reality. Secondly, it takes into account only one dimension (Qx) of the direction of flow. Here, the flow is considered to be parallel to the two piezometers, and therefore perpendicular to the ditch. The actual direction of flow is not necessarily perpendicular. Consequently, this application does not take into account the Qy dimension (figure 16).

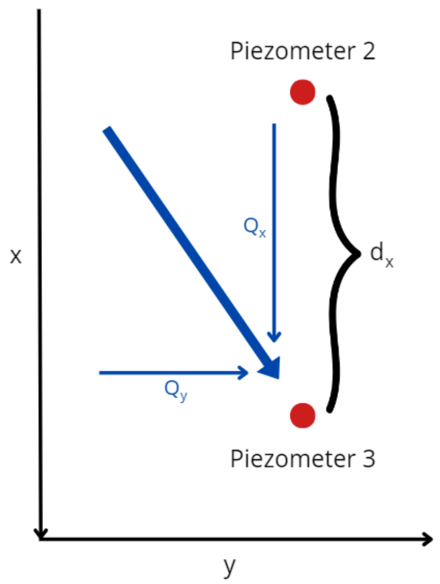

Figure 16: Diagram of groundwater flow dimensions (Author : Rasmus Jes Petersen, modified by Solène Moreau)

3.2 - Methodological comparison

3.2.1 - Open cavity slug test

There is another way of using the slug test method, with a tube without water. Instead of removing water, we plant the tube and create a hole in depth by pressure. Then, we add water and we measure the time it takes for the water to spread into the soil (and level water). The advantage of this technique is that it removes the bias caused by the piezometer screen. Sediments can become trapped in the screen, distorting the data.

Only three piezometers were used to measure hydraulic conductivity using both methods because open cavity slugtest is a new method in the Ecoscience department. The results are shown in figure 17.

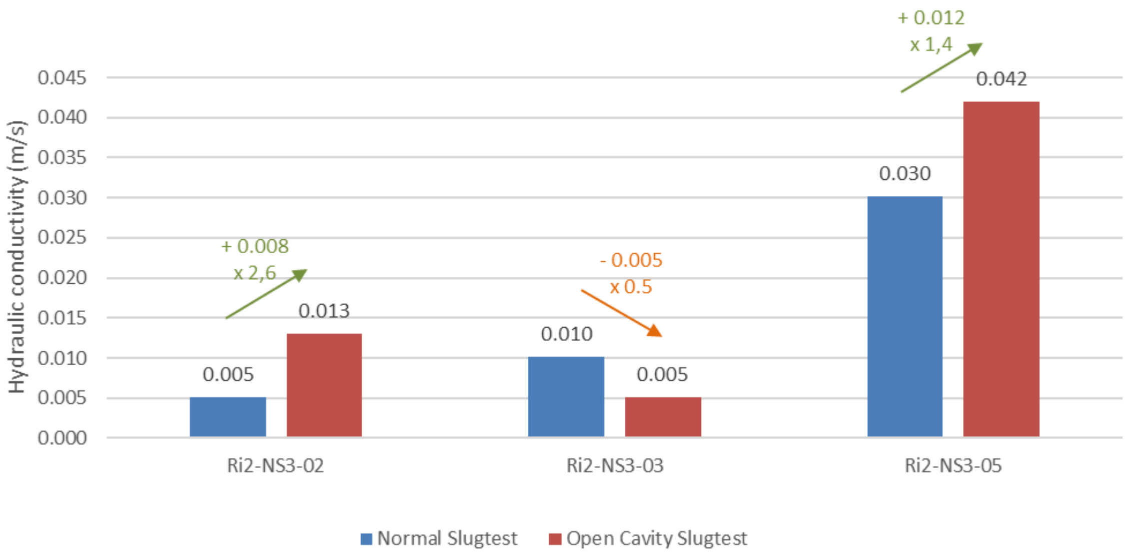

Figure 17: Methodological comparison of hydraulic conductivities

Initially, we observed a difference of between 0.005 and 0.012 m/s between piezometers. The open cavity slug test method can give values from twice as low to more than twice as high as the normal method. Due to the low number of data, we cannot assert that the normal method gives significantly underestimated results compared to the real hydraulic conductivity.

Despite the small number of data, it is possible to perform the Wilcoxon statistical test, which has the advantage of being usable with a small sample. This test indicates whether the results are significantly different between two matched groups of data. In other words, it shows whether the differences between the two methods are due to chance or not. The null hypothesis (H0) is that there is no difference between the two methods. The Wilcoxon test gives a V-value = 1 and a p-value = 0.5. A V-value of 2 indicates that the observed differences are fairly small, or that there is little data (more likely here). The p-value here is greater than 0.05, which means that the null hypothesis cannot be rejected. In other words, there is a 50% probability that the observed differences are due to chance. There is therefore insufficient evidence to assert that the differences observed are significant.

These initial results, although too few in number, underline the value of this comparison. It would therefore be interesting to carry out new open cavity slug tests to determine whether the classical method has a bias that influences the calculation of hydraulic conductivity.

In order to obtain the most accurate conclusion possible, it would be preferable to carry out these new tests under conditions as similar as possible to the classic slug tests. The two tests should therefore be carried out on the same piezometer at fairly short intervals, to rule out differences due to weather conditions, for example.

In practice, the open cavity slug test technique takes a long time to set up and remains uncertain. Once the hole has been created in the ground, it is impossible to know whether the walls of the ground are collapsing or not. Furthermore, this technique cannot be used on all textures. Friable textures such as sand cannot be used for this technique, as the risk of collapse is high.

4. Conclusion

5.1 - Potential of slug tests in comprehension of hydrology in wetlands

The study of hydraulic conductivity on peat bogs has produced mitigated results and conclusions regarding the technique used and the values obtained.

Firstly, the slug test technique has the advantage of measuring hydraulic conductivity in situ. The open cavity slug test technique even eliminates the bias caused by the first technique. Both techniques are inexpensive, allow several slug tests to be carried out on the same piezometer and require few operators to perform them. However, they do have the disadvantage of being time-consuming to set up and collect little data. In fact, a working day with two to three operators enables around 15 hydraulic conductivity values to be obtained (a triplicate is performed for each piezometer). Although the values used in this report are the result of slug tests carried out since 2019, one of the conclusions of this work is the lack of data to validate the hypotheses. In addition, the open cavity slug test technique, which was devised very recently and has only been tested on three piezometers so far, still needs to be perfected to ensure that it is carried out correctly. The risk of the cavity collapsing could bias the results.

A new technique, the Borehole Nuclear Magnetic Resonance (BNMR), has recently appeared in the field of peatland groundwater hydrology (Mashhadi et al., 2024). Based on the principle of nuclear magnetic resonance, this technique is seen as promising, having provided hydraulic conductivity values in sand and gyttja within an acceptable error range, although not very effective in peat. The study by Mashhadi et al (2024) considers this technique to be a robust, rapid and reliable tool for studying the hydrology of peatlands.

It is still difficult to obtain satisfying results for soil texture in relation to hydraulic conductivity. Only the results for sand are promising, although further data would be needed to validate the hypotheses. In the case of sand, hydraulic conductivity could therefore be affected by average depth, density via a positive correlation and the quantity of organic matter via a negative correlation.

These hydraulic conductivity data show their value by being used in hydraulic modelling, between the peatland and a ditch in this report. By taking into account the quantity of nutrients measured in the peatland, it would be possible to assess the total quantity of these nutrients through groundwater flows.

Finally, the open cavity slug test technique did not show any correlation with the values obtained using the conventional technique. However, the small amount of data used does not allow us to rule out the open cavity slug test as a promising solution to the bias of the first technique.

5.2 - Personal conclusion

This internship was an opportunity to study more peatlands, ecosystems that I had not been able to study much during my academic background. Field work has taught me to perform slug tests with increasing ease, using various tools such as the water level detector, and to use and configure loggers. Through the recurrent use of programming, I was able to rediscover this discipline which I had previously found very difficult. The precise context of the codes to be produced motivated me to improve my skills. This discipline has enabled me to develop skills in automating data sorting, skills that will be useful in my future academic and professional career. It was also an opportunity to use R to produce new graph techniques such as the scatter plot matrix.

In my opinion, this internship was closely linked with the skills and level acquired during my studies. There was a good balance between tasks requiring already-acquired skills and new tasks, enabling me to enrich my knowledge. Although my professional ambitions are not focused on the world of research, the work and productions carried out represent a lot of knowledge and skills that will be useful to me in the future, both in the pursuit of my studies and in my future professional life.

Finally, I am grateful for what this international experience has given me, both during my internship and in my daily life. These three months in Denmark enabled me to step out of my comfort zone and gain in confidence, motivation and open-mindedness, while greatly improving my English. The way of life and the way of working, which are different from my usual habits, are now encouraging me to rethink the way I organize my daily life.

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ANNEXES

Annexe 1: Code for hydraulic conductivity calculation (pumping water version)

```
# ***** First configurations *****
rm(list = ls()) # Clean environnement
cat("\014") # Clean console
# Load required libraries
library(dplyr)
library(ggplot2)
library(writexl)
library(Bessel)

# Function for processing a CSV file and returning results
process_file <- function(filepath, boreholes) {
  calculate_K <- function(data, initialWL, min_index) {
    bd <- data[(min_index):nrow(data), ]
    # Check that 'bd' is not empty and contains no NA in critical columns
    if (nrow(bd) == 0 || all(is.na(bd$LEVEL))) {
       warning(paste("Le fichier", filepath, "contient des données invalides après filtrage."))
      return(list(K_h = NA, K_z = NA, initialWL = NA, slope = NA, H_f = NA, Z_f = NA, nb_points = 0))
    }
    # Calculation of h (mutate comes from dplyr)
    bd <- bd %>%
      mutate(h = initialWL - LEVEL)
    # The initial displacement, the greater of h
    h0 <- bd[1, "h"]
    # Ratio calculation
    bd <- bd %>%
      mutate(ratio = h / h0)
    # Filter data for ratio to stable period
    filtred_bd <- subset(bd, ratio >= 0.15 & ratio <= 0.4)
    nb_points <- nrow(filtred_bd)
    # Check that filtred_bd is not empty
    if (nb_points == 0) {
      warning(paste("The file", filepath, "contains no data in the specified ratio range."))
      return(list(K_h = NA, K_z = NA, initialWL = NA, slope = NA, H_f = NA, Z_f = NA, nb_points = nb_points))
    }
    filtred_bd$log_ratio <- log(filtred_bd$ratio)
    # Check that there is no NA in log_ratio
```

```
    if (all(is.na(filtred_bd$log_ratio))) {
      warning(paste("The file", filepath, "contains only NA values in log_ratio."))
       return(list(K_h = NA, K_z = NA, initialWL = NA, slope = NA, H_f = NA, Z_f =
NA, nb_points = nb_points))
    }
    # Linear model on filtered data
    model <- lm(log_ratio ~ Time, data = filtred_bd)
    slope <- coef(model)[2]
    # Calculate R-squared
    r_squared <- summary(model)$r.squared
    # Extract file name without path and extension
    filename <- basename(filepath)
    filename <- gsub(".csv$", "", filename)
    piezometer_name <- substr(filename, 1, nchar(filename) - 2)
    # Search for the piezometer line containing the name
    matching_rows <- grep(piezometer_name, row.names(boreholes), value = TRUE)
    # Check that we have found a unique match
    if (length(matching_rows) != 1) {
      warning(paste("the piezometer", piezometer_name, "did not find a unique match
in the borehole data."))
       return(list(K_h = NA, K_z = NA, initialWL = NA, slope = NA, H_f = NA, Z_f =
NA, nb_points = nb_points, r_squared = NA))
    }
    # Use the corresponding line
    borehole_row <- boreholes[matching_rows, ]
    top <- as.numeric(borehole_row["TOP"])
    bottom <- as.numeric(borehole_row["BOTTOM"])
    L <- bottom - top
    rw <- 0.025
    rc <- 0.0215
    H <- as.numeric(borehole_row["H"])
    D <- as.numeric(borehole_row["D"])
    # Hvorslev factor (H_f) calculation
    H_f <- asinh(L / (2 * rw))
    # Zlotnik factor (Z_f)calculation
    nmax <- 1000
    n <- 1:nmax
    betan <- pi * (n - 0.5)
    sumn <- numeric(nmax)

    for (i in 1:nmax) {
      term1 <- cos(betan[i] * H / D)
      term2 <- cos(betan[i] * (H - L) / D)
      besselK0 <- Bessel::BesselK(betan[i] * rw / D, 0)
      besselK1 <- Bessel::BesselK(betan[i] * rw / D, 1)
      if (is.finite(besselK0) && is.finite(besselK1) && besselK1 != 0) {
        sumn[i] <- ((term1 - term2)^2 * besselK0) / (betan[i]^3 * besselK1)
```

```
      } else {
        sumn[i] <- 0
      }
    }
    cumsum_sumn <- sum(sumn)
    Z_f <- L * rw / (2 * D^2 * cumsum_sumn)

    # Calculating K with Hvorslev
    K_h1 <- ((slope * (rc^2) * H_f) / (-2 * L)) * (3600 * 24)
    K_h <- round(K_h1, 2)
    # Calculating K with Zlotnik
    K_z1 <- ((slope * (rc^2) * Z_f) / (-2 * L)) * (3600 * 24)
    K_z <- round(K_z1, 2)

    return(list(K_h = K_h, K_z = K_z, initialWL = initialWL, slope = slope, H_f = H_f, Z_f = Z_f, nb_points = nb_points, bd = bd, filtred_bd = filtred_bd, filename = filename, r_squared = r_squared))
  }
  data <- read.csv2(filepath)
  # Add a time column
  data$Time <- 1:nrow(data)
  # Switch Time column to left
  data <- data[, c("Time", names(data)[!names(data) %in% "Time"])]
  # Make sure the Time column is numeric
  if (!is.numeric(data$Time)) {
    data$Time <- as.numeric(data$Time)
  }
  # Ensure that the LEVEL column is digital
  if (!is.numeric(data$LEVEL)) {
    data$LEVEL <- as.numeric(data$LEVEL)
  }
  # Determine the initial height of the water table (max. value)
  initialWL <- max(data$LEVEL, na.rm = TRUE)
  # Find the index of the maximum LEVEL value (withdrawal peak)
  min_index <- which.min(data$LEVEL)
  min_index <- as.numeric(min_index)

  result <- calculate_K(data, initialWL, min_index)

  if (!is.na(result$K_h) && !is.na(result$K_z)) {
    # Création des graphiques
    p1 <- ggplot(data, aes(x = Time, y = LEVEL)) +
      geom_line() +
       labs(title = paste("Evolution of the water level during the slug test for", result$filename),
           x = "Time (s)",
           y = "Level (m)") +
```

```
      theme_bw() +
      theme(plot.title = element_text(size = 12))

    p2 <- ggplot(result$bd, aes(x = Time, y = ratio)) +
      geom_line() +
      labs(title = paste("Ratio vs Time for", result$filename),
           x = "Time",
           y = "Ratio") +
      theme_bw() +
      theme(plot.title = element_text(size = 12))

    p3 <- ggplot(result$filtred_bd, aes(x = Time, y = ratio)) +
      geom_point() +
       geom_smooth(method = "lm", formula = y ~ exp(result$slope * x), se = FALSE,
col = "red") +
      labs(title = paste("Exponential trend curve for", result$filename),
           x = "Time",
           y = "Ratio") +
      theme_bw() +
      theme(plot.title = element_text(size = 12))

    # Save the graphs
    output_dir <- paste0("graph_R/", result$filename)
    if (!dir.exists(output_dir)) {
      dir.create(output_dir)
    }
             ggsave(filename  =  file.path(output_dir,  paste0(result$filename,
"_water_level.png")), plot = p1, width = 8, height = 6)
     ggsave(filename = file.path(output_dir, paste0(result$filename, "_ratio.png")),
plot = p2, width = 8, height = 6)
             ggsave(filename  =  file.path(output_dir,  paste0(result$filename,
"_exponential_trend_curve.png")), plot = p3, width = 8, height = 6)
  }
  return(result)
}

# ***** Piezometer data *****
# Check that the file exists in the specified path
if (!file.exists("data/Boreholes.csv")) {
  stop("The file data/Boreholes.csv does not exsit.")
}
boreholes <- read.csv2("data/Boreholes.csv")
boreholes$nom <- paste(boreholes$BOREHOLENO, boreholes$SCREENNO, sep = "-")
row.names(boreholes) <- boreholes$nom
View(boreholes)

# ***** Handling multiple files *****
```

```r
# List of CSV files in directory
files <- list.files(path = "data/slugtests_M", pattern = "*.csv", full.names = TRUE)
# Create output folder if none exists
if (!dir.exists("graph_R")) {
  dir.create("graph_R")
}
# List for storing results
results <- list()
# Loop over each file and process
for (file in files) {
  if (file != "data/Boreholes.csv") {
    cat("Processing file:", file, "\n")
    result <- process_file(file, boreholes)
    if (!is.na(result$K_h) && !is.na(result$K_z)) {
      results[[file]] <- result
         cat("\033[1;31mThe hydraulic conductivity for", file, "is:", result$K_h, "m/day (Hvorslev)", result$K_z, "m/day (Zlotnik)\033[0m\n")
    } else {
       results[[file]] <- list(K_h = NA, K_z = NA, initialWL = NA, slope = NA, H_f = NA, Z_f = NA, nb_points = result$nb_points, r_squared = NA)
        cat("\033[1;31mSkipped file due to invalid data or unmatched piezometer:", file, "\033[0m\n")
    }
  }
}
# Convert the results list into a data frame
results_df <- data.frame(
  File = names(results),
  Initial_WL = sapply(results, function(x) x$initialWL),
  Slope = sapply(results, function(x) x$slope),
  r_squared = sapply(results, function(x) x$r_squared),
  nb_points = sapply(results, function(x) x$nb_points),
  H_f = sapply(results, function(x) x$H_f),
  Z_f = sapply(results, function(x) x$Z_f),
  K_h = sapply(results, function(x) x$K_h),
  K_z = sapply(results, function(x) x$K_z),
  stringsAsFactors = FALSE
)

# Check that the File column is a vector of characters
results_df$File <- as.character(results_df$File)
# Remove path and extension from file name
results_df$File <- basename(results_df$File)  # Remove path
results_df$File <- gsub(".csv$", "", results_df$File)  # Remove .csv extension
# Adjust file names in results_df by removing the last 2 characters
```

```
results_df$Adjusted_File <- substr(results_df$File, 1, nchar(results_df$File) - 2)

# Add columns D and Conf_Unconf to results_df
results_df$D <- sapply(results_df$Adjusted_File, function(file) {
  borehole_row <- boreholes[grepl(file, row.names(boreholes)), ]
  if (nrow(borehole_row) > 0) {
    return(borehole_row$D[1])
  } else {
    return(NA)
  }
})
results_df$Conf_Unconf <- sapply(results_df$Adjusted_File, function(file) {
  borehole_row <- boreholes[grepl(file, row.names(boreholes)), ]
  if (nrow(borehole_row) > 0) {
    return(borehole_row$Conf_Unconf[1])
  } else {
    return(NA)
  }
})
# Delete the Adjusted_File intermediate column if no longer required
results_df$Adjusted_File <- NULL
# Save results in an Excel file
write_xlsx(results_df, path = "hydraulic_conductivity_results_R.xlsx")

# Print results
results_df
```

Annexe 2: Table of Von Post scale (Armstrong & Castle, 2015)

Table 34–2. Van Post humification scale for the description of peat soils (This version taken from Castle et al., 1984).

Degree of decomposition	Nature of liquid expressed on squeezing	Proportion of peat extruded between fingers	Nature of plant residues	Description
H1	Clear, colorless	None	Plant structure unaltered, fibrous, elastic	Undecomposed
H2	Almost clear, yellow-brown	None	Plant structure distinct, almost unaltered	Almost undecomposed
H3	Slightly turbid, brown	None	Plant structure distinct, most remains easily identifiable	Very weakly decomposed
H4	Strongly turbid, brown	None	Plant structure distinct, most remains identifiable	Weakly decomposed
H5	Strongly turbid, contains a little peat in suspension	Very little	Plant structure clear but becoming indistinct, most remains difficult to identify	Moderately decomposed
H6	Muddy, much peat in suspension	One-third	Plant structure indistinct but clearer in the squeezed residue than in the undisturbed peat, most remains unidentifiable	Well decomposed
H7	Strongly muddy	One-half	Plant structure indistinct but recognizable, few remains identifiable	Strongy decomposed
H8	Thick mud, little free water	Two-thirds	Plant structure very indistinct, only resistant remains such as root fibers and wood identifiable	Very strongly decomposed
H9	No free water	Nearly all	Plant structure almost unrecognizable, practically no identifiable remains	Almost completely decomposed
H10	No free water	All	Completely amorphous	Completely decomposed

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Measurements and application of hydraulic conductivity and groundwater flows in wetlands

Résumé :

The study of groundwater hydrology in peatlands is particularly relevant to understanding hydrologic pathways and nutrients fluxes. Hydraulic conductivity, a parameter that can be measured using the slug test technique, is therefore used to study peatland hydrology. Comparisons of this conductivity with soil parameters and texture have shown promising results for sandy textures, where density, quantity of organic matter and depth seem to have an impact on this parameter. Results are more limited for other textures. Its use in hydraulic modelling provides an example of its application, useful for quantifying and identifying groundwater flow paths. Finally, initial tests and results of the open cavity slug test technique, intended to eliminate the bias caused by the principal technique, are insufficient to justify or rule out its use.

Mots Clés : wetland, ground water hydrology, hydraulic conductivity, slug test, hydraulic modelling, soil parameters, texture, open cavity slug test

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