Practical guide

Manuals for water resources fieldwork experiments

TNTM107	Practical of Surface Water Resources Monitoring and Investigation
TND111	Practical of Analysis and Evaluation of Water Quality
TNĐ113	Practical of Underground Resources Observation and Investigation

ĐẠI HỌC TÀI NGUYÊN VÀ MÔI TRƯỜNG HÀ NỘI
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Preface

This practical guide was written for educational use at the Hanoi University of Natural Resources and Environment. It is intended to be used by students and teachers for fieldwork in Cuc Phuong. It contains manuals describing different experiments related to surface water, groundwater, and water quality.

This document was written by Kristian van der Lek, Pieter Geenen, Marijn van Alten, and Peter Nelemans from the Delft University of Technology, the Netherlands, from February through April 2023. We wrote this practical guide as part of a multidisciplinary project, aimed at developing fieldwork at HUNRE. During our project, we were guided by our main supervisors Khoa Thi (HUNRE) and Thom Bogaard (TU Delft). We received additional guidance from Cong Mai Van (TU Delft) and Lindsey Schwidder (TU Delft). We would like to sincerely thank them for their support, feedback, input, and guidance.

The fieldwork was developed in collaboration with the staff of the Faculty of Water Resources of HUNRE. We want to thank them as well from the bottom of our hearts for their help, input, advice, and hospitality. Special thanks as well to the students from HUNRE who accompanied us during the experiments in Cuc Phuong.

This project would not have been possible without the financial support from the Delft Global Student Club and the FAST fund TU Delft, who were kind enough to sponsor the project. A very special thanks as well to the Orange Knowledge Program from the Netherlands Universities Foundation For International Cooperation, who not only supported our project but also provided the funds for many of the equipment needed for the experiments.

There are many more people whom we should thank and/or mention by name, but the list would be almost endless. We hope the fieldwork proves as much fun as we had here in Vietnam, and that the experience and educational value of the fieldwork will eventually result in better water engineers.

The AquaBros, 13-04-2023

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1. Introduction

1.1 The study of water

1.1.1 The importance of water

Nothing is as essential to life on Earth as water. Although there are organisms that exist without sunlight or oxygen, there is no creature on this planet that can survive without water. No wonder water has been studied since the dawn of mankind. Ever since people started practicing agriculture, we have been interested in the behavior of water.

Even as society developed from the pre-historic era to the modern and incredibly complex one it is today; the importance of water has not decreased one bit. Even more so, it has only become increasingly important! Water is an essential part of the energy sector, our food supply, industry, the transportation sector, and the fishing sector. Many more aspects of our society deal with water, like sanitation, construction, mining, flood protection, ecosystems, and many more.

1.1.2 The need for practical experience

The study of water is thus without question an extremely important one, and with rising global temperatures and sea levels due to anthropogenic climate change, it will only become more and more essential. However, one cannot study water by only reading books or attending lectures. We can learn a lot by studying the theory, but in the end, it is extremely valuable to go out in the field to practice and see for ourselves. The educational value of fieldwork lies not just in seeing theory become reality, but also in the process of data gathering, which often proves much more difficult than expected.

Therefore, students from Hanoi University of Natural Resources and Environment (HUNRE) will take part in a field trip. This field trip is organized every year for third-year students of HUNRE and is part of the courses “TNTM107 Practical of Surface Water Resources Monitoring and Investigation”, “TND111 Practical of Analysis and Evaluation of Water Quality”, and “TND113 Practical of Underground Resources Observation and Investigation” from the Water Management educational program issued in 2021.

1.1.3 Learning goals

During the field trip, students perform various experiments related to groundwater, surface water, and water quality. They will prepare the experiments, perform them, collect data, process this data to obtain results, and reflect on the experiment. The goal of this field trip is to train students how to:

- use measurements to assess a water system.
- determine which data is needed for scientific research.
- present data and results from an experiment.
- work in a team in the field.
- use different kinds of equipment related to water measurements.
- assess and deal with data reliability.

1.2 Practical information

1.2.1 Location

The field trip lasts several days and takes place near the national park of Cuc Phuong in the province of Ninh Binh. Experiments will usually take about half a day. During this week the students stay in a Homestay. Most of the experiments can be carried out in a small catchment, shown in Figure 1.1, at walking distance from the Homestay.

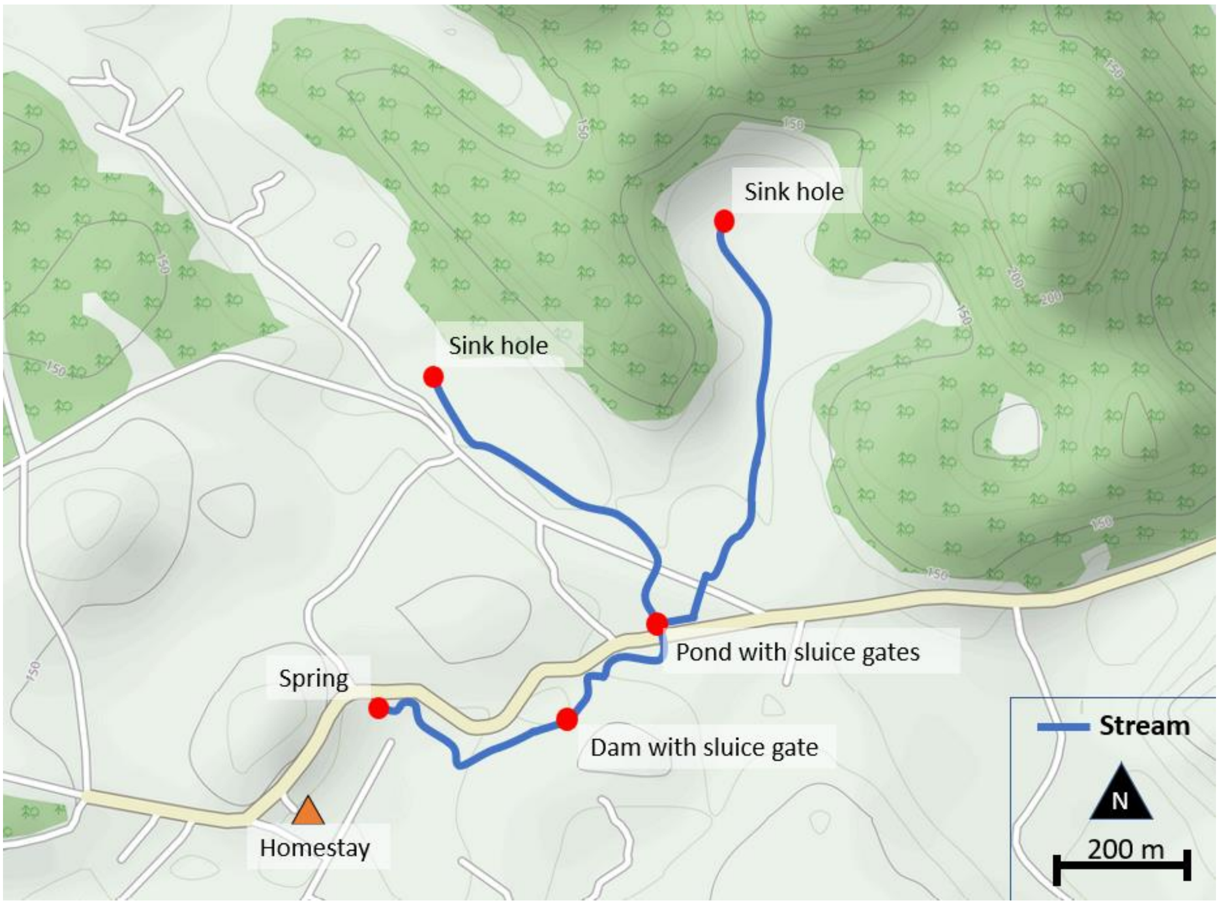

Figure 1.1: Map of the nearby stream with some interesting locations.

Some experiments related to discharge are performed at a different location a bit further away. This location can be seen in Figure 1.2. The only exception is the pumping test, which is performed at the campus of HUNRE. Some experiments are partially done at HUNRE because of the need for specific equipment that cannot be brought to Cuc Phuong.

Figure 1.2: Map showing all experiment locations

1.2.2 What to bring

For every experiment, a list of equipment needed is given. Check this beforehand and make sure you bring everything you need to perform the experiments in Cuc Phuong. Some of the things you need are not experiment-specific. These are listed below:

- Identity card
- Rain clothes
- Boots and slippers
- Sunscreen
- Insect repellent
- Swimming clothes
- All record sheets printed, make sure you have enough.
- Pen, pencil, eraser, ruler, calculator, marker
- Enough cash, since an ATM is not always close-by

1.2.3 How to use this practical guide

This practical guide contains manuals for ten different experiments. Before you go to Cuc Phuong, you can print this document. When you go out in the field, you can bring the manual for the specific experiment you are going to perform.

Each experiment manual has the same setup. First, the experiment is introduced. Then, the underlying theory is discussed. All equations needed for an experiment are discussed in this section. Then, a step-by-step guide for the experiment is given. A list of the equipment and materials needed, and pictures of the experiment are provided as well. Then it explains how the data can be processed to obtain the results. For this, the equations discussed in the theory will have to be used. The data processing is not always described in great detail; you will have to figure out the exact steps yourself. Finally, each manual concludes with some questions that make you reflect on the experiment and the results. Try to answer these yourself, and do not worry about getting the perfect answer. These questions are intended to make you think about what you have done, help you understand the experiment, and achieve the learning goals; they are not related to your grade.

Each experiment has a record sheet, which can be found in Appendix E: Record sheets. Make sure you take a proper look at the record sheet before doing your experiment. You will need to print these record sheets beforehand; make sure you print enough. Keep in mind that an experiment rarely goes right the first time. Some record sheets allow you to note the data of multiple experiments. Some experiments have additional appendices besides the record sheets. These are mentioned in the relevant experiments.

Of each record sheet a digital version exists. You can copy the data from your physical record sheet to these digital ones in Excel. Do this on the same day as your experiment. That way, you still remember what you have done and any errors or uncertainties in the record sheets can be fixed immediately. For one experiment, the solute experiment, also a fully worked out Python script is available which does not require any Python skills.

It is not always mentioned in the manuals, but if you have time left after performing an experiment, it can be a good idea to do it again. Results are rarely the same.

At the end of this practical guide is an integral assignment. It is not an experiment; you do not have to measure anything. Instead, you will go out in the field and use all the knowledge and experience from the experiments to make the assignment.

1.3 Geology

The national park Cuc Phuong is located in between two karst (limestone) mountain ranges of the Dong Giao formation dating from the middle Triassic period. By the influence of rain, the limestone has eroded, creating complex underground flow systems, as shown also in Figure 1.3. On the downstream end of the catchment, several sinkholes can be spotted. During the wet season streams and sinkholes are full of water whereas in the dry season, most flow occurs underground. Rainwater that precipitates in the national park drains rather quickly via the natural underground drainage system. The catchment under investigation receives water at the edge of the park in the form of springs.

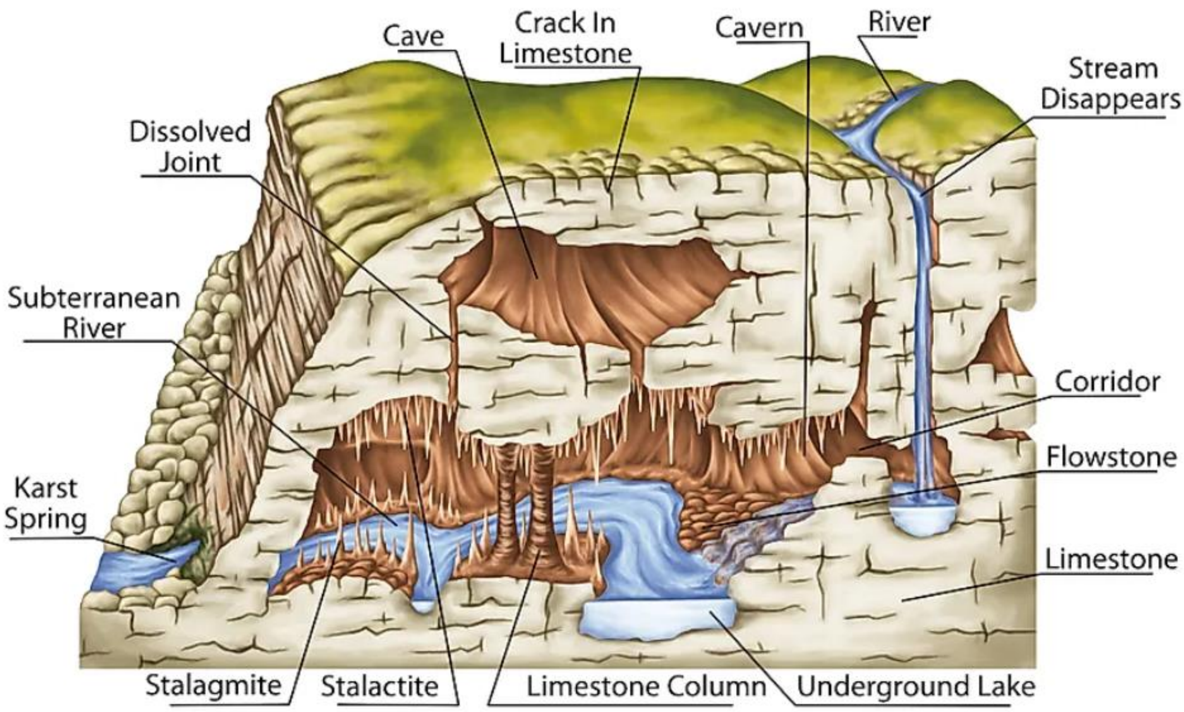

Figure 1.3: An overview of karst topography. From Mala (2021) "Different types of karst landforms". Retrieved from WorldAtlas: https://www.worldatlas.com/articles/what-is-karst.html

1.4 For teachers

This is the teacher's version of the practical guide. It has everything that the student version has but it also has some additional content. For each manual, at the end of the data processing section, an example is given. Each example can also be found in Excel. For some experiments, the example is so elaborate that it is only given in Excel.

Furthermore, answers are given for the reflective questions. These are not the only possible answers, but they indicate what is more or less expected of the students. Everything that is exclusively in the teacher's version of the practical guide is in red, just like this paragraph (which is also only in the teacher's version).

2. Velocity area method

2.1 Introduction

2.1.1 Discharge

You are going to measure the discharge. The discharge of a stream can be described as the volumetric flow rate of water. It plays a significant role in water safety, usage, and quality. Therefore, it is an important quantity to measure. The Cuc Phuong catchment is quite special because it contains multiple wells and sinkholes. Water appears and disappears from and into the ground, which makes it a very complex system. Measuring discharges in this catchment can give better insight into the behavior of the system.

2.1.2 Learning goals

During this experiment, you will learn how to perform a discharge measurement by applying the velocity area method and by using a propeller current meter measurement technique. You will learn for what type of stream, and under which conditions this method is suitable. You will also learn the theory behind this method.

The equipment that is used for this experiment is the complete Geopacks advanced flow meter set. This device consists of a propeller mounted on a stick, which converts the number of revolutions to flow velocity. You will learn how to use this equipment.

Figure 2.1: Geopack advanced flow meter sets

2.2 Theory

The discharge of a stream can be computed according to equation 2.1.

$$Q = v \cdot A \tag{2.1}$$

where:

Q	discharge
v	flow velocity
A	cross-sectional area of stream

The discharge of a stream can be determined by measuring the velocity representative for a certain segment of the cross-section and measuring the cross-sectional area of said segment. The discharge is then computed according to equation 2.2.

$$Q = \int v \, dA \approx \sum_{i=1}^{n} v_i \cdot A_i \tag{2.2}$$

where:

v_i	flow velocity of segment i
A_i	cross-sectional area of segment i
n	number of segments

By doing this, the discharge of every segment is computed. The cross-sectional area of a segment is simply a function of the width and depth of the segment, according to equation 2.3.

$$Q = \sum_{i=1}^{n} Q_i = \sum_{i=1}^{n} b_i * d_i * v_i \tag{2.3}$$

where:

Q_i	discharge of segment i
b_i	width of segment i
d_i	depth of segment i

This concept is also shown in Figure 2.2.

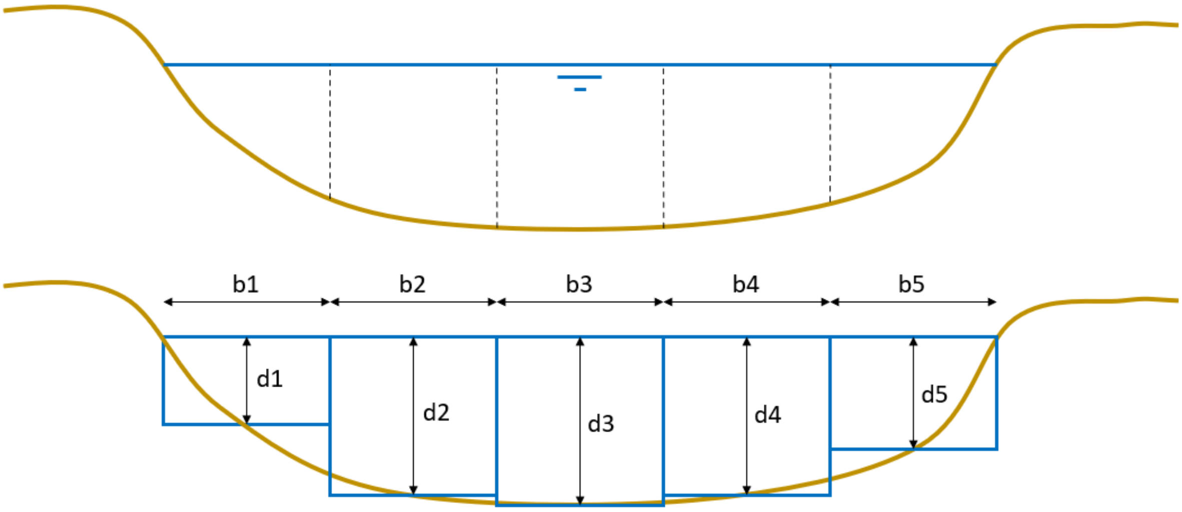

Figure 2.2: Cross section made up of multiple segments. For every segment, the area and the velocity are measured. The discharge of each segment can be computed. The sum of the discharge for every segment is the total discharge.

The velocity in a stream is not constant over the depth but will be higher at the water surface and lower near the bed. As a rule of thumb, a good location to determine the average velocity, under the assumption of a perfect logarithmic distributed flow velocity in the vertical direction, is at 0.6 of the depth of the water below the surface. At this depth, the faster surface flow is averaged out against the slower bed flow, and it is generally accepted as an empirical guideline for shallow streams. This concept is also shown in Figure 2.3.

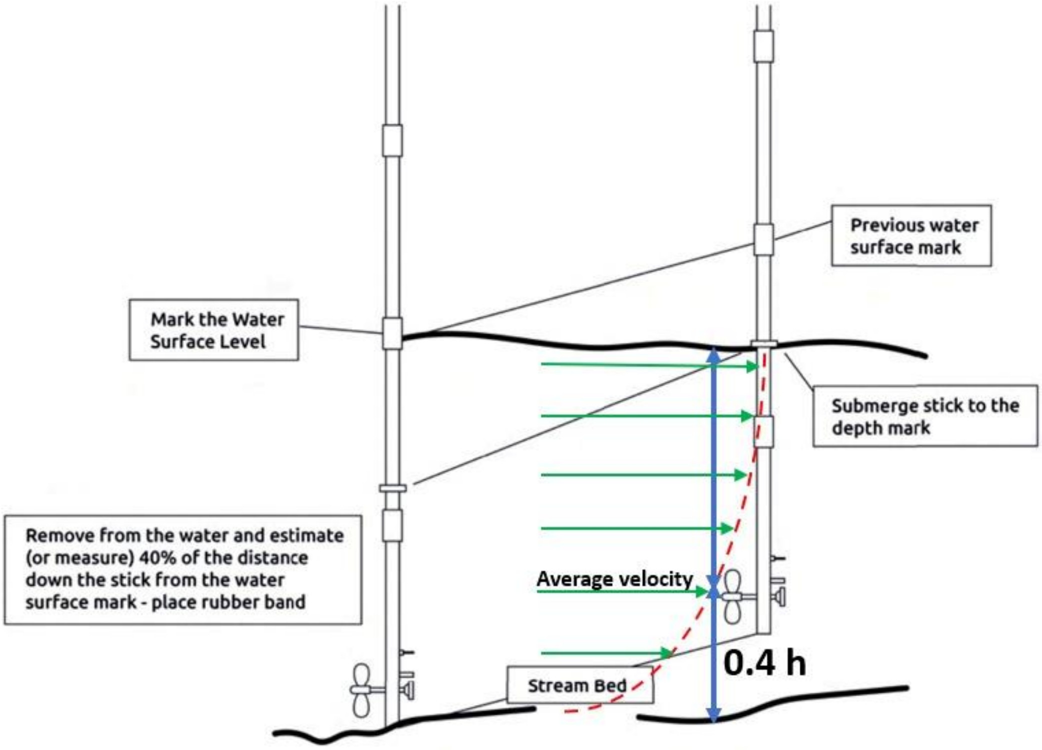

Figure 2.3: Positioning of the current meter in the water column at 0.6 of the water depth. This will approximately result in a measurement of the average flow (Geopacks, 2021).

2.3 Experiment

The equipment and material needed for this experiment are listed in Table 2.1. A record sheet for this experiment can be found in Appendix E: Record sheets.

Table 2.1: The equipment and materials needed for discharge measurement with the

Equipment/material	**Quantity**	**Purpose**
Geopacks current meter	1	Measuring flow velocity
Measuring tape	1	Measuring distance from bank/depth
Staff gauge	1	Measuring depth
Pen and paper	1	Draw schematized cross-section and note down the measured values

First, read through all the steps before doing anything.

1. Find a suitable location to perform the measurement. There are requirements for selecting a cross section for discharge measurements. The flow meter requires a certain minimum velocity to overcome the friction and to let it rotate smoothly. Thus, there must be a significant flow velocity (>0.15 m/s) to achieve reliable data. Also, make sure the water depth is significant to fully submerge the propeller. Recirculation zones must be avoided. The cross-section should be in a straight section of the stream. See also Figure 2.4. In general, a cross-section should have the following characteristics:
   - Straight reach with the threads of velocity parallel to each other
   - Stable streambed free of large rocks, weeds, or other obstacles that create turbulence
   - Flat streambed profile to eliminate vertical components of velocity

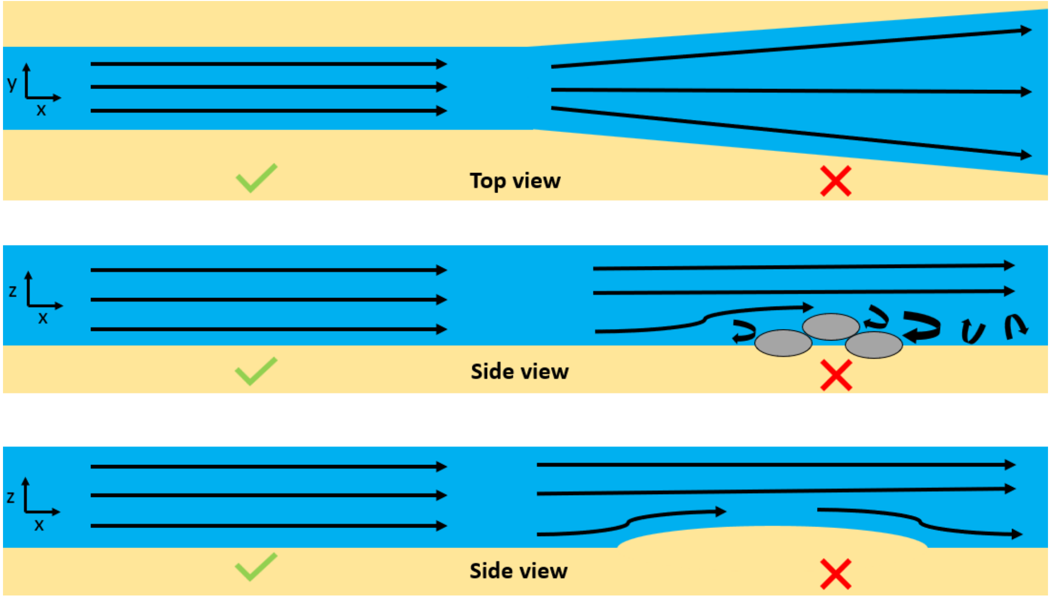

Figure 2.4: Cross-section criteria that make the stream suitable for measuring the discharge with the velocity area method.

2. Measure the total width of the stream at the chosen location.
3. Divide the cross-section into equal segments by selecting verticals at a sufficient number of points (at least five) to ensure an adequate sample of the bed profile and velocity distribution. The spacing of the verticals can vary from site to site and depends on the width, character, and unevenness of the bed, and the variations in velocity distribution throughout the cross-section. See also Figure 2.2.
4. Install the current meter. First, put the batteries in. The device will automatically turn on. Otherwise, press ON. Secondly, press MENU. Use the arrows until the display shows 'FINISH', then press SEL. Lastly, press the arrow pointing downwards until it shows 'FLOW = 0 m/s'. The device is now ready for measurement.
5. Measure the depth and subsequently the depth-averaged flow velocity for each segment. This velocity can be found at a depth of 0.4 times the water depth above the bed (or 0.6 the water depth below the water surface). Note that the depth and flow velocity must be measured in the middle of each segment. Use a measuring tape to determine the distance between the segment and the bank. It is important to ensure the operator's body does not affect the flow pattern. The best position is to stand downstream of the meter and an arm's length from it. The rod is kept vertical throughout the measurement with the meter parallel to the direction of flow. See Figure 2.5 for an example.

Figure 2.5: Measuring the depth of a segment, followed by measuring the flow velocity of a segment

6. Sketch the total cross-section with the dimensions and flow velocities for each segment. See Figure 2.6 for an example.

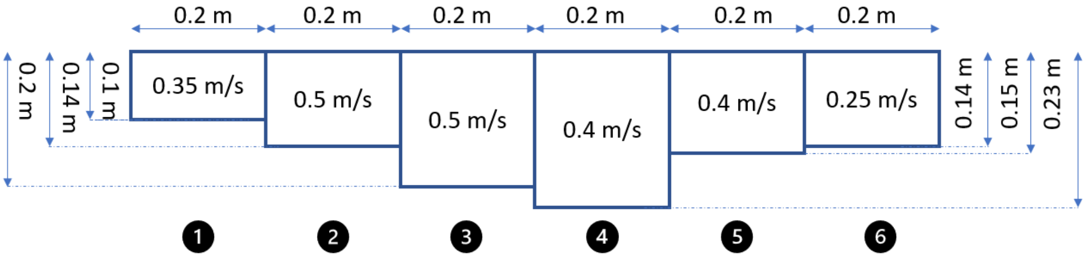

Figure 2.6: Example cross section including dimensions and velocities of six segments

7. Repeat the discharge measurement at a location more upstream or downstream for comparison. Make sure that the discharge in the stream has not changed due to bifurcations or confluences.
8. After using the current meter, take out the batteries and store them inside the bag.

2.4 Data processing

When all the measurements are finished, the collected data is used to compute the discharge. Excel is a useful tool for this.

1. Compute the area of each segment using the depth and width of said segment.
2. Using the area and average velocity of each segment, compute the discharge for each segment
3. Compute the total discharge by summing the discharge of every segment. This is done using the width, depth, and flow velocity of each specific segment. Summing up the discharges of all segments will result in the total discharge. Excel is a useful tool for this.

An example of the data processing is presented below. Figure 2.6 shows some sample data that was collected in the field. This is used as input for the data processing.

The data from the sketch is converted into a table in which the discharge for every segment is calculated, see Table 2.2. After adding up the computed values of the segments, a total discharge of 78.4 l/s can be found.

Table 2.2: Sample data for velocity area method

Segment	**Distance from bank [m]**	b_i [m]	d_i [m]	A_i [m^2]	v_i [m/s]	Q_i [m^3/s]
1	0.1	0.2	0.10	0.020	0.35	0.0070
2	0.3	0.2	0.14	0.028	0.50	0.0140
3	0.5	0.2	0.20	0.040	0.50	0.0200
4	0.7	0.2	0.23	0.046	0.40	0.0184
5	0.9	0.2	0.15	0.030	0.40	0.0120
6	1.1	0.2	0.14	0.028	0.25	0.0070
					Total	**0.0784**

An example can also be found in the Excel file.

2.5 Reflective questions

1. During this experiment you measured the discharge using the current meter on at least two segments of the river. Do the results of the two measurements compare? Can you

explain any differences? Think about your simplified cross-section or look back at the requirements for the cross-section noted in step 1.

The results can certainly differ, but they should be in the same order of magnitude. If not, the students probably have made a mistake in their computations. Differences could be because of inaccuracies in the flow velocity measurement, simplifications of the streambed, the flow velocity not being average at 0.6 of the total depth, etc.

2. How do the results compare with the other discharge measurement techniques? (e.g., solute or weir method). Which method is more suitable for the stream where you did your measurement? Why?

Measuring discharge with solute is only suitable if sufficient lateral mixing occurs. It is suitable for this location, but not necessarily better than using the velocity area method. Both these methods have some criteria and are not possible for every section of this stream. Sections that are suitable for the velocity area method are not always suitable for the solute method.

Using a small V-notched weir is only possible in small streams. It is not suitable for this stream.

3. What modifications to this experiment could you make to improve the accuracy?

Increase the number of verticals, measure the velocity at multiple depths, etc.

2.6 References

Geopacks. (2021). Downloadable Catalogues and Manuals. Retrieved from Geopacks website: https://cdn.shopify.com/s/files/1/1602/0217/files/Adv_Flowmeter_Manual_2021-compressed_1.pdf?v=1673265159

Rantz, S. E. (1982). *Measurement and computation of streamflow* (Vol. 2175). US Department of the Interior, Geological Survey.

3. Measuring discharge with a weir

For an introduction to the definition and importance of the discharge of a stream, please see the introduction of chapter 2: "Velocity area method" on a discharge measurement using the velocity area method.

3.1 Introduction

3.1.1 Weirs and discharge

You are going to measure the discharge of a stream with a weir. Weirs are a widely used method to measure discharge. They require no complicated equipment during use and are generally quite accurate. The flow rate can be deducted from the water level occurring on top of this weir. The relation between the discharge and the water level on top of a weir depends on the type of weir that is used.

In this experiment, a thin metal V-notched weir is used to measure the discharge. Such a weir is depicted in Figure 3.1. The advantage of such a small weir is that it is portable and can be installed anywhere in a small stream. For larger streams, weirs have to be constructed. These larger weirs are usually made from concrete, and they are of course not portable. Since they are always in the same location, the discharge can only be measured at that specific location.

Figure 3.1: A portable weir installed in a stream

3.1.2 Volumetric method

The discharge can also be determined by filling a jar with the water that is flowing over this weir while keeping track of the time. This is known as the volumetric method, which you are also going to learn. Afterward, these measurements can be compared to each other.

3.1.3 Learning goals

In this experiment you learn two methods of measuring the discharge: with a weir and with the volumetric method. You will learn when and how to apply these methods, and when they are and are not suitable for a discharge measurement.

3.2 Theory

3.2.1 Measuring discharge with a weir

When water flows over a weir, the water height relative to the weir is related to the discharge over the weir. This relation is given in equation 3.1.

$$Q = C_d \cdot \frac{8}{15} \cdot \tan\left(\frac{\alpha}{2}\right) \cdot \sqrt{2g} \cdot h^{\frac{5}{2}} \tag{3.1}$$

where:

Q	discharge over the weir	[m^3/s]
C_d	coefficient of discharge	[-]
α	notch angle	[°]
g	acceleration due to gravity	[m/s^2]
h	water depth above the weir	[m]

When using $C_d = 0.58$ and $\alpha = 90^\circ$ equation 3.1 simplifies into equation 3.2.

$$Q \approx 1.37 \cdot h^{\frac{5}{2}} \tag{3.2}$$

Note that equation 3.2 is thus only valid for a V-notched weir with a 90-degree angle, as shown in Figure 3.2.

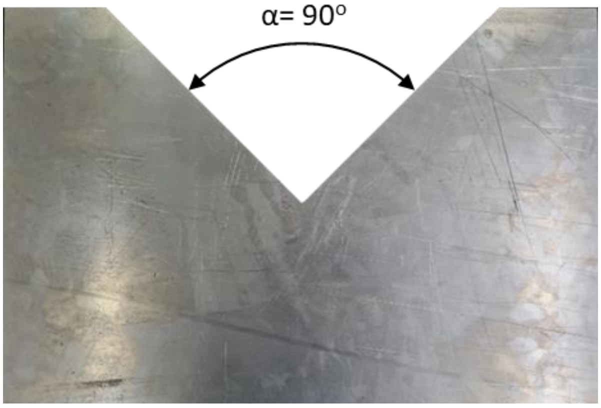

Figure 3.2: A V-notched weir with a 90-degree angle

This equation assumes free flow that is only affected by upstream conditions. It is important to create a sufficient water level difference, so the downstream water level does not influence the flow over the weir.

3.2.2 Volumetric method

If the discharge over the weir is not too big, it can also be measured using the volumetric method. By filling some jar or measuring cup with a certain volume, while timing how long it takes to fill this volume, the discharge can easily be computed according to equation 3.3.

$$Q = \frac{V}{t} \tag{3.3}$$

where:

V	volume of water	[m^3]
t	time needed to fill this volume	[s]

3.3 Experiment

The equipment and materials needed for this experiment are given in Table 3.1. A record sheet for this experiment can be found in Appendix E: Record sheets.

Table 3.1: The equipment and materials needed for a discharge measurement using a portable weir

Equipment/material	**Quantity**	**Purpose**
Thinly plated weir	1	Creating free flow conditions
Steel bars	2	Stabilizing the weir
Shovels	2	Closing off the dam with clay
Measuring tape	1	Measuring water height above weir
Jar/measuring cup	1	Measuring water volume over weir

Perform the following steps:

1. Find a location to perform the measurement. A suitable location has a cross-section in which the weir can be placed, without too much free space around it. Furthermore, the surrounding banks must have a significant height to prevent the water from flowing around the weir. Prepare the bottom of the stream by removing any rocks so that the weir can be placed on a flat surface.

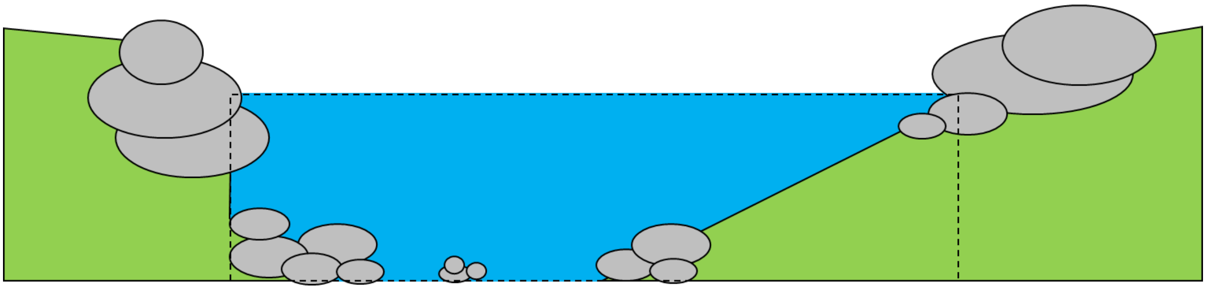

Figure 3.3: Cross-section of a stream where a weir could be installed

2. Place the weir in the stream. The water level must be slightly above the lowest part of the weir opening, as depicted in Figure 3.4. Make sure the weir is standing straight using some rocks for balance. Also, two steel bars can be used at the downstream side of the weir to counteract the water pressure that is acting on the structure.

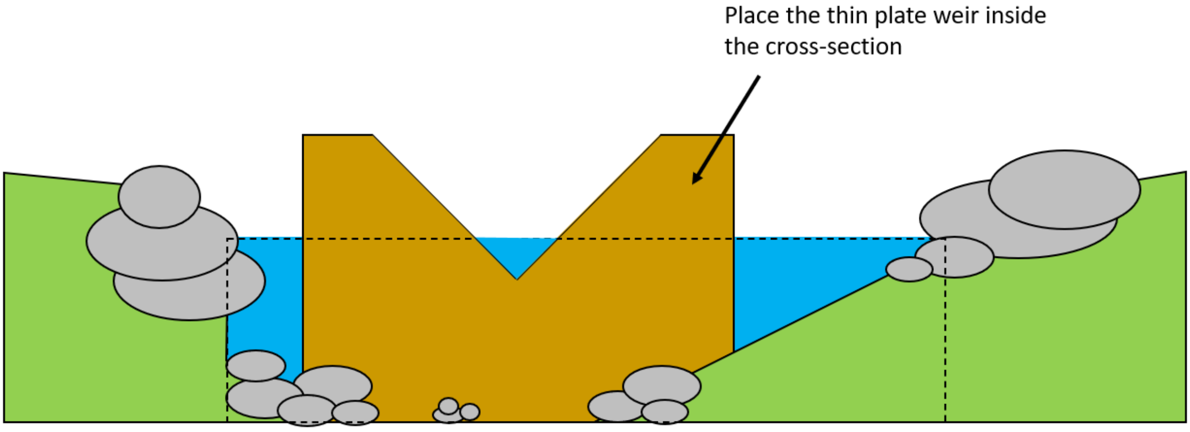

Figure 3.4: The weir placed into the stream.

3. Create a dam by closing the entire cross section with clay, as shown in Figure 3.5. Use shovels (2 students) to move the clay and use your hands (2 students) to carefully fill all the remaining gaps, as shown in Figure 3.6. Make sure no water is flowing underneath or around the structure.

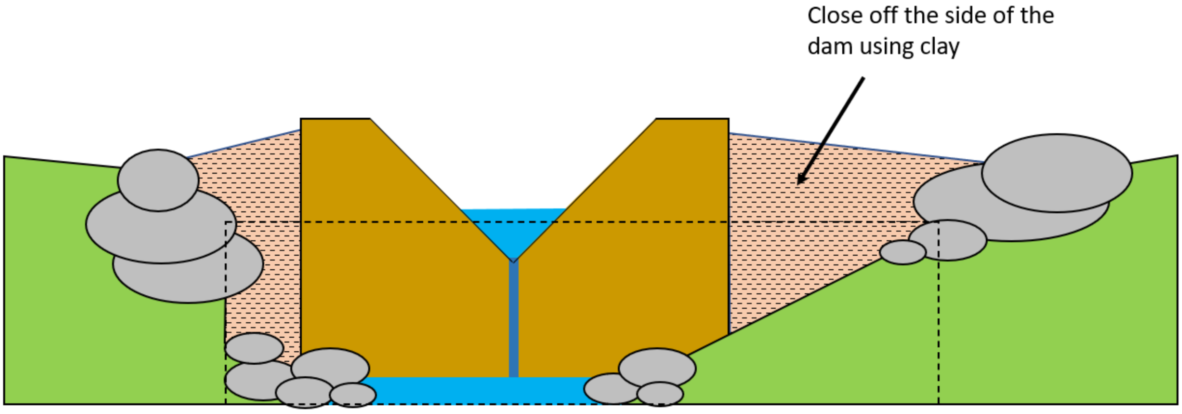

Figure 3.5: Closing of stream, so all the water flows over the weir

Figure 3.6: Students close off the stream with shovels and their hands.

4. Wait for some time to let the stream reach a new equilibrium state. Depending on the location this can take from about half an hour to two hours. The upstream water level will rise a little bit, resulting in a bigger flow over the weir, see also Figure 3.7. Check if there is still no water seeping through. If so, reinforce the dam with extra clay.

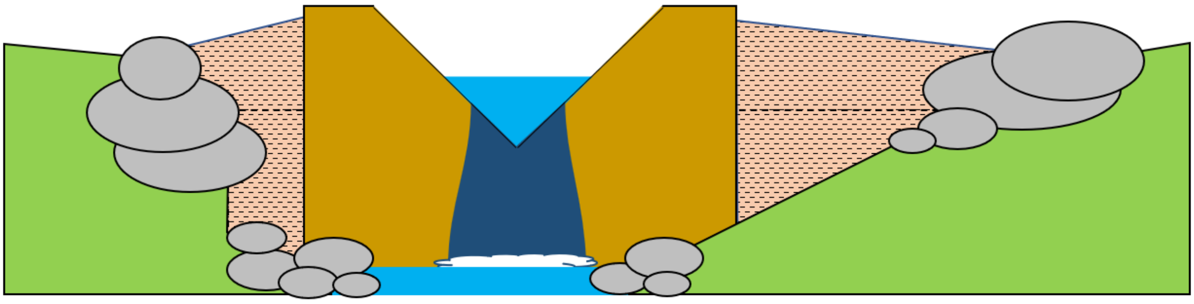

Figure 3.7: The water level behind the weir rises, resulting in an increased discharge.

5. Measure the height of the water flow exactly above the weir opening, as shown in Figure 3.8 and Figure 3.9. Position the measuring tape in the flow direction so it does not block the water and prevents backwater effects.

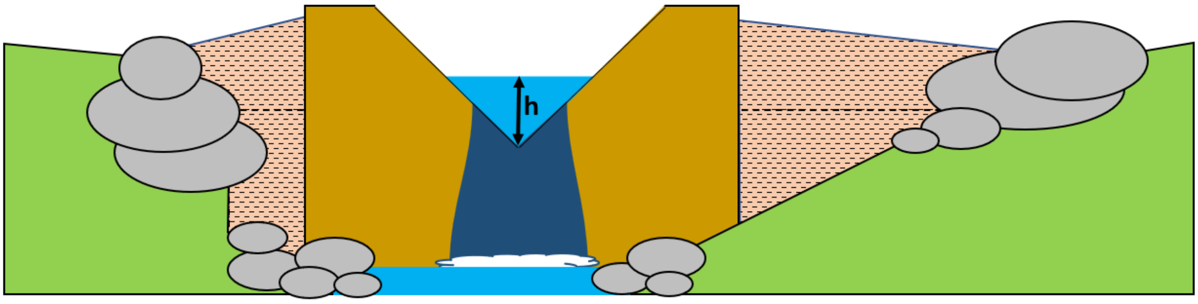

Figure 3.8: The water height above the weir, which is the quantity of interest

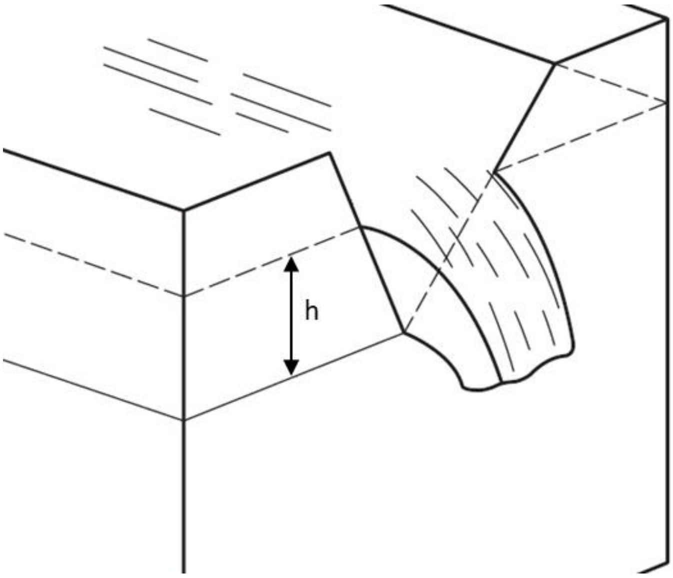

Figure 3.9: A picture of the water height h above the weir.

6. Collect the water flowing over the weir by filling a jar or bucket until a certain volume, as shown in Figure 3.10. Simultaneously, another student measures the time it takes for the water to fill the jar or bucket, using a stopwatch. Do this multiple times.

Figure 3.10: Measuring the discharge using the volumetric method. This method is sometimes called the bucket-and-stopwatch method.

3.4 Data processing

1. Compute the discharge using equation 3.2.
2. Compute the discharge using equation 3.3.

An example of the data processing is given below. An example can also be found in the Excel.

If a water depth of 3 cm is measured above the V-notched weir, then the discharge is

$$Q \approx 1.37 \cdot h^{\frac{5}{2}} = 1.37 \cdot 0.03^{\frac{5}{2}} \approx 0.00021\, m^3/s$$

So the discharge is about 0.21 l/s. If a bucket is filled with 1.1 liters of water in 4.8 seconds, the discharge is

$$Q = \frac{V}{t} = \frac{1.1}{4.8} \approx 0.23\, l/s$$

So the discharge is about 0.23 l/s.

3.5 Reflective questions

1. During this experiment you measured discharge using two different methods. Do the results of the two measurements compare? Can you explain any differences? Which of the measurements do you think is more accurate?

Depends on how the experiment went and how the weir was constructed. In general, the weir method is considered more accurate.

2. It is not strictly necessary to use a weir with a V-notch. You could also use just a rectangular metal plate, instead of one with a V-notch. The equation would be a bit different, but it is possible. Why do we still prefer to use a weir with a V-notch?

The water flows over a larger width if you use a rectangular plate, thus the water depth would be smaller. A tiny inaccuracy in measuring the water depth would thus result in quite a large error.

3.6 References

Rantz, S. E. (1982). *Measurement and computation of streamflow* (Vol. 2175). US Department of the Interior, Geological Survey

4. Solute transport

This chapter describes two experiments. The first experiment uses solute to measure both the discharge and the dispersion of a stream. The second experiment is different but also uses solute to measure the discharge.

4.1 Introduction

4.1.1 Solute and discharge

When we dissolve a substance in a liquid, we call this a solution. The liquid is called the dissolvent, while the dissolved substance is called the solute. In these experiments, solute is injected into a stream. As a solute, salt is used. The salt concentration downstream of the injection can be measured, which can tell us a lot about the discharge and the dispersion of the stream.

The discharge is a very important property of a stream but measuring it can prove difficult. That is why it can be useful to have multiple methods of measuring discharge. The two experiments described here use solute to measure discharge, but there are other methods of measuring discharge using different techniques. By comparing multiple discharge measurements obtained using different methods, the confidence of a measurement can be better assessed.

4.1.2 Dispersion

Dispersion is the process of a substance spreading in a liquid. The dispersion coefficient of a stream tells us something about the mixing within a stream. This can be useful when modeling pollution in a river. The dispersion coefficient is not constant but can vary greatly over the course of the stream, as well as over time (depending often on the discharge). Actually, a stream has three dispersion coefficients: one for each dimension (length, width, and depth). The length-dimension of a stream is also called the longitudinal direction. For example, we say that the water flows longitudinally in a stream. The width-dimension of a stream is also called the lateral direction. So, if you walk from one side of the stream to the other, you have crossed the stream laterally. See also Figure 4.1. The depth dimension of a stream is also called the vertical direction.

Figure 4.1: The longitudinal and lateral directions of a stream

4.1.3 Learning goals

In these experiments, you will learn how to measure the discharge and dispersion of a stream using solute (dissolved salt). You will also learn about the relationship between salt and electro-conductivity. Furthermore, you will learn how to use equations based on the mass balance, which is an often-used concept in water management. You will learn how to use the GMH3431 electro-conductivity meters.

4.2 Theory

4.2.1 Salt and electro-conductivity

Water naturally conducts electricity; this is called electro-conductivity (EC). Water is able to conduct electricity because of ions in the water. Ions are positively or negatively charged particles dissolved in water. The more ions are present, the higher the EC of the water. The EC is also dependent on other factors, like temperature.

If natrium chloride (table salt) is dissolved in water, it turns into sodium ions (Na^+) and chloride ions (Cl^-). There are always some ions (not just sodium or chloride) naturally present in water, even in freshwater. Thus, water naturally conducts electricity, although not as well as metals for example.

If we add salt to water the EC goes up, because now there are more ions in the water. If we add salt to a stream and simultaneously measure the EC downstream of this injection, we will see the EC thus goes up. However, over time, all the salt will have flowed passed and the EC would go down again. The increase and subsequent decrease of the EC can be measured using an EC meter. After the EC is converted to a salt concentration, this data can be used to compute the discharge and/or the dispersion.

To convert EC to concentration (sodium or chloride) we use an empirical equation, given in equation 4.1.

$$\phi = 3 \cdot 10^{-6} \cdot \sigma^2 + 0.5309 \cdot \sigma \tag{4.1}$$

where:

ϕ	salt concentration	[g/m³]
σ	electrical conductivity	[µS/cm]

4.2.2 Measuring discharge using solute

Using solute, the discharge of a stream can be measured in two ways.

Gulp injection method

The first method of measuring discharge with solute is called the gulp injection method. In this type of experiment, a certain mass of salt m is dissolved in some water and then injected into the stream. The salt is injected all in one go, hence the name "gulp injection".

The solute will mix with the water and flow downstream. The salt concentration of the stream ϕ will increase, but only where the solute has mixed with the water. At the point of injection, you will thus see an immediate increase in EC. However, further downstream, the EC will not immediately increase. It will take some time for the solute to flow further downstream. Only then will the EC increase. The increase will also be less strong because the solute will have mixed more and thus be diluted more. Once all the solute has passed, the EC will be back at its natural level again. This concept is visualized in Figure 4.2.

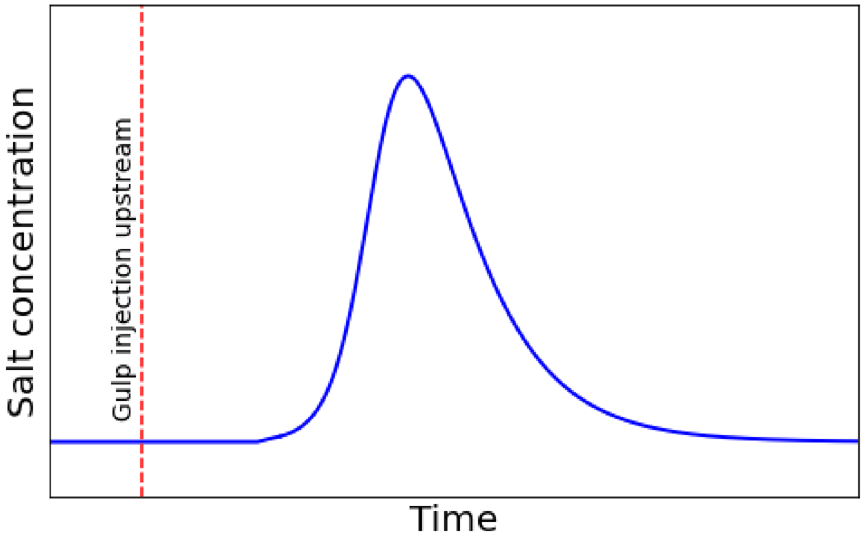

Figure 4.2: The increase in salt concentration at a point downstream of a gulp injection.

No matter how far a measurement point is downstream from the injection point, at some moment all the solute will have passed. If we assume the solute is fully mixed laterally and the added discharge from the injection is negligible, the discharge of the stream Q can be computed by continuously measuring the EC downstream of the injection point and converting this to a concentration $\phi(t)$. The computation of the discharge is done according to equation 4.2.

$$Q = m \div \int_{0}^{\infty} (\phi(t) - \phi_{natural}) dt \tag{4.2}$$

where:

Q	discharge of the stream	[m^3/s]
m	mass of the salt	[g]
t	time after injection	[s]
$\phi(t)$	salt concentration at time t	[g/m^3]
$\phi_{natural}$	naturally occurring salt concentration	[g/m^3]

The derivation of this equation can be found in a manual written by Rantz (1982) for the United States Geological Survey.

Constant rate injection method

The second method of measuring discharge with solute is called the constant rate injection method. In this type of experiment, solute is added with a constant discharge (thus at a constant rate, hence the name). This is done using a Mariotte bottle, which can be seen in Figure 4.3. Such a Mariotte bottle is closed off from the top, except for an air tube that reaches to the bottom of the Mariotte bottle. At the end of this tube, atmospheric pressure occurs. When the tap is opened, water will flow out of the tap at a constant rate, since the water pressure is kept constant due to the air tube.

Figure 4.3: A Mariotte bottle, which discharges at a constant rate

Downstream of the injection, the EC is measured. Before solute is injected the stream has a constant salt concentration and thus a constant EC. When solute is injected, the EC will go up. Because solute is continuously added, the EC will at one point reach a new constant level, higher than the natural EC of the stream. Only after the injection of solute stops will the EC go down again until it finally reaches its natural EC again. This may take quite a while. In Figure 4.4 the course of the salt concentration in a stream at a certain point downstream of the injection can be seen.

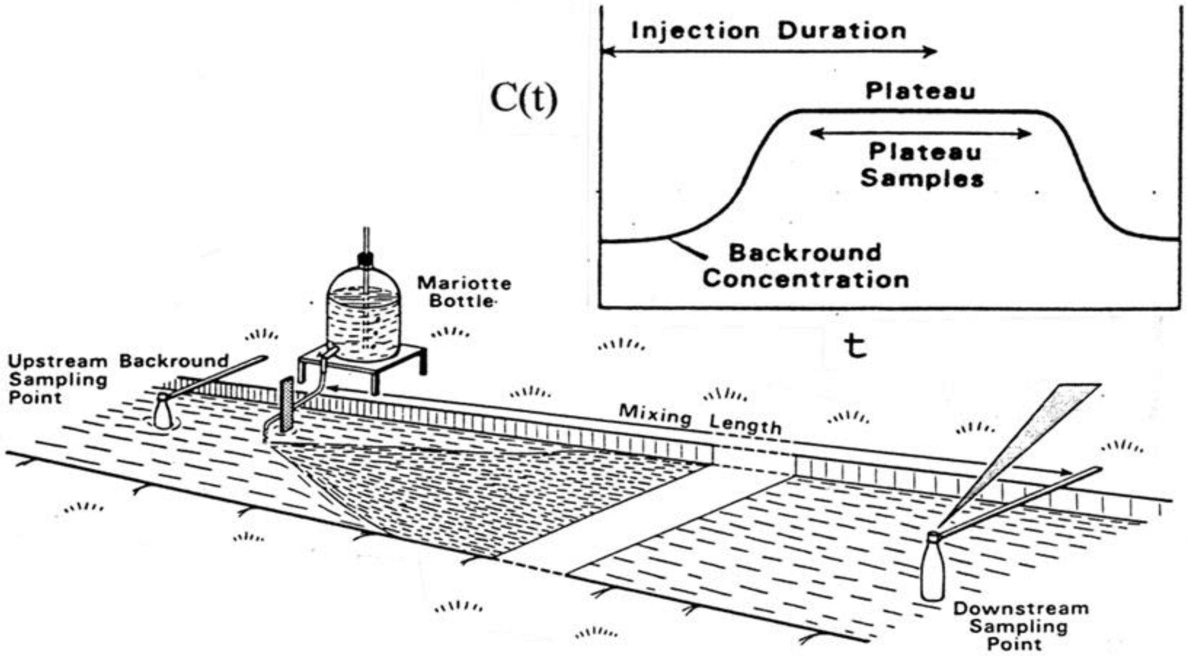

Figure 4.4: The salt concentration of a stream at a certain point downstream of the injection of solute. The solute is added at a constant rate.

If we assume that the added discharge from the injection is negligible and that the solute is fully mixed laterally, the discharge of the stream Q can be computed based on the concentration of the injection and the constant concentration the stream reaches after a certain amount of time, together with the discharge of the injection. This is done according to equation 4.3.

$$Q = Q_{injection} \cdot \frac{\phi_{injection}}{\phi_{increased} - \phi_{natural}} \tag{4.3}$$

where:

$Q_{injection}$	discharge of the injection
$\phi_{injection}$	concentration of the solution
$\phi_{increased}$	increased constant concentration

The derivation of this equation can be found in a manual written by Rantz (1982) for the United States Geological Survey.

4.2.3 Measuring dispersion using solute

If salt solute is added to a stream, it will mix with the stream, both in the lateral and longitudinal directions. The further downstream we are from the injection, the more the solute will have mixed with the stream; it is thus more diluted further downstream. Close to the injection, the solute has only spread locally. Thus, the salt concentration is still high, but only for a small part of the stream. Further downstream the solute has spread over a much larger part of the stream, but the concentration is also lower. This can also be seen in Figure 4.5.

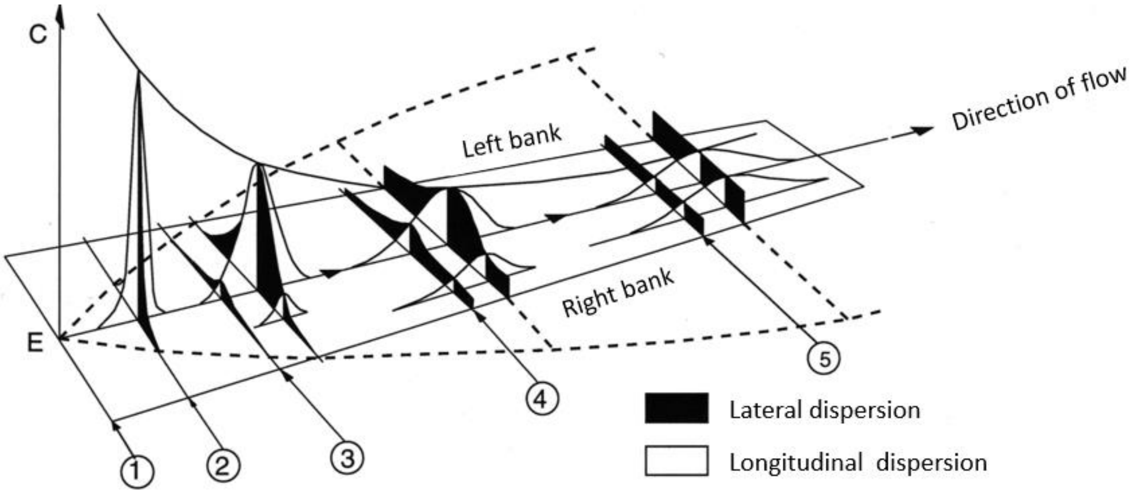

Figure 4.5: The salt concentration in a stream over time after the gulp injection of solute. Note how the salt concentration is more spread out further downstream of the injection, both in longitudinal and lateral directions. At cross-section 1 at location E, the injection occurs and the concentration is very local. At cross-section 5 the solute has completely mixed laterally; the concentration is the same over cross-section 5.

Imagine a gulp injection of solute into a stream and you are measuring the concentration downstream of this injection. You can assume complete lateral mixing has been achieved (as shown in cross-section 5 of Figure 4.5); we are only interested in longitudinal mixing for now. Close to the injection, the solute will not have mixed a lot; the solute is not diluted a lot and has only spread locally. The concentration will be very high, but the peak will also pass quickly. Further downstream, the solute will have mixed more. It has spread to a larger section of the river but is therefore also more diluted. The concentration will be lower, but the peak will pass slower. It will also take more time for the peak of the concentration to be reached for the location far from the injection compared to the location closer to the injection. This is because the distance between the injection and the measurement point is longer, thus the travel time is also longer.

How quickly the solute mixes longitudinally with the stream depends on the turbulence of the stream. In very turbulent water, the mixing will be very quick. This means the solute will have spread quickly over the length of the stream. If the flow is less turbulent, the longitudinal mixing will be slower, so the solute will spread slowly over the length of the stream.

This phenomenon is depicted in Figure 4.6. The left graph is from a stream with less turbulent flow, and there is little mixing over the length of the river. The distribution of the concentration further downstream of the injection point looks thus quite similar to the distribution of the concentration closer to the injection point. It is a bit more spread out and the peak is slightly lower, but it is still quite the same. The right graph is from a stream with turbulent flow, and there is more mixing over the length of the river. The distribution is more spread out, and the peak is lower.

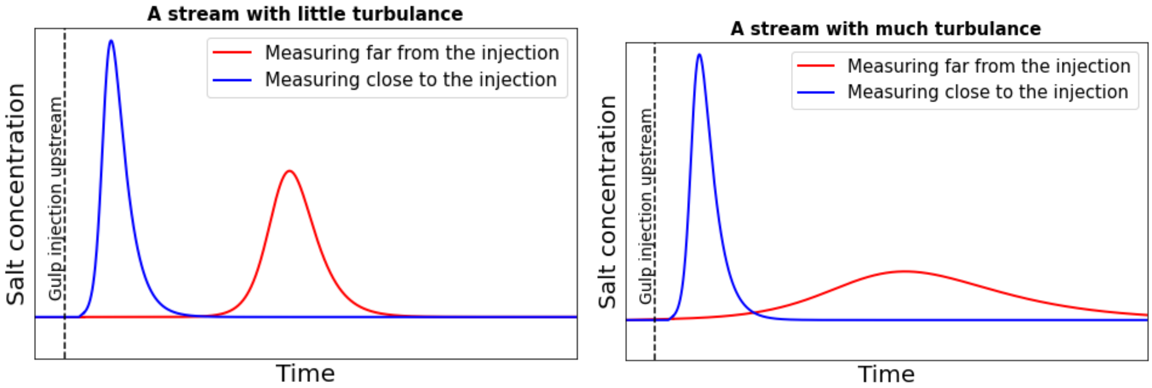

Figure 4.6: The salt concentration in two streams after a gulp injection, both close and far from the injection. Left: a less turbulent stream with little mixing. Right: a more turbulent stream with more mixing.

The magnitude of longitudinal mixing is called the longitudinal dispersion coefficient. With this coefficient, it is actually possible to model the mixing of salt solute in a stream after a gulp injection. The concentration of salt in a stream after a gulp injection can be computed at any point in the stream at any moment. For this, the equation of Taylor (1954) can be solved analytically; the result is equation 4.4.

$$\phi(x,t) = \phi_{natural} + \frac{m}{A\sqrt{4\pi D_x t}} e^{\left(-\frac{(x-vt)^2}{4D_x t}\right)} \tag{4.4}$$

where:

x	distance from injection	[m]
$\phi(x,t)$	concentration at time t after and distance x from injection	[g/m^3]
A	cross-sectional area	[m^2]
v	flow velocity	[m/s]
D_x	longitudinal dispersion coefficient	[m^2/s]

If downstream the salt concentration is continuously measured after a gulp injection, the value of the longitudinal dispersion coefficient D_x can be calibrated using this equation. Keep a close eye on the units in this equation.

Note that this just concerns mixing in one direction (length). It assumes immediate and complete mixing in the other two directions, width and depth. This is of course not completely true; mixing in these directions is not instantaneous and can likewise be modeled using a lateral dispersion coefficient and a vertical dispersion coefficient. The 2D or 3D modeling of solute mixing is based on the same concept, but the equations quickly get very complicated, as well as the process of calibration. Thus, the assumption is made that the mixing in the lateral and vertical directions is instantaneous.

4.3 Experiments

Using a gulp injection, both the discharge and the longitudinal dispersion coefficient can be computed. This can be done in a single experiment. Measuring the discharge using a constant rate injection requires a slightly different setup, but many of the steps are the same.

4.3.1 Gulp injection for measuring discharge and dispersion

The equipment and materials needed to perform a gulp injection and measure the discharge and the longitudinal dispersion coefficient of a stream can be seen in Table 4.1. You need at least five persons to perform this experiment. A record sheet for the measuring of the cross-sectional area can be found in Appendix E: Record sheets. A record sheet for the gulp injection itself can also be found in Appendix E: Record sheets.

Table 4.1: The equipment and materials needed for a gulp injection to measure discharge and longitudinal dispersion coefficient.

Equipment/material	**Quantity**	**Purpose**
Salt	2.5 kg	Solute
Scale	1	Weighing the salt
EC meter	3	Measure EC
Stopwatch	1	Timing the experiments (a phone is fine)
Coloring agent	1 bottle	Finding turbulent water
Boots	4 pairs	Entering the stream without getting wet feet
Yardstick	1	Measuring water depth
9-volt batteries	4	Powering the EC meters
Bucket	1	Mixing solute or coloring agent with water
Clipboard with pen	3	Notating EC during the experiment
Rope	1	Indicating locations of the stream
Duct tape	1 roll	Closing the bags of salt
Measuring tape	10 meters	Measuring distances

First read through all the steps before doing anything.

1. Find a suitable location for your experiment
    1.1. Streams change over time, so it is impossible to say a location that was suitable last time is still suitable. You will have to find a suitable location yourself. A suitable location meets a few requirements:
        - It has a nice injection point, like a small waterfall or some rapids where the flow is very turbulent, the width of the stream is small, and all the water should pass through this point. This way the injected solute will quickly mix laterally. An example of a nice injection point is given in Figure 4.7.

Figure 4.7: A suitable injection point, where the water is quite turbulent with some rapids, and all the water flows through a narrow cross-section

- Downstream of the injection point, the stream does not have any major turns or large stagnant zones. The cross-sectional profile should be constant as much as possible downstream of the injection point. It can be different from the injection point, but the first 10-15 meters after the injection point should have a constant cross-section. An example of a nice downstream section is depicted in Figure 4.8.

Figure 4.8: A suitable downstream section, with more or less a constant cross-section and no major turns

- The location is safe, meaning the water is not dangerously deep and can be easily reached. Safety should always have the highest priority.

1.2. If you have found a spot that you think is suitable, you can test it. You are going to visually test the turbulency of the stream using a coloring agent. Take a bucket and fill it with some water from the stream.

1.3. Mix plenty of coloring agent into the water in the bucket. Make sure it is enough to still be visible when the mixture is injected into the stream. Inject it into the stream and see if it mixes laterally properly, as shown in Figure 4.9.

Figure 4.9: Injecting coloring agent into the stream to see if it has sufficient turbulent mixing. Here, a yellow coloring agent is used. Red or green are often more suitable.

1.4. If proper lateral mixing is achieved, this location can be used to perform the discharge experiments. If not, repeat at a different location.

2. Measure the cross-sectional area
   2.1. Span a rope or a measuring tape across the stream, downstream of the injection point. Make sure it is orthogonal to the direction of flow. See Figure 4.10.

Figure 4.10: Spanning a measuring tape across the stream, orthogonal to the direction of flow

2.2. Measure the water depth along the rope for every 10 cm. Start at one side of the stream to the other side, as depicted in Figure 4.11.
2.3. Do this again at a few different locations downstream of your injection point.

Figure 4.11: Measuring the water depth

3. Prepare the solute
   3.1. Visually estimate the discharge of the stream. How much salt do you think you need to get a nice peak?
   3.2. Dissolve the amount of salt you think is suitable in a bucket filled with water from the stream. See also Figure 4.12. Keep in mind the maximum amount of salt you can dissolve in water. Make sure all the salt is dissolved.

Figure 4.12: Dissolving salt into a bucket. Notice how the salt is carefully weighed.

4. Getting into position
    4.1. You are going to inject the solute, while continuously measuring the EC downstream. One person will do the injection at the injection point, by emptying the bucket in one go.
    4.2. Three persons will measure the EC downstream of the injection, at different distances downstream of the injection. They should all stand in the middle of the stream as shown in Figure 4.13. Measure the exact distance each person stands downstream of the injection.

Figure 4.13: A person measuring the EC in the middle of the stream. In one hand, the observer holds the clipboard with the record sheet. Firmly attached to the clipboard is the EC meter, with the probe hanging into the water. The probe is completely submerged, but not touching the bottom of the river. In his other hand, the observer holds the pen and writes down the measured EC.

    - 4.3. A fifth person keeps track of time. This person gives a signal every five seconds. See also Figure 4.14.

Figure 4.14: A person timing using their phone, giving a signal every five seconds

5. Performing the experiment
    - 5.1. The solute is injected all in one go. At this exact moment, the timer starts.
    - 5.2. Every five seconds, a signal is given by the person timing. The people measuring the EC write down the measured value every five seconds
    - 5.3. The EC will not increase immediately, since it takes some time for the solute to travel from the injection point to the measurement points. When it reaches a measurement point, you will see a strong increase. After the peak, the EC will go down again slowly. When the EC finally reaches the original natural value at every measurement point, you can stop measuring and timing.
    - 5.4. Were you able to nicely measure the EC at every location? Think about the amount of salt used and the distance between a measurement point and the injection point. Do not be afraid to redo an experiment. It is a process of trial and error, and you will probably have to adjust accordingly.
6. Cleaning up
    - 6.1. Rinse the bucket and put it away. Do not rinse the bucket while the measurement is still going on.
    - 6.2. Carefully store the EC meters. Take out the batteries and make sure the meter and the batteries are completely dry. The EC meters are not waterproof.
    - 6.3. Clean the scale; make sure it is completely dry. Put it away carefully.
    - 6.4. Make sure you have all your equipment. Leave nothing behind, take any trash with you, and dispose of it properly at home.

4.3.2 Constant rate injection for measuring discharge

The equipment and materials needed to perform a constant rate injection to measure discharge can be seen in Table 4.2. You need at least four people to perform this experiment. A record sheet for this experiment can be found in Appendix E: Record sheets.

Table 4.2: The needed equipment for a constant rate injection to measure discharge

Equipment/material	**Quantity**	**Purpose**
Salt	5 kg	Solute
Scale	1	Weighing the salt and water
EC meter	3	Measure EC
Coloring agent	1 bottle	Finding turbulent water
Boots	4 pairs	Entering the stream without getting wet feet
9-volt batteries	4	Powering the EC meters
Mariotte bottle	1	Injecting solute at a constant rate
Bucket	1	Mixing solute or coloring agent with water
Clipboard with pen	3	Notating EC and other data during experiment
Duct tape	1 roll	Closing the bags of salt
Measuring tape	10 meters	Measuring distances

First read through all the steps before doing anything.

1. Find a suitable location for your experiment
    1.1. Streams change over time, so it is impossible to say a location that was suitable last time is still suitable. You will have to find a suitable location yourself. A suitable location meets a few requirements:
    - It has a nice injection point, like a small waterfall or some rapids where the flow is very turbulent, the width of the stream is small, and all the water should pass through this point. This way the injected solute will quickly mix laterally. See Figure 4.15 for an example of a nice injection point.
    - The location is safe, meaning the water is not dangerously deep and can be easily reached. Safety should always have the highest priority.

Figure 4.15: A suitable injection point, where the water is quite turbulent with some rapids, and all the water flows through a narrow cross-section

1.2. If you have found a spot that you think is suitable, you can test it. You are going to visually test the turbulency of the stream using a coloring agent. Take a bucket and fill it with some water from the stream.

1.3. Mix plenty of coloring agent into the water in the bucket. Make sure it is enough to still be visible when the mixture is injected into the stream. Inject it into the stream and see if it mixes laterally properly, as shown in Figure 4.16.

Figure 4.16: Injecting coloring agent into the stream to see if it has sufficient turbulent mixing. Here, a yellow coloring agent is used. Red or green are often more suitable.

    1.4. If proper lateral mixing is achieved, this location can be used to perform the discharge experiments. If not, repeat at a different location.

2. Check the discharge of Mariotte bottle
    2.1. Fill the Mariotte bottle with water.
    2.2. Take a measuring cup and time how long it takes to fill the measuring cup with a certain volume. What is the discharge of the Mariotte bottle?
    2.3. Repeat this a couple of times. What is the average discharge of the Mariotte bottle?

3. Prepare the solute
    3.1. Visually estimate the discharge of the stream. What concentration do you think you will need to get a nice increase in EC?
    3.2. Make a salt solution with this concentration using the scale, as shown in Figure 4.17. Keep in mind the maximum amount of salt you can dissolve in water. Make sure all the salt is dissolved.

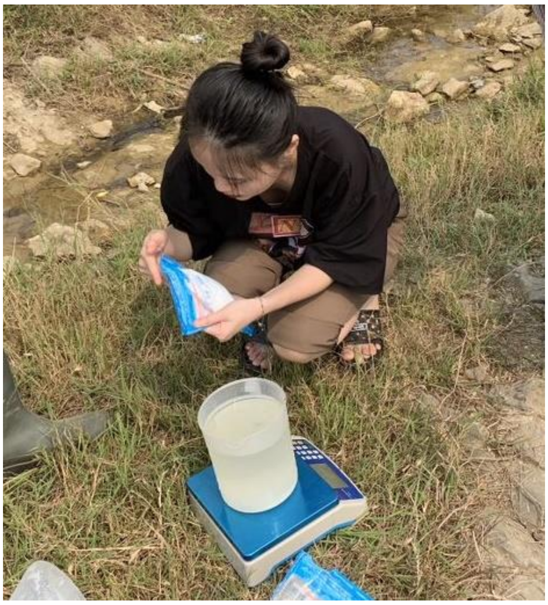

Figure 4.17: Making the desired salt solution by carefully weighing the amount of water and salt

    3.3. Fill the Mariotte bottle with this solution.

4. Getting into position
    4.1. You are going to inject the solute, while continuously measuring the EC downstream. One person will do the injection at the injection point by opening the Mariotte bottle.
    4.2. Three people will measure the EC downstream of the injection, at different distances downstream of the injection. They should all stand in the middle of the stream, as depicted in Figure 4.18. Measure the exact distance each person stands downstream of the injection.

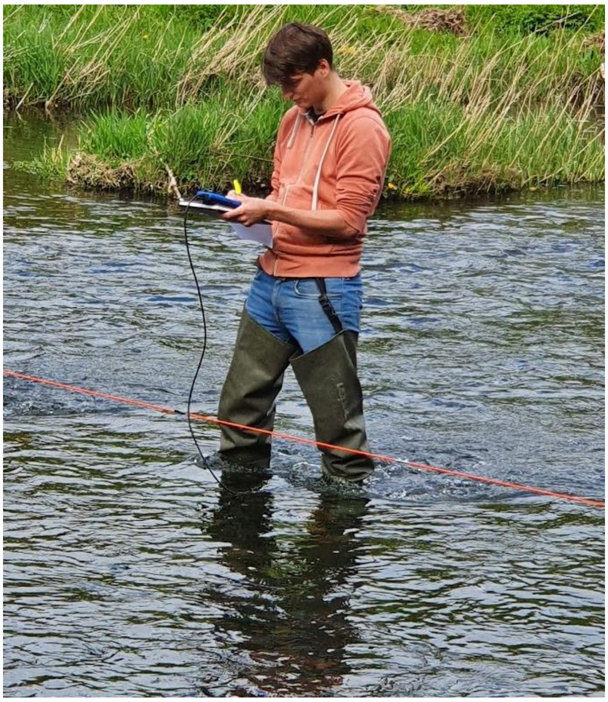

Figure 4.18: A person measuring the EC in the middle of the stream. In one hand, the observer holds the clipboard with the record sheet. Firmly attached to the clipboard is the EC meter, with the probe hanging into the water. The probe is completely submerged, but not touching the bottom of the river. In his other hand, the observer holds the pen and writes down the measured EC.

5. Performing the experiment
    - 5.1. Measure the natural EC of the stream.
    - 5.2. Open the Mariotte bottle, injecting the solute in the middle of the stream.
    - 5.3. Measure the EC. If all goes well, it will increase until it reaches a new constant level. After all the solute is injected, the EC will go down again, and you can stop measuring.
    - 5.4. Were you able to nicely measure the EC at every location? Think about the salt concentration and the distance between a measurement point and the injection point. Was the Mariotte bottle able to inject long enough to reach a new constant EC? Do not be afraid to redo an experiment. It is a process of trial and error, and you will probably have to adjust accordingly.

6. Cleaning up
    - 6.1. Rinse the Mariotte bottle and put it away. Do not rinse it while the measurement is still going on.
    - 6.2. Carefully store the EC meters. Take out the batteries and make sure the meter and the batteries are completely dry. The EC meters are not waterproof.
    - 6.3. Clean the scale; make sure it is completely dry. Put it away carefully.
    - 6.4. Make sure you have all your equipment. Leave nothing behind, take any trash with you, and dispose of it properly at home.

4.4 Data processing

It is important to process your data as soon as possible, as you will properly remember how the experiment went. If you have made any mistakes, you can retry the experiment the next day.

4.4.1 Computing discharge and dispersion coefficient with gulp injection

1. You have written down your measurements during these experiments. Carefully copy the data to a digital record sheet.
2. Use the water depth data across a cross-section to draw a cross-sectional profile. Do this for every cross-section you have measured
3. Compute the cross-sectional area for every cross-section. What is the average computed cross-sectional area?
4. Convert the measured EC of every measurement to a corresponding concentration.
5. Compute the discharge for every concentration time series. What is the average computed discharge?
6. Based on the average cross-sectional area and average computed discharge, what is the average velocity?
7. Calibrate the dispersion coefficient based on the average cross-sectional area and the average velocity.

4.4.2 Computing discharge with constant rate injection

1. You have written down your measurements during these experiments. Carefully copy the data to a digital record sheet.
2. Convert the measured EC of every measurement to a corresponding concentration.
3. Compute the discharge for every concentration time series. What is the average computed discharge?

An example of the data processing for the gulp injection can be found in a separate Excel. It is also possible to use Python code for this.

An example of the data processing for the constant rate injection is given below.

The natural EC of the stream is 190 µS/cm. The natural salt concentration of the stream is then:

$$\phi = 3 \cdot 10^{-6} \cdot \sigma^2 + 0.5309 \cdot \sigma = 3 \cdot 10^{-6} \cdot 190^2 + 0.5309 \cdot 190 \approx 100.98\, mg/l$$

The natural salt concentration of the stream is thus 100.98 mg/l. The concentration of the solute is 120 g/l. The increased constant EC downstream of the injection is 229 µS/cm. The increased constant concentration level is then:

$$\phi = 3 \cdot 10^{-6} \cdot \sigma^2 + 0.5309 \cdot \sigma = 3 \cdot 10^{-6} \cdot 229^2 + 0.5309 \cdot 229 \approx 121.73\, mg/l$$

The discharge from the Mariotte bottle is 0.01 l/s, as measured with the volumetric method. The discharge of the stream is then computed as:

$$Q = Q_{injection} \cdot \frac{\phi_{injection}}{\phi_{increased} - \phi_{natural}} = 0.01 \cdot \frac{120 \cdot 1000}{121.73 - 100.98} \approx 57.8\ l/s$$

Discharge of the river is thus 57.8 l/s.

4.5 Reflective questions

Note that some of the questions for the gulp injection and the constant rate injection are the same. However, the answers can differ depending on the method, so think about each question carefully.

4.5.1 Discharge and dispersion coefficient with gulp injection

Experiment setup

1. Do you think the location was suitable for the experiment? What could be different about the location to make it more suitable for this experiment? Explain why.

More turbulence and more lateral mixing are almost always preferred and would have made the experiment more accurate. The downstream section of the stream also is rarely perfect; it has some stagnant zones, some turns, etc. The cross-section is rarely constant but varies. The location can however still be considered quite suitable.

2. Do you think the amount of salt used was suitable? Would you use more or less salt next time? Explain why.

If the peak was too high, you cannot accurately measure it since it varies so strongly, and it would be better to use a bit less salt. If the peak was too low, a small measurement error can lead to a larger error in the computation of the discharge.

3. What do you think about the distance between measurement locations and the injection point? Would you change the measurement locations and/or the injection location next time?

The distance should be enough to not have the concentration peak too quickly. If this is the case, you cannot accurately record it, since you only measure every five seconds. Also, the peak can be high because of this, and then you cannot accurately measure it since it varies so strongly. If you are too far downstream, the experiment simply may take very long. Furthermore, the peak will be very low, and a small measurement error could lead to a larger error in the computation of the discharge.

4. You measure the EC with a frequency of five seconds. Do you think this is enough to adequately capture the peak?

If the right amount of salt and the right distance downstream is used, this is fine. A higher frequency will usually result in a more accurate computation of the discharge, but a frequency of five seconds should be enough to accurately measure the discharge. Students should understand the importance of and connection between the amount of salt used, the distance downstream, and the frequency of measurements. They are related and should be tuned to one another.

Results

5. For every measurement location and every injection, you computed the discharge. Theoretically, they should all be the same. Is this the case? If not, explain why not.

If they differ, this can be due to measurement errors, stagnant zones, or different levels of lateral mixing.

6. You also calibrated the dispersion coefficient for every measurement location. Are they the same for every location and every injection? Should they be the same for every location? Should they be the same for every injection? Explain your answer.

They are probably not the same, and they do not have to be. The longitudinal dispersion coefficient is a quantity that can vary spatially quite a lot. In the temporal time scale, they can also vary due to changing stream courses and varying discharges. Locations with a lot of turbulence, like rapids and waterfalls, will have a higher coefficient than locations with little turbulence.

7. Maybe you measured the discharge of this stream with different methods, like the constant rate injection method, velocity-area method, weir method, etc. Compare these with your measurements from the gulp injection. How do they differ? Which one do you think is most suitable for this stream?

Measuring discharge with solute is only suitable if sufficient lateral mixing occurs. It is suitable for this location, but not necessarily better than using the velocity area method. Both these methods have some criteria and are not possible for every section of this stream. Sections that are suitable for the velocity area method are not always suitable for the solute method.

A gulp injection and a constant rate injection have the same criteria for a stream and are both equally suitable. However, gulp injection is often a bit easier and a bit less sensitive to measurement errors, and thus often preferred.

Using a small V-notched weir is only possible in small streams. It is not suitable for this stream. The volumetric method is also not possible for this stream.

8. The salt concentration has a different progression depending on the location of the measurement. What causes these differences?

If there is more turbulence, due to rapids or waterfalls, the salt will have mixed more and thus be more distributed.

If the water flows rather quickly, the peak will also pass quicker.

Assumptions

9. You assumed that the natural concentration of the stream is constant during your experiment. Do you think this is correct? Why/why not?

On the timescale of the experiment, this will be correct. Over long timescales the concentration can vary, but usually only a tiny bit.

10. When you calibrate the dispersion coefficient, you assume a constant cross-section. You measured the cross-section at multiple locations. Was the assumption of constant cross-section correct? If not, how will this influence your calibration? Explain your answer.

No, the cross-section is almost certainly not constant. However, the longitudinal dispersion coefficient is not either. Since an average of the cross-sectional area is used, and this average is considered representative of the stream segment, the longitudinal dispersion coefficient will also be an average representative of the stream segment. The actual coefficient will vary locally just like the cross-section. The varying cross-section will not negatively affect the calibration, since this variance is inherent to the longitudinal dispersion coefficient.

11. You also assume a constant velocity in a cross-section. Do you think the velocity is the same everywhere in a cross-section? Where will the velocity be higher or lower compared to the average velocity of a cross-section? Explain your answer.

No, the velocity is not the same everywhere. Close to the stream banks, the velocity will likely be lower, while in the middle it will be higher than the average. Over the depth the velocity will also vary, being higher at the water surface and lower close to the stream bed.

12. Furthermore, you assume the velocity is constant in the longitudinal direction. Do you think it is constant in the longitudinal direction? Was your assumption of constant velocity, correct? If not, how will this influence the calibration?

No, since the cross-sectional area varies, the velocity will also very likely vary. Larger cross-sections will have a lower average velocity. This does not negatively affect the calibration. The velocity is not constant, but the longitudinal dispersion coefficient is not either. Since an average velocity is used, and this average is considered representative of the stream segment, the longitudinal dispersion coefficient will also be an average representative of the stream segment. The actual coefficient will vary locally just like the velocity and the cross-sectional area. The varying velocity will not negatively affect the calibration, since this variance is inherent to the longitudinal dispersion coefficient.

13. Finally, you assumed there was immediate lateral and vertical mixing. Do you think that assumption is correct? Think of the visual test with a coloring agent. How will this influence your calibration? How will this influence the computation of the discharge? Explain your answer.

No, this is not correct. As can be seen with the injection of a coloring agent, there is seldom instantaneous complete lateral mixing. Vertical mixing is usually achieved at the point of injection in the middle of the stream, but not at the sides or further downstream. The measured concentration downstream of the injection is thus often a bit higher than it would be if there was complete lateral and vertical mixing. The computed discharge is thus a bit on the low side; in reality, it will be higher. The longitudinal dispersion coefficient is also higher in reality than the one measured. There will have been more longitudinal mixing than you measure, but because of the improper lateral mixing, this is not detectable.

4.5.2 Discharge measurement with constant rate injection

Experiment setup

1. Do you think the location was suitable for the experiment? What could be different about the location to make it more suitable for this experiment? Explain why.

More turbulence and more lateral mixing are almost always preferred and would have made the experiment more accurate. The location can however still be considered suitable.

2. What do you think about the distance between measurement locations and the injection point? Would you change the measurement locations and/or the injection location next time?

The distance should not be too far. Otherwise, it will take too long to reach a new constant concentration level and the Mariotte bottle will run out of solute. However, if you are too close, there will not be enough lateral and vertical mixing. In general, with a constant rate injection, you want the measurement to be closer to the injection, compared to a gulp injection.

3. Did the Mariotte bottle have enough solution to keep the injection going for long enough to reach an increased constant EC?

Look at the data of the students. The EC should have reached an increased level and stayed more or less on this level for some time.

4. Was the concentration of the solution high enough to produce a visible increase in concentration?

Look at the data of the students. The increase should be clearly visible.

Results

5. The discharge of the Mariotte bottle is an important and influential part of computing the stream discharge. You measured the discharge of the Mariotte bottle multiple times. Was it always the same? What does that tell you about the accuracy of your discharge computations?

The discharge of the Mariotte bottle probably varied a little bit for each measurement, thus the accuracy of the discharge computations will not be very high, but still quite good if all else was done correctly.

6. For every measurement location and every injection, you computed the discharge. Theoretically they should all be the exact same. Is this the case? If not, explain why not.

If they differ, this can be due to measurement errors, stagnant zones, or different levels of lateral mixing.

7. Maybe you measured the discharge of this stream with different methods, like the gulp injection method, velocity-area method, weir method, etc. Compare these with your measurements from the gulp injection. How do they differ? Which one do you think is most suitable for this stream?

Measuring discharge with solute is only suitable if sufficient lateral mixing occurs. It is suitable for this location, but not necessarily better than using the velocity area method. Both these methods have some criteria and are not possible for every section of this stream. Sections that are suitable for the velocity area method are not always suitable for the solute method.

A gulp injection and a constant rate injection have the same criteria for a stream and are both equally suitable. However, gulp injection is often a bit easier and a bit less sensitive to measurement errors, and thus often preferred.

Using a small V-notched weir is only possible in small streams. It is not suitable for this stream. The volumetric method is also not possible for this stream.

8. The salt concentration has a different progression depending on the location of the measurement. What causes these differences?

If there is more turbulence, due to rapids or waterfalls, the salt will have mixed more and thus be more distributed.

If the water flows rather quickly, the peak will also pass quicker.

Assumptions

9. You assumed there was immediate lateral and vertical mixing. Do you think that assumption is correct? Think of the visual test with coloring agent. How will this influence your computation of the discharge? Explain your answer.

No, this is not correct. As can be seen with the injection of a coloring agent, there is seldom instantaneous complete lateral mixing. Vertical mixing is usually achieved at the point of injection in the middle of the stream, but not at the sides or further downstream. The measured concentration downstream of the injection is thus often a bit higher than it would be if there was complete lateral and vertical mixing. The computed discharge it thus a bit on the low side; in reality it will be higher.

10. You assumed that the natural concentration of the stream is constant during your experiment. Do you think this is correct? Why/why not?

On the timescale of the experiment this will be correct. Over long timescales the concentration can vary, but usually only a tiny bit.

4.6 References

Rantz, S. E. (1982). *Measurement and computation of streamflow* (Vol. 2175). US Department of the Interior, Geological Survey.

Taylor, G. I. (1954). The dispersion of matter in turbulent flow through a pipe. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 223*(1155), 446-468.

5. Seepage test

5.1 Introduction

5.1.1 Seepage

You are going to measure seepage using piezometers and a seepage meter. Seepage is the flow of water up from the ground through the surface. The catchment under investigation is particularly interesting because the streamflow almost fully originates from groundwater seepage. This upwelling groundwater originates from the Cuc Phuong National Park. In the downstream part of the catchment the stream infiltrates back into the ground through several sinkholes. Thus, if we want to understand a catchment close to or in Cuc Phuong, we have to be able to measure this seepage. Figure 5.1 shows these seepage and infiltration ponds in the catchment close to the Homestay.

Figure 5.1: Left: groundwater welling up into a seepage pond in the upstream part of the catchment. Right: sinkhole in the downstream part of the catchment, where water infiltrates into the ground.

5.1.2 Learning goals

In this experiment, you learn how to measure seepage and infiltration. These are important aspects that are part of many hydrological systems. You will also learn how to use a piezometer and a seepage meter. You will learn how to read the landscape and identify locations where seepage or infiltration occurs.

5.2 Theory

Seepage can occur under specific topographic conditions. At the edge of mountainous areas, as the slope decreases, the groundwater table will get closer to the surface. If the slope abruptly changes to a flat surface, groundwater will sometimes flow upwards out of the surface. At these locations with upwelling groundwater, surface waterbodies will sometimes have formed. See Figure 5.2 for an illustration of this phenomenon.

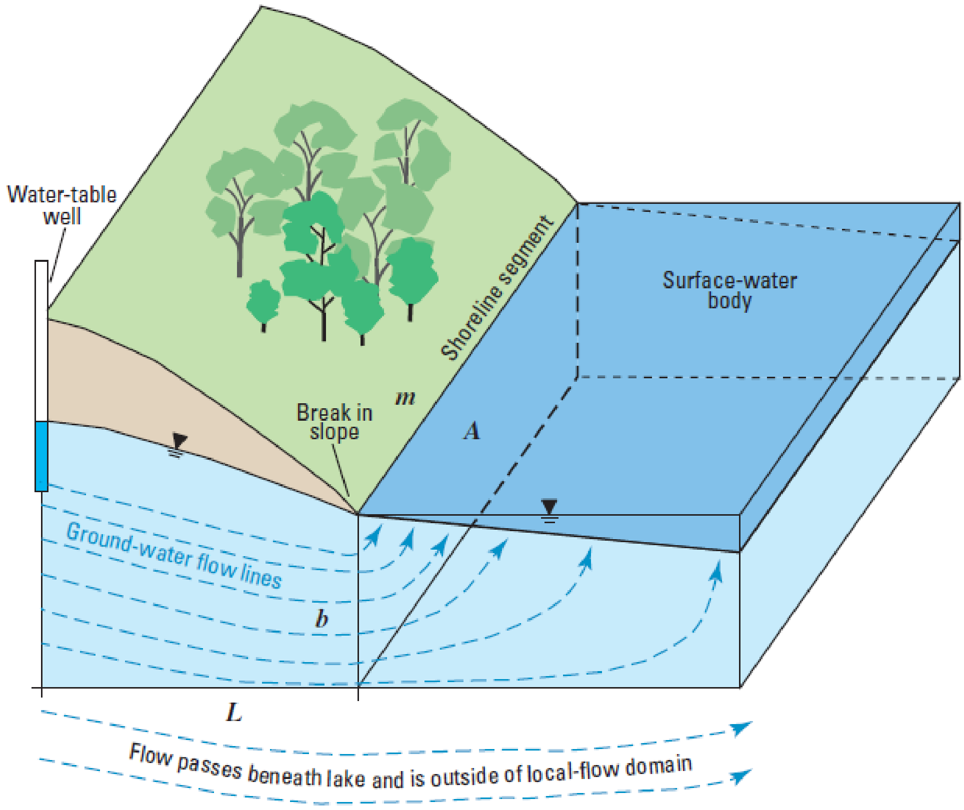

Figure 5.2: Illustration of groundwater entering a surface-water body (Rosenberry, LaBaugh & Hunt, 2008)

5.2.1 Piezometer and seepage/infiltration

Due to pressure differences between the groundwater and the water inside the stream, seepage or infiltration occurs. To determine which of the two processes takes place, a piezometer can be used. This is a pointy metal tube with some holes at the lower side. The piezometer is installed in the riverbed until a depth has been reached at which all holes will be below the stream bed. This way, groundwater can flow into the tube via the holes or the other way around. At the start of the experiment, the water level in the piezometer is equal to the water level in the stream. After some time, the water level in the tube can show the process that is taking place at that location. In the case of seepage, the water level in the piezometer will be higher than the water level in the stream, as shown in Figure 5.3. If the water level in the piezometer is lower than the surrounding water level, infiltration occurs.

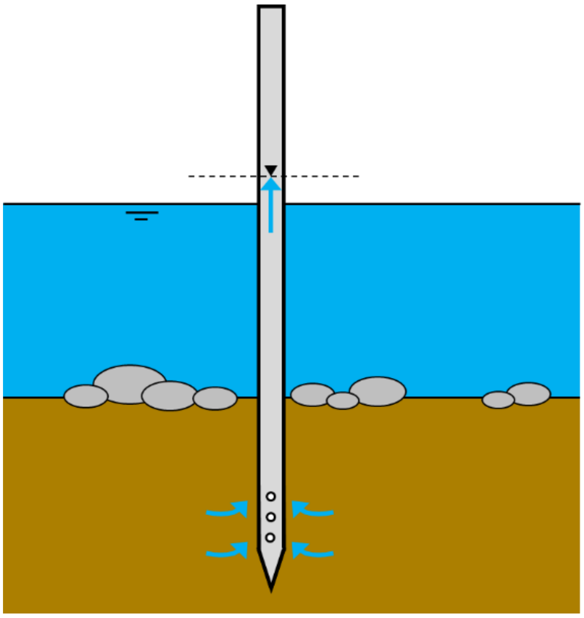

Figure 5.3: Measuring seepage using a piezometer

5.2.2 Seepage meter

If it has been determined with the piezometer that seepage or infiltration occurs, the seepage (or infiltration) rate could be measured, but this requires a different kind of device. The so-called seepage meter is a relatively simple device that enables direct measurements of flow between surface water bodies and groundwater. It was first introduced by Lee (1977) and since then several modifications have been developed. However, even the simplest form of the seepage meter can give a reliable estimate of the seepage rate. Figure 5.4 shows an illustration of the device. The seepage meter consists of a cylinder that is installed into the bottom sediments of the water body.

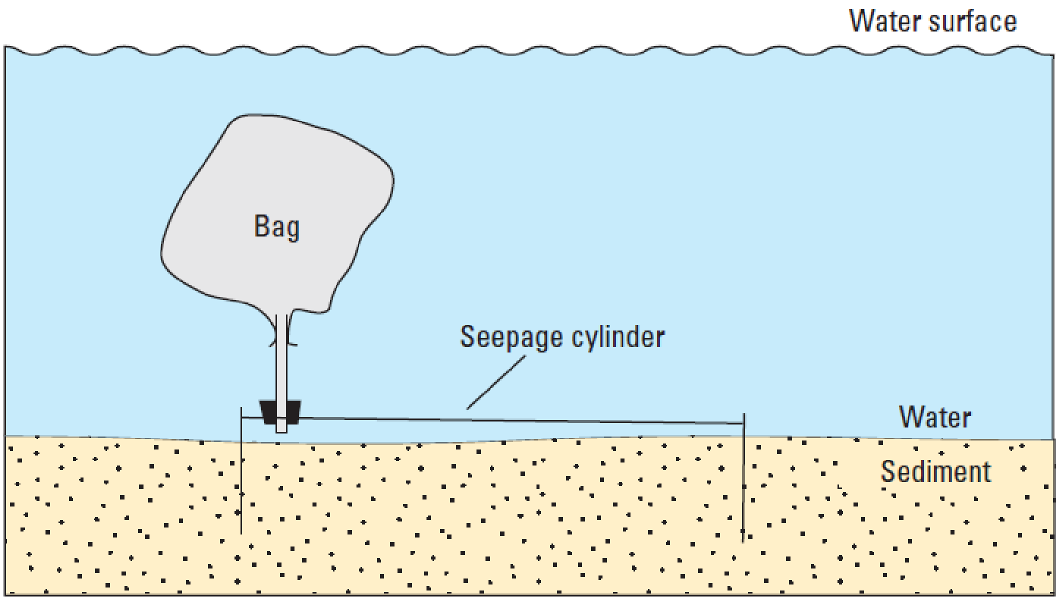

Figure 5.4: Illustration of the seepage meter set-up (Rosenberry, LaBaugh & Hunt, 2008)

The lost or gained volume inside the bag after a certain period is used to calculate the seepage rate, according to equation 5.1. If the seepage rate is negative, it is not seepage but infiltration.

$$q = \frac{\Delta V}{t \cdot A} \tag{5.1}$$

where:

q	seepage (or infiltration if <0)
ΔV	change in volume in the bag
t	duration of the measurement
A	area of the cylinder

5.3 Experiment

5.3.1 Detecting seepage/infiltration with a piezometer

Table 5.1 shows the equipment and materials needed to perform the seepage test with a piezometer. A record sheet for this experiment can be found in Appendix E: Record sheets.

Table 5.1: The equipment and materials needed for a seepage test with a piezometer

Equipment/material	Quantity	Purpose
Piezometer	1	Measuring water pressure underneath the riverbed
Steel hammer	1	To assist in installing the piezometer
Piece of wood	1	
Acoustic water level meter	1	To measure the water level inside the piezometer

The two piezometers available can also be seen in Figure 5.5.

Figure 5.5: The piezometers available at HUNRE.

First read through all the steps before doing anything.

1. Find a suitable location. For this, you need to guess if the surface water has interactions with the groundwater.
    - To assess seepage (inflow from groundwater) you could look for a pond that does not receive any water from streams. These ponds will most likely be found at the edge of hills in the more elevated parts of a given catchment.
    - To assess infiltration (disappearing of surface water) you need to follow the stream and look for points where streamflow suddenly comes to a halt. A potential location could be one of the sinkholes in the downstream part of the catchment.
2. Hammer the piezometer into the bed until all holes are far enough below the bed, as shown in Figure 5.6. The piezometer can only be hammered into a fine sediment layer. When encountering a rocky layer, stop the hammering and try to find another location.

Figure 5.6: Hammering the piezometer into the riverbed

2. Fill the tube with water until the same water level is reached as in the pond. Use an acoustic water level meter to make sure the water level inside the piezometer is equal to the level of the surface water, as shown in Figure 5.7

Figure 5.7: Measuring the water level inside the piezometer

3. Check the water level in the piezometer again after several hours. If it has changed, ask yourself if seepage or infiltration has occurred.
4. During installation soil can enter the tube through the holes. Therefore, after using the portable piezometer it should be cleaned. Clean the piezometer by filling the tube with water under sufficient pressure. Figure 5.8 shows an example.

Figure 5.8: Cleaning the portable piezometer using water pressure

5.3.2 Measuring seepage/infiltration with a seepage meter

In the case that seepage has been measured using the piezometer, the seepage meter could be installed to measure the flow between groundwater and surface water. Table 5.2 shows the equipment and materials needed.

Table 5.2: The equipment and materials needed for a seepage test using a seepage meter.

Equipment/material	Quantity	Purpose
Seepage meter	1	isolates the sediment bed from the water body
Infuse bag	1	expand or shrink depending on seepage or infiltration in the bucket
Latex tube	1	connecting the bucket and the bag.
Measuring cup	1	measuring the volume of water inside the bag.
Bathing suit	1	
Slippers/boots	1 pair	

The goal of the seepage test with a seepage meter is to quantify the incoming or outgoing flow from surface water to groundwater. Using the dimensions of the metal bucket of the seepage meter the total area of the surface where seepage comes through can be calculated. By filling the bag only partially before installing the meter, the net upward flow or downward flow can be calculated by measuring the change in water volume inside the bag. For an accurate estimation of seepage, multiple tests need to be performed. By using only one seepage meter you assume that the rate of seepage is uniformly distributed inside the water body. In reality, the seepage rate will differ because of the heterogeneity of the soil.

First read through all the steps before doing anything.

1. After you have found a suitable pond, you need to first investigate the bottom of the surface water body. On the exact location of the seepage meter the bottom should be flat and the sediment not too rocky. If the bucket is placed in an uneven bottom, there will be open connections between the bucket and the surface water, as shown in Figure 5.9.

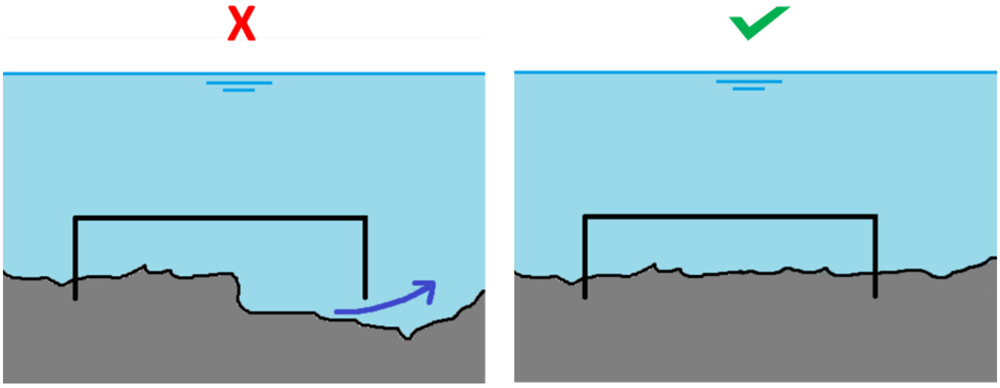

Figure 5.9: A suitable bottom should be even.

2. The bucket should be firmly pressed into the soil. This can be done by rotating the bucket carefully, as depicted in Figure 5.10. When the bottom is made out of sand or gravel it might be necessary to also stand on top of the bucket to press the bucket into the ground.

Figure 5.10: Installing the seepage meter into the bottom of the pond.

3. Fill the infusion bag for approximately 50% with water, as shown in Figure 5.11. Write down the exact amount of water in the bag before connecting it to the bucket. Make sure that there is not too much air in the bag by pressing it out.

Figure 5.11: The bag is filled for 50%.

4. Connect the infusion bag to a tube as shown in Figure 5.12.

Figure 5.12: The infusion bag connected to the tube.

5. Connect the bag to the bucket using the hose as shown in Figure 5.13. While connecting make sure that the hose is connected firmly to the bucket. The bag should remain completely underwater.

Figure 5.13: The bag is connected to the bucket through the hose. The bag is completely underwater.

6. Note the time at which the bag is connected to the bucket. The experiment preferably takes about 1 day.
7. After 1 day the seepage bag can be extracted again from the bucket. Check and note the amount of water stored inside the bag. If the amount of water cannot be read accurately from the bag, you should pour the contents of the bag inside a measuring cup.
8. Now retrieve the bucket. While extracting the bucket it should be checked that the bucket is still firmly pressed in the soil. You should apply noticeable force during pulling out. If this is not the case, the bucket was probably not installed properly.

To get more reliable estimates, the seepage test can be performed on several locations within the water body. Alternatively, two buckets can be installed and connected to one bag to estimate the total seepage rate inside the pond. See Figure 5.14 for such a setup.

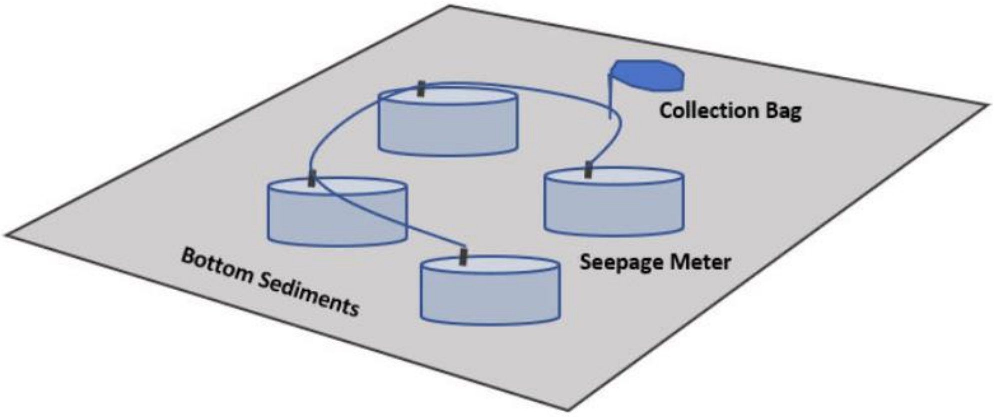

Figure 5.14: Linked seepage meters with seepage collection directed to a single bag (Rosenberry, LaBaugh, & Hunt, 2008)

5.4 Data processing

1. Compute the change in volume of the water in the bag
2. Compute the area of the cylinder.
3. Using the area, the change in volume, and the total duration of the experiment, compute the seepage (or infiltration) rate.

An example is given below. An example can also be found in a separate Excel.

The starting volume inside the bag is 500 ml. After one day the total volume inside the bag has increased to 700 ml. The change in the volume of the water in the bag is thus $\triangle V = 0.2$ l. The volume has increased ($\triangle V>0$), thus seepage is occurring. The diameter of the bucket is 0.4 m, so the area is $0.25 \cdot \pi \cdot 0.4^2 = 0.126$ m². The seepage rate is then

$$q = \frac{0{,}0002\ \mathrm{m}^3}{1\ \mathrm{day} * 0{,}126\ \mathrm{m}^2} = 0{,}00159\ \mathrm{m/day} = 1{,}6\ \mathrm{mm/day}$$

Thus 1.6 mm/day is seeping up through the ground into the pond.

5.5 Reflective questions

1. For each measurement location: Do you measure seepage or infiltration? Can you explain these results?

If the piezometer showed an increase in water level, seepage occurs. If the piezometer showed a decrease, infiltration occurs. They should be explained based on the geography of the location.

2. Why should the bag be underwater?

The collection bag must be submerged to maintain the same hydraulic head in the seepage meter and surrounding surface water.

3. The volume of the bag may stay the same, despite clear indications that seepage is occurring in a location. What could be the cause of this?

Improper installation.

5.6 References

Lee, D. R. (1977). A device for measuring seepage flux in lakes and estuaries 1. *Limnology and Oceanography*, 22(1), 140-147.

Rosenberry, D. O. (2005). Integrating seepage heterogeneity with the use of ganged seepage meters. *Limnology and Oceanography*: Methods, 3(2), 131-142.

Rosenberry, D. O., LaBaugh, J. W., & Hunt, R. J. (2008). Use of monitoring wells, portable piezometers, and seepage meters to quantify flow between surface water and ground water. *Field techniques for estimating water fluxes between surface water and ground water*, 4, 39-70.

6. Water quality

6.1 Introduction

6.1.1 Water quality

Water quality describes the condition of the water usually with respect to its suitability for a particular purpose such as drinking, swimming, or irrigation. The quality of water is expressed in different parameters that cover *physical, chemical,* and *biological characteristics*. A wide variety of parameters can be measured using a large variety of measurement techniques. Depending on the purpose of the water and the source of the water, you determine which parameters to use. Parameters that are frequently monitored for water quality include temperature, dissolved oxygen, pH, electrical conductivity, and turbidity.

6.1.2 Learning goals

By doing the experiments presented in this manual you will learn how to determine some important water quality parameters in the field. Experiments will be carried out on different water sources which will allow you to compare the different results. Explaining the differences will give you a better understanding of the relation between water quality and its influencing factors such as geology, land use, and pollution.

The experiments are carried out using several handheld meters with probes (dissolved oxygen, pH, electrical conductivity, turbidity) and some test strips which can all be brought into the field.

6.2 Theory

Water quality parameters can be divided into three categories.

6.2.1 Physical

Physical parameters are observable properties of a material or substance. In water quality, physical parameters include color, taste, odor, temperature, turbidity, dissolved solids, and electrical conductivity. The following tools for measuring physical parameters will be present on the field trip:

- The *electrical conductivity probe/meter* (EC meter) measures how well a solution conducts electricity. When the probe is inserted into the solution, electrical current flows between the two electrons inside the probe, set apart at a specific distance. The ion concentration of the substance determines if the conductivity is high or low. The higher the ion concentration, the higher the conductance will be as the ions are capable of passing on the current. A lower ion concentration will result in a lower conductance. Distilled water (barely any ions) has a conductivity of 0.05 µS/cm. Sea water (a lot of ions due to salt) has a conductivity of 55000 µS/cm. Figure 6.1 shows an EC meter and a multimeter.

Figure 6.1: Left: the EC meter. Right: the multimeter with DO probe (HACH, 2023). If a different probe is used, the multimeter can also measure EC.

- The *turbidity meter* and *transparency tube* can both be used to determine turbidity**.** Turbidity refers to how cloudy water is. The turbidity meter measures *the ability that light has to pass through water*. The Secchi tube uses the same principle but is carried out manually. Figure 6.2 shows both.

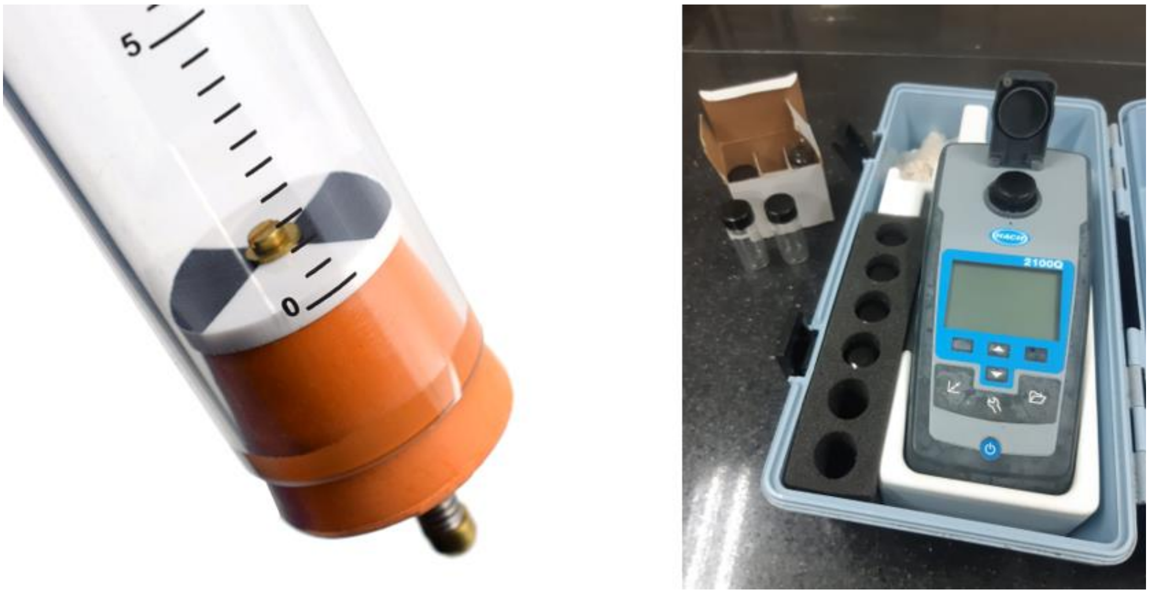

Figure 6.2: Left: Bottom of the transparency tube (hBARSCI, 2023). Right: the turbidity meter.

6.2.2 Chemical

In contrast to the physical parameters, a chemical parameter cannot be determined just by viewing or touching the substance. It can only be measured when the chemical identity of the substance is changed. Examples of chemical parameters include dissolved oxygen, pH, alkalinity, chlorine, hardness, chemical oxygen demand (COD), biological oxygen demand

(BOD), and all nutrients and trace metals that can dissolve in water. The following tools for measuring physical parameters will be present on the field trip:

- *Dissolved oxygen probe/meter* (DO-probes) work by measuring the amount of oxygen that diffuses across a permeable (or semi-permeable) membrane into a probe (sensor). Once oxygen is inside the sensor, a chemical reduction reaction occurs, producing an electrical signal. This signal is read by the DO probe and is displayed on a meter. Eutrophic conditions (an excess of nutrients in the water) often cause low concentrations of dissolved oxygen as bacteria use the oxygen to decompose the nutrients. An oxygen-deficient situation can occur in which many organisms cannot survive as displayed in Figure 6.3.

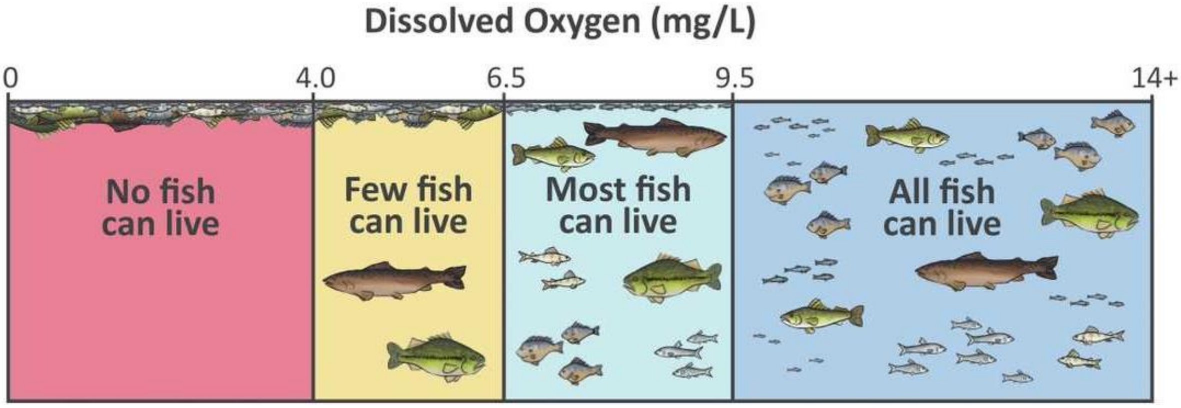

Figure 6.3: The influence of the DO concentration on fish populations (DataStream Initiative. 2021).

- The *pH probe/meter*, seen in Figure 6.4, works by measuring the electrical potential (voltage) produced by the solution being tested, using the potential difference to determine the pH. An acidic solution has more positively charged hydrogen ions than an alkaline solution, therefore, the solution has a greater electrical potential to produce an electrical current.
- The *test strips,* as shown in Figure 6.4, can be used to measure the chemical parameters of the water such as the concentration of nitrate, phosphate, and ammonia. The test strips contain a chemical coating. When inserted into the water a chemical reaction occurs between certain chemicals in the water and the chemical coating. As a result, the color of the test strips changes, and one can deduce the concentration of a specific chemical. It is important to note that test strips are one-time-use only and they cost about 40000 VND per piece. It is thus important to use them selectively.

Figure 6.4: Left: the pH meter. Right: the test strips

6.2.3 Biological

Biological water quality parameters of concern are bacteria, viruses, and algae in the water. These are important parameters to determine the suitability of the water for swimming or drinking.

Macroinvertebrate biomonitoring

Biological monitoring or biomonitoring is the study of organisms and their responses. It can be used to determine environmental conditions. Common biological organisms to use for biomonitoring are fish, algae, or macroinvertebrates. In the context of the fieldwork, we focus on the biomonitoring of macroinvertebrates.

Macroinvertebrates are organisms that are large (macro) enough to be seen with the naked eye and lack a backbone (invertebrate). They inhibit all types of running waters, from fast-flowing streams to slow-moving muddy rivers. Examples of aquatic macroinvertebrates include insects in their larval or nymph forms, crayfish, clams, snails, and worms.

The basic principle behind the study of macroinvertebrates is that some are more sensitive to pollution than others. Therefore, if a stream is inhabited by organisms that can tolerate pollution, while the more pollution-sensitive organisms are missing, a pollution problem is likely. Note that by biomonitoring you do not directly measure a water quality parameter at a certain moment. Instead, you get an idea of the general “health” of the water over a longer time.

Aquatic macroinvertebrates are good indicators of stream quality because:

- They are affected by the physical, chemical, and biological conditions of the stream.
- They cannot escape the pollution and show the effects of short- and long-term pollution events.

- They may show the impacts from habitat loss not detected by traditional water quality assessments.
- They are a critical part of the stream's food chain.
- Some are very intolerant of pollution.
- They are relatively easy to sample and identify.

Parameters out of the scope of this fieldwork
The measurements that you will carry out in the field do not give a complete picture of the quality of the water. Important parameters that are not measured are:

- Major ions. Consisting of:
    - Major cations: calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K)
    - Major anions: bicarbonate (HCO_3), chloride (Cl), and sulfate (SO_4).
- Pollutants. Consisting of:
    - Trace metals (toxic in high doses) such as chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), magnesium (Mg), Selenium (Se), and Zinc (Zn).
    - Heavy metals (toxic in low doses) such as mercury (Hg), cadmium (Cd), arsenic (As), chromium (Cr), thallium (Tl), and lead (Pb)
    - Pesticides

To analyze these parameters a sample will have to be collected in the field and transported to a laboratory with advanced instruments. Section 6.3.9 contains instructions on how to collect, preserve and transport a sample.

Water quality standards
The Vietnamese Ministry of Natural Resources and Environment has published a report that contains the National technical regulation on Surface water quality (Ministry of Science and Technology, 2023). This report contains two tables with water quality parameter standards that can be used to determine the suitable categorization of water.

One table contains the limit values of some water quality parameters that are potentially dangerous to human health. Water that is directly used by humans (without treatment) for different purposes is not allowed to exceed these limit values to protect human health. Table 6.1 contains the water quality parameters from this list that students can measure in the field with the instruments that are present. The complete list of standards can be found in Appendix D: Water quality standards.

Table 6.1: Maximum limit of values of parameters affecting human health (Ministry of Science and Technology, 2023).

Parameter	Unit	Value limit
Ammonium (NH_4-N)	mg/l	0.3
Nitrite (NO_2-N)	mg/l	0.05
Iron (Ferrum) (Fe)	mg/l	0.5

The National technical regulation on Surface water quality also contains a table with limit values for aquatic habitat protection in rivers, streams, canals, and ditches. Based on the values for some water quality parameters the water is categorized into four classes that signify the ecological condition of the water. Table 6.2 contains the limit values per category for the parameters that the students can measure in the field. The complete list of standards can be found in Appendix D: Water quality standards.

Table 6.2: Limit values of parameters in surface water for classification of water quality in rivers, streams, canals, and ditches (Ministry of Science and Technology, 2023) Note that the limit values for PO_4^3—P and NO_3-N are taken from old water quality standards QCVN 08-MT:2015/BTNMT (Vietnamese Ministry of Natural Resource and Environment, 2015) as the new standards contain standards for total phosphate and total nitrate (instead of PO_4^3—P and NO_3-N) which the students are not able to measure with current instruments. In this case. use of the old standards is allowed as stated in the notice (13/03/23) from the Ministry of Natural Resources and Environment (Ministry of Natural Resources and Environment, 2023).

Parameter				**Water quality classification level**
pH	**DO (mg/l)**	**Phosphate (PO_4^{3-}-P) (mg/l)**	**Nitrate (NO3-N) (mg/l)**	
6.5 – 8.5	≥ 6.0	≤ 0.1	≤ 2	A
6.0 – 8.5	≥ 5.0	≤ 0.2	≤ 5	B
6.0 – 8.5	≥ 4.0	≤ 0.3	≤ 10	C
< 6.0 or > 8.5	≥ 2.0	> 0.3	> 10	D

The classification of the water quality can be interpreted as described in Table 6.3. The class is determined by the worst scoring parameter.

Table 6.3: Each water class with its corresponding use (Ministry of Science and Technology, 2023).

Class	Possible water usage based on class
A	Good water quality. Ecosystems in aquatic environments with high dissolved oxygen (DO) content. Water can be used for domestic water supply, swimming, or water play after appropriate treatment.
B	Average water quality. The aquatic ecosystem consumes a lot of dissolved oxygen due to a large amount of pollutants. Water can be used for industrial and agricultural purposes after applying appropriate treatment measures.
C	Bad water quality. Ecosystems in water have a sharp decrease in dissolved oxygen due to the presence of a large amount of pollutants. Water does not cause unpleasant odors and can be used for industrial purposes after applying appropriate treatment measures.
D	The water is of very poor quality, which can greatly affect fish and other organisms living in the aquatic environment due to its low dissolved oxygen concentration and high pollutant concentration. The water can be used for navigation purposes and other purposes with low-quality water requirements.

6.3 Experiments

The equipment and materials needed to perform the water quality tests by one group of students can be seen in Table 6.4. A record sheet for this experiment can be found in Appendix E: Record sheets.

Table 6.4: The equipment and materials needed to perform the water quality measurements by one group.

Equipment/material	Quantity	Purpose	Price per measurement
Multimeters	1	Measuring EC, DO, and pH using probes	-
DO probe	1	Measuring EC	-
EC probe	1	Measuring DO	-
pH probe	1	Measuring pH	-
Turbidity meter	1	Measuring turbidity	-
Transparency tube	1	Measuring turbidity	-
Nitrate test strips	3	Measuring nitrate/nitrogen concentration	40.000 VND per strip
Phosphate test strips	3	Measuring phosphate concentration	40.000 VND per strip
Ammonium test strips	3	Measuring ammonium concentrations	40.000 VND per strip
Pen and record sheet	1	For writing down the results	-
GPS tracker (optional)	1	To determine coordinates. Phone also fine	-
Water sample vials (optional)	1	For bringing samples to the lab	-
Cooler (optional)	1	For preserving the samples	-

You will go out into the field and measure the quality of the water in the catchment as it moves from the spring to the sinkhole. The catchment in which you will do your measurements is susceptible to eutrophication. This means that there are too many nutrients in the water leading to harmful algal blooms, dead zones, and fish kills. These nutrients end up in the water when untreated wastewater, fertilizer, or animal feces enter the stream. Your goal will be to analyze whether eutrophication is a problem in the catchment.

First read through all the steps before doing anything.

6.3.1 Preparing the measurement campaign

1. Why do you go into the field? Determine the research question you want to answer.
2. Determine the parameters that you want to measure when you go into the field.
3. Make sure you get an insight into the catchment. Study the map. What are interesting locations to do your measurements?
4. Prepare the equipment that you will need. Make sure that all instruments are properly calibrated in line with the instructions in the related manuals.

6.3.2 Measuring EC

1. Insert the probe into the water.
2. Wait till the number on the screen has stabilized.
3. Note down the result on the record sheet. Make sure to note the measurement location (coordinates) using the GPS tracker or your phone.

6.3.3 Measuring turbidity with a turbidity meter

1. Collect the water in the compatible vial.
2. Make sure the outside of the vial is dry, clean, and free of stains.
3. Insert the vial into the turbidity meter.
4. Close the lid and press read.
5. Note down the resulting value on the record sheet. Make sure to also note the sample location coordinates.

6.3.4 Measuring turbidity with transparency tube

1. Collect the sample in a beaker. Make sure the sample is representative of the water of interest. Do not disturb the sediments as this will make the water more turbid.
2. Carefully stir or swish the water in the beaker or bottle until it is homogeneous, taking care not to produce air bubbles (these will scatter light and affect the measurement).
3. Take the readings in open but shaded conditions. Avoid direct sunlight by turning your back to the sun.
4. Pour the water in the beaker slowly into the tube while looking down into the tube. Measure the depth of the water column in the tube when the black and white disk

(Secchi disk) at the bottom just disappears. First, only use the bottom tube (the tube with the Secchi disk). If you can still see the Secchi disk when this tube is full, add the other tube as in Figure 6.5, and continue pouring until the just disappears.

Figure 6.5: Left: using the bottom section of the transparency tube. Middle: using the bottom and top sections. Right: Secchi tube visible through the water

5. Observe the height of the water in the tube using the measuring tape on the tube.
6. Use Table 6.5 to convert to the NTU unit and note the value down on the record sheet.

Table 6.5: Converting the height measured with a Secchi tube to an NTU unit (Fetter & Koch, 2022).

cm	NTU	cm	NTU	cm	NTU
<6.4	>240	21.7 to 24.1	35	44.6 to 47.0	13
6.4 to 7.0	240	24.2 to 26.7	30	47.1 to 49.5	12
7.1 to 8.2	185	28.8 to 29.2	27	49.6 to 52.1	11
8.3 to 9.5	150	29.3 to 31.8	24	52.2 to 54.6	10
9.6 to 10.8	120	31.9 to 34.3	21	54.7 to 57	9
10.9 to 12.0	100	34.4 to 36.8	19	57 to 60	8
12.1 to 14.0	90	36.9 to 39.4	17	60 to 70	7
14.1 to 16.5	65	39.5 to 41.9	15	70 to 85	6
16.6 to 21.6	40	42.0 to 44.5	14	>85	<5

6.3.5 Measuring DO

1. Insert the probe into the water. Make sure to get rid of the air on the probe.
2. Gently stir the probe in the water.
3. Wait till the number on the screen has stabilized.
4. Note down the result on the record sheet. Make sure to note the measurement location (coordinates) using the GPS tracker or your phone.

6.3.6 Measuring pH

1. Insert the probe into the water.
2. Wait till the number on the screen has stabilized. This can take a while.
3. Note down the number on the record sheet. Make sure to note the measurement location (coordinates) using the GPS tracker or your phone.

6.3.7 Test strips

1. Collect a sample of water or apply the test strips directly to the water body.
2. Carefully follow the instructions on the jar, as seen in Figure 6.6.
3. Note down the number and the unit on the record sheet. Make sure to note the measurement location (coordinates) using the GPS tracker or your phone.

Figure 6.6: Using a test strip.

6.3.8 Macroinvertebrate biomonitoring

1. At a measuring location, turn around some rocks and look carefully at their backside.
2. Do you see any organisms? If yes, try to identify them with the help of the search card in Appendix C: Macroinvertebrate biomonitoring.
3. Use the instructions from the guide in Appendix C: Macroinvertebrate biomonitoring. Calculate the total score of the river. What is the ecological category (condition) of the stream? Write it down on the record sheet.

6.3.9 Collecting and preserving a water sample

1. Pick a sampling location. Make sure that the water you sample is representative of the water that you are interested in. In the case of a stream, flowing water in the middle of the stream is more representative than stagnant water on the sides (Vietnam Standard and Quality Institute, 2018).
2. Rinse the sampling container with the water of interest by collecting some water and shaking it for a few seconds. Also, make sure to rinse the lid. Throw away the water just downstream of your sampling location such that the rinse does not contaminate the water where the sample is to be taken.
3. Submerge the container. The opening of the container should face upstream. While submerged and full of water put on the lid. Prevent solid matter like leaves, algae, bottom sludge, or organic matter from entering the sampling container. Also, try to collect as little air as possible in the container.
4. Label the sample. Write the location, date, time, and the name of the person who took the sample on the sampling container (Vietnam Standard and Quality Institute, 2016).
5. Store the collected sample in a cooler with a temperature of 5 °C ± 3 °C. After collection water samples should be analyzed within 48 hours for chemical analysis and 24 hours for microbiological analysis (Hoang et al., 2023)

6.4 Data processing

1. Make a map of the catchment you inspected. Clearly mark all the different sampling locations on this map. Include a scale and a North arrow.
2. Visually present the found data using tables, graphs, or box plots. Make sure that the relation between the different sampling locations is clear.

An example of the data processing can be found in a separate Excel.

6.5 Reflective questions

1. Can you identify a pattern in the water quality as you plot the results from upstream to downstream? Which parameters show a pattern? Can you explain this pattern?

Some parameters may show a pattern. Surrounding land use, the geography, or spills into the stream at certain locations could all be causes for changes in a parameter.

2. What other relationships between measuring locations (e.g., spring water, stagnant water, flowing water, sinkhole water) and water quality parameters can you identify? Can you explain these relationships?

In general, the further downstream the more polluted the water will be. Water that is stagnant will in general also be more polluted than water that is flowing.

3. For turbidity two measurement techniques were used. How do the results compare? Can you explain any discrepancies?

In general, the measurement using a Secchi tube will be much less accurate. If the measurement with the Secchi tube was performed correctly, it could be more or less in the same order of magnitude as the measurement with the turbidity meter. Discrepancies could be due to incorrect measuring with the turbidity meter due to the vial not being dry, clean, or free of stains. It could also be that the Secchi tube was not used correctly, due to sediments being stirred up when filling the tube, air bubbles getting into the tube, or the influence of sunlight.

4. How does the quality of the water in the catchment compare to the water quality standards for surface water?

Students should compare the water quality they measured with the water quality standard given in Appendix E: Record sheets. The class to which the water body belongs depends on the worst scoring parameter.

5. Do the results from the macroinvertebrate biomonitoring agree with the results from the other parameters (DO, nitrate, nitrite, phosphate, ammonia)? If not, why not?

Could be. If they disagree, the results from the macroinvertebrate biomonitoring are likely worse than the results from the other parameters, due to some unmeasured parameter being very bad. Students should note that not every water quality parameter is being measured, but that those could of course still influence the macroinvertebrate.

6.6 References

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7. Pumping test

7.1 Introduction

7.1.1 Hydraulic conductivity

You are going to perform a pumping test. The main goal of a pumping test is to determine the characteristics of an aquifer. One of the hydrogeological parameters of an aquifer is the transmissivity. The transmissivity of an aquifer is the product of the hydraulic conductivity and the aquifer thickness. The hydraulic conductivity k is an important parameter for groundwater models because it determines the flow velocity of the groundwater. Some indicative values for hydraulic conductivity are given in Table 7.1.

Table 7.1: Soil types and their corresponding mean grain size. Indicative values for hydraulic conductivity are also given. Not that sandy clay and loam are mixtures, thus they do not have a mean grain size.

Soil type	Mean grain size	k [m/day]
Gravel	> 2 mm	> 200
Coarse sand with fine gravel	1,0 – 2 mm	50 – 200
Coarse sand	0,2 – 1,0 mm	10 – 100
Fine sand	63 μm – 0,2 mm	1 – 10
Loam		0,01 – 1
Very fine sand	0,09 – 0,12 mm	0,001 – 1
Sandy clay		0,00001 – 0,005
Clay	< 2 μm	< 0,00001

7.1.2 Learning goals

You are going to learn how to perform a pumping test. You will also learn how to process the data from a pumping test to understand the characteristics of an aquifer. For this, you will also learn the underlying theory covering the basic aspects of an aquifer.

You will learn how to operate a pump and take measurements in a well. You will also learn how to use a flow meter.

7.2 Theory

7.2.1 Aquifers

An aquifer is a layer in the ground in which water is able to flow. In contrast, an aquitard is a layer in which water will flow very slowly; it has low permeability. Sometimes the flow in an aquitard is so slow that we consider them impermeable. We then also assume no flow in the aquitard.

There are multiple kinds of aquifers:

- *A confined aquifer* is bounded above and below by an aquiclude. The water pressure is usually higher than that of the atmosphere. If the water in a well stands above the ground surface, it is called a free-following or artesian well.
- *An unconfined aquifer or a water table aquifer* is bounded below by an aquiclude but is not restricted by any confining layer above it
- *A leaky aquifer or semi-confined aquifer* is an aquifer whose upper and lower boundaries are aquitards, or one boundary is an aquitard and the other is an aquiclude. Water is free to move either upward or downward

These different kinds of aquifers can also be seen in Figure 7.1.

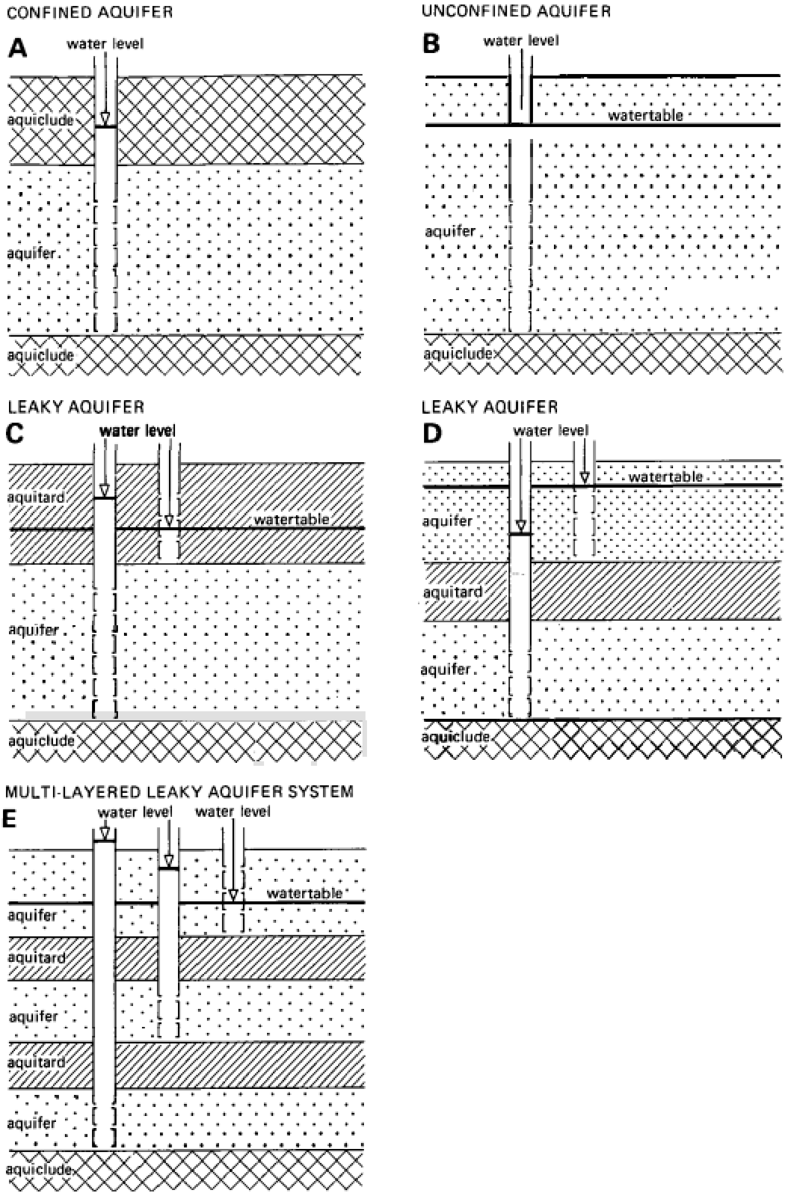


Figure 7.1: Different types of aquifers. A) Confined aquifer. B) Unconfined aquifer. C & D) Leaky aquifers. E) Multi-layered leaky aquifer (Kruseman & de Ridder, 1970)

7.2.2 Partially and fully penetrating wells

If we want to extract water from an aquifer, we install a pumping well in the aquifer. A distinction can be made between a partial penetration well and a full penetration well (see Figure 7.2). The latter occurs when the well penetrates the entire thickness of the aquifer.

The main difference between a full penetration well and a partial penetration well is that during extraction the flowlines near a fully penetrating well are straight, while in the partially penetrating well the flowlines are curved, as shown in Figure 7.2.

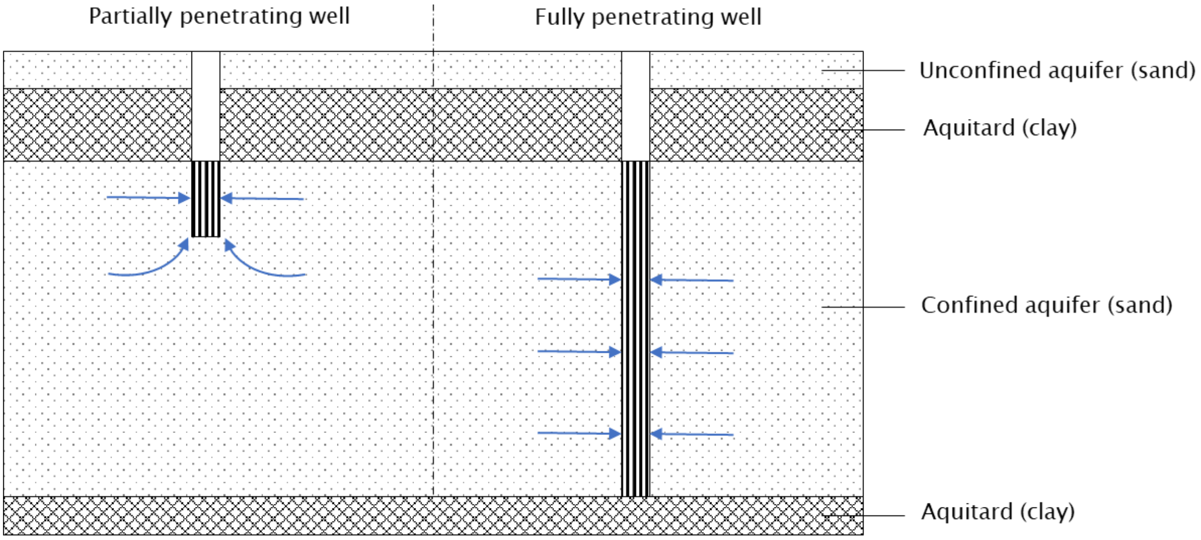


Figure 7.2: Two types of wells. a) Partial penetration well, and b) Full penetration well.

7.2.3 Pumping test

We can use a pumping well to study the characteristics of an aquifer. During a pumping test, water is extracted from a pumping well at a constant rate. This will cause the piezometric head inside the aquifer to lower. The further away from the pumping well, the smaller the drop in groundwater level. When the aquifer reaches a steady state, the piezometric head will not change anymore.

To perform a pumping test, there should be at least one, but preferably two observation wells close to the pumping well. By comparing the change in piezometric level between the pumping well and the observation well the hydraulic properties of the aquifer can be derived. At the HUNRE campus site, there is one observation well available.

Due to friction between the pumping well and the surrounding soil, there is some head loss. Because of this, the water level inside the well casing drops lower than outside. For this reason, you ideally want to perform the test using at least two observation wells, as shown in Figure 7.3. For the purpose of this manual, the head loss inside the pumping well will be neglected and a single observation well is sufficient.

Moreover, some assumptions for the pumping test should be taken into account:

- The aquifer is confined
- Infinite areal extent
- Homogeneous, isotropic, uniform thickness
- Piezometric surface is horizontal
- Constant discharge rate
- Full penetration well
- The decline of hydraulic head follows instantaneously after the extracting of water.
- The diameter of the well is small, so the storage in the well can be neglected.

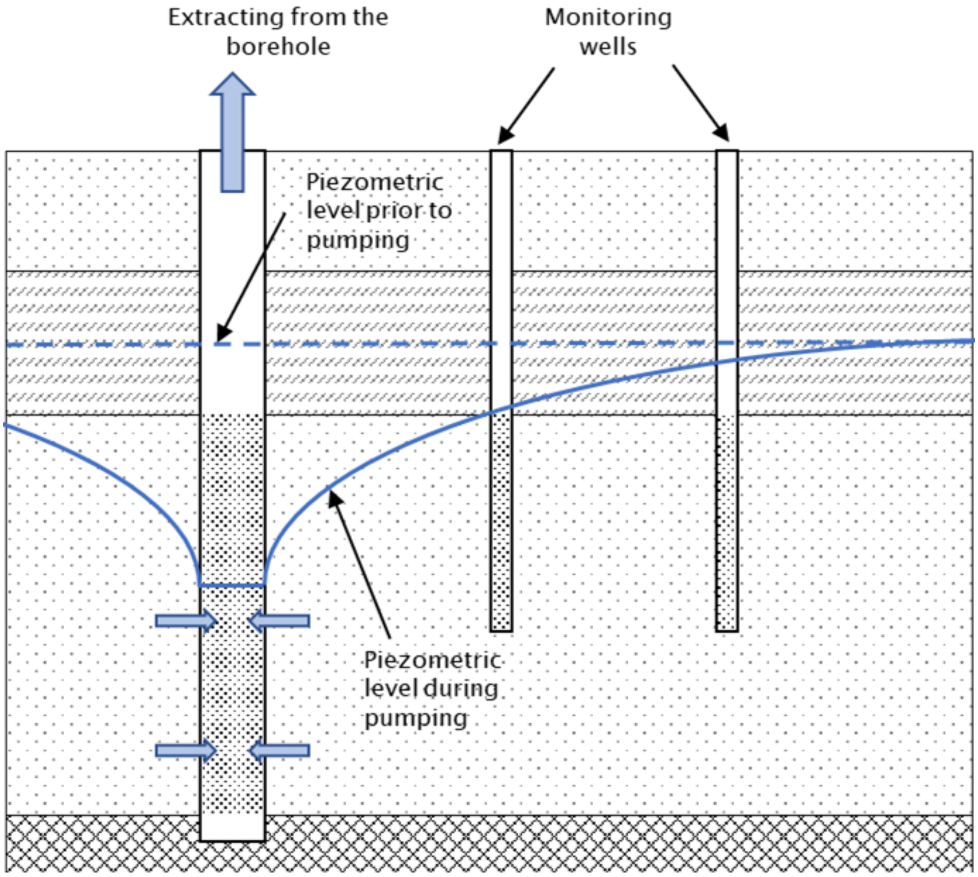


Figure 7.3: Schematic of the pumping test in a fully penetrating well.

The pumping well and observation well at the campus of HUNRE are located within a semi-confined (leaky) aquifer, but for simplicity, we will assume it is a confined aquifer. An overview of the geological cross-section at this location can be found in Appendix B: Borehole description at HUNRE. There is some leakage coming from the layer above, but this leakage can only be quantified using observations in the unconfined aquifer as well. Since these wells are not available, and since this would make the computations more complicated, this will not be further analyzed in this manual.

7.2.4 Thiem's method (steady-state flow)

The transmissivity is an important parameter of an aquifer, as it tells us how easily water is able to flow in the aquifer. A higher transmissivity means there is less resistance to the water flowing. For a confined aquifer, we can compute the transmissivity with a pumping test using equation 7.1. This formula is also referred to as Thiem's method (Thiem, 1906). This formula assumes the flow to be in a steady state. In reality, this will only occur after a long time of pumping.

$$Q = \frac{2\pi \cdot KD \cdot \left(s_{pw} - s_{ow}\right)}{2.3 \log\left(\frac{r}{r_{pw}}\right)} \tag{7.1}$$

where:

Q	pumping rate	$[m^3/h]$
KD	transmissivity	$[m^2/h]$
s_{pw}	drawdown in the pumping well	[m]
s_{ow}	drawdown in the observation well	[m]
r_{pw}	radius of the pumping well	[m]
r	distance between pumping and observation well	[m]

The hydraulic conductivity of the aquifer can be computed from the transmissivity according to equation 7.2.

$$k = \frac{KD}{D} \tag{7.2}$$

where:

k	hydraulic conductivity
D	thickness of the aquifer

7.2.5 Theis' method (unsteady flow)

An alternative to the formula of Thiem is the method developed by Theis (1935). In this method, the flow is not assumed to have reached a steady state but rather is still unsteady. This means the flow is still changing over time. This method can only be used for the measurements inside an observation well. Using Theis' method for confined aquifers, the drawdown is computed according to equation 7.3.

$$\mathrm{s} = \frac{Q}{4\pi KD} W(u) \tag{7.3}$$

where:

s	drawdown in the aquifer at distance r and at time t after the start of pumping	[m]
$W(u)$	well function; this involves complex calculations.	[-]
S	storage coefficient	[-]

t	time	[h]

The well function is a function of u, which is computed according to equation 7.4.

$$u = \frac{r^2 S}{4KD \cdot t} \tag{7.4}$$

The well function is not easy to calculate. Therefore, we will use the graphical method that was developed by Theis to determine the aquifer parameters. In Figure 7.4 the well function is plotted against 1/u on a log-log paper. We will use this during the data processing in order to calculate KD and S.

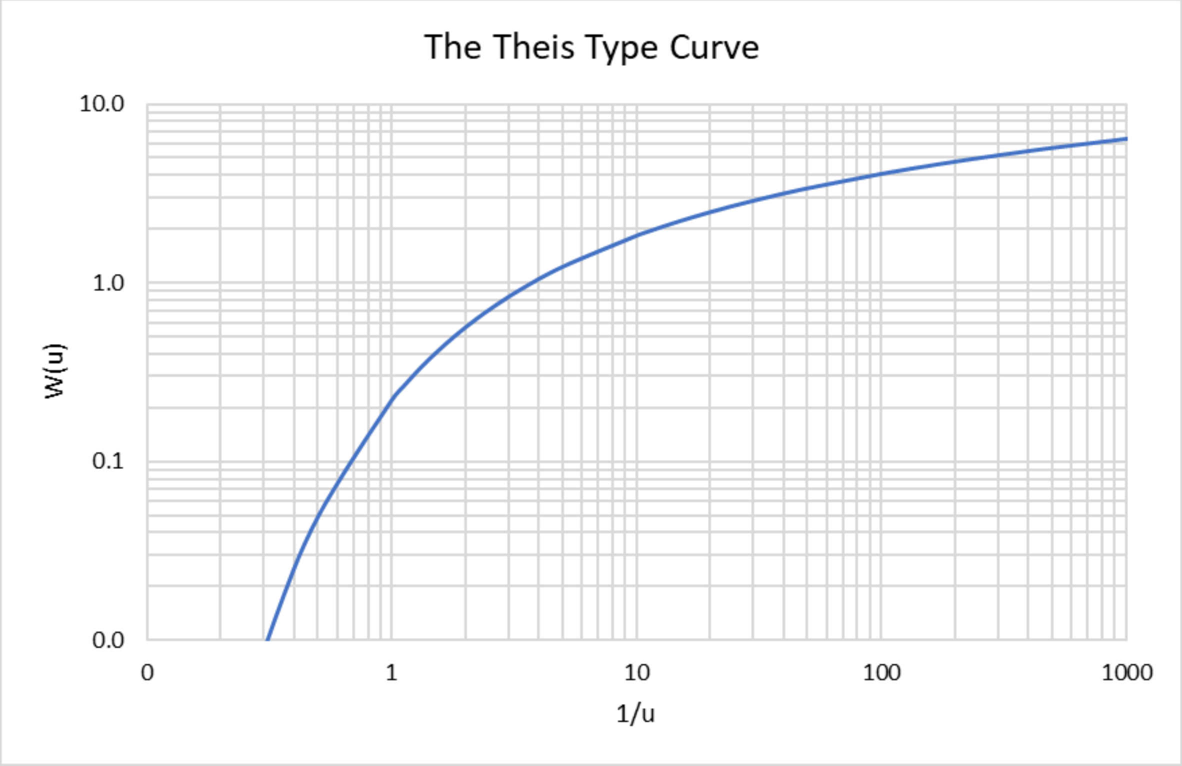


Figure 7.4: Well function plotted against 1/u

We can rewrite equation 7.4 into equation 7.5.

$$\frac{\mathrm{t}}{\mathrm{r}^2} = \frac{S}{4KD}\frac{1}{u} \tag{7.5}$$

In Figure 7.5 we compare equations 7.3 and 7.5 and we find that the relationship between t/r^2 and s should be the same as the relationship between $1/u$ and $W(u)$. This only holds when the pumping rate Q stays constant during the test.

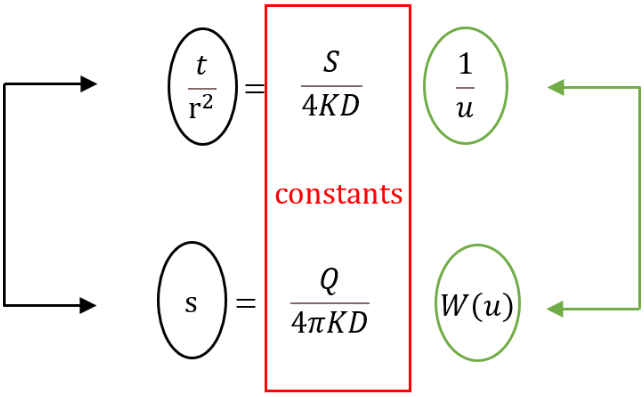


Figure 7.5: Relationship between the two Theis' equations

The main principle of Theis' method is to plot and fit t/r^2 and s on the same graph as $1/u$ and $W(u)$. If it is possible to fit both graphs on top of each other, then the correct values for S and KD can be calculated.

7.3 Experiment

In Table 7.2 the needed materials are listed for performing the pumping test at the HUNRE site. Other necessities, like the submerged pump and flow meter, are already provided at the test site. A record sheet for this experiment can be found in Appendix E: Record sheets. Print this out and take it to the test site.

Table 7.2: Equipment list to prepare for the pumping test

Equipment/material	**Quantity**	**Purpose**
TD-diver	2	Automatic measurements of the water- and atmospheric pressure.
BARO-diver	1	Automatic measurement of atmospheric pressure.
Metal string	2	Attach the divers for hanging inside the boreholes.
Diver reader	1	For communicating diver data to a laptop.
Laptop with Diver Office installation	1	Setting up the divers and downloading data.
Manual water level meter	1	Manual measurements for calibration of the divers.

You will perform the pumping test at the HUNRE campus. There is already a submerged pump installed which extracts water from the second aquifer. This water is extracted to provide tap water and flush toilets. In Appendix B: Borehole description at HUNRE the description of the boreholes at the HUNRE campus is shown. Use this to estimate the thickness of the second aquifer. Figure 7.6 shows the observation well and outflow point of the pump.

Figure 7.6: Overview of the observation well site

The steps for performing the pumping test are provided below:

1. Set up the TD divers and BARO diver on your PC. Appendix A: Diver Manual gives a handout for this.
2. The water level needs to be measured manually before conducting the experiment using a hand water level meter, as depicted in Figure 7.7. Note this value for both wells.

Figure 7.7: Doing a manual measurement of the water level inside the pumping well (left) and observation well (right)

3. Install the TD divers in the pumping well and observation well.
   3.1. The maximum water pressure on top of the TD divers is 10 m. A larger water depth will result in the diver breaking down. Therefore, you will hang the diver about 5 meters below the water level that you have measured.

3.2. Take out the spool with metal string rolled around it and start unrolling it from the spool. Hold both the metal string and the measuring tape from the hand water level meter and unroll the metal string until the length of the metal string is equal to the water depth, as shown in Figure 7.8. Then add another 5 meters of metal string.

Figure 7.8: Getting the right length of metal string.

3.3. Now calculate the cable length and note it down on the record sheet. The cable length is the sum of the measuring depth, the diver length, and the 5 meters of metal spring. See also Figure 7.9.

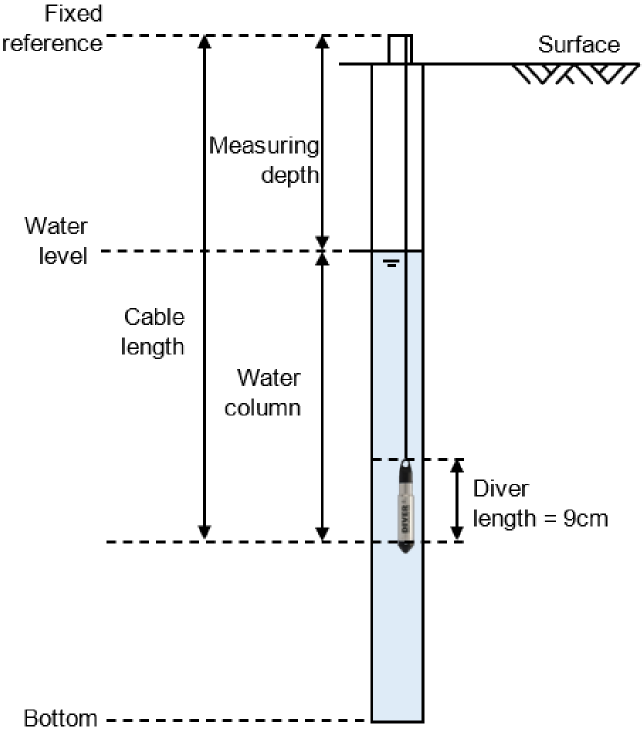


Figure 7.9: Measuring levels diver

4. In addition, you need to also turn on one BARO-diver and place it on the surface. This instrument will later be used to retrieve the actual water depth on top of the TD divers.
5. Estimate the distance between the pumping well and the observation well.
6. Now all necessary information is recorded in preparation for the test. The pump can now be activated. After turning on the pump the water level in the pumping well and observation well will go down. The installed divers will measure this water level drop very precisely. To make sure that the divers are working properly, you need to also do hand measurements at given intervals. These measurements can be noted down on the record sheet.
7. The discharge of the pump can only be calculated manually with a bucket if the discharge is small. This is done by pouring the extracted water into a bucket and counting the amount of time before the bucket is filled. However, for pumping discharges of more than 5 m^3/hour a simple bucket is too small to do this. The pump at the HUNRE campus has a larger discharge than 5 m^3/hour. For measuring the discharge, you will need to use a flow meter, which is installed near the observation well, and which is depicted in Figure 7.10.

Figure 7.10: Flow meter

7.4 Data processing

1. To start, check the manual discharge measurements during the test. Ask yourself if the pumping discharge was constant throughout the whole test, or if you need to divide your results into segments based on the different discharge values. In general, you would like to use the period with the longest constant discharge.
2. Extract the measurements from the TD-divers and BARO-diver using the Diver-Office software. See Appendix A: Diver Manual for instructions.

3. Combine the measurements from all divers in one Excel sheet and calculate the water column over time in each borehole. To explain this step in more detail, a simple example is given:

   3.1. In this example the TD-diver is submerged in a glass of water.

   3.2. At the same time a BARO-diver has been turned on to calculate the atmospheric pressure. See Figure 7.11.

Figure 7.11: Two divers, one submerged in water.

   3.3. For this test the measurement frequency was set to 10 seconds. The results from this can be seen in Figure 7.12.

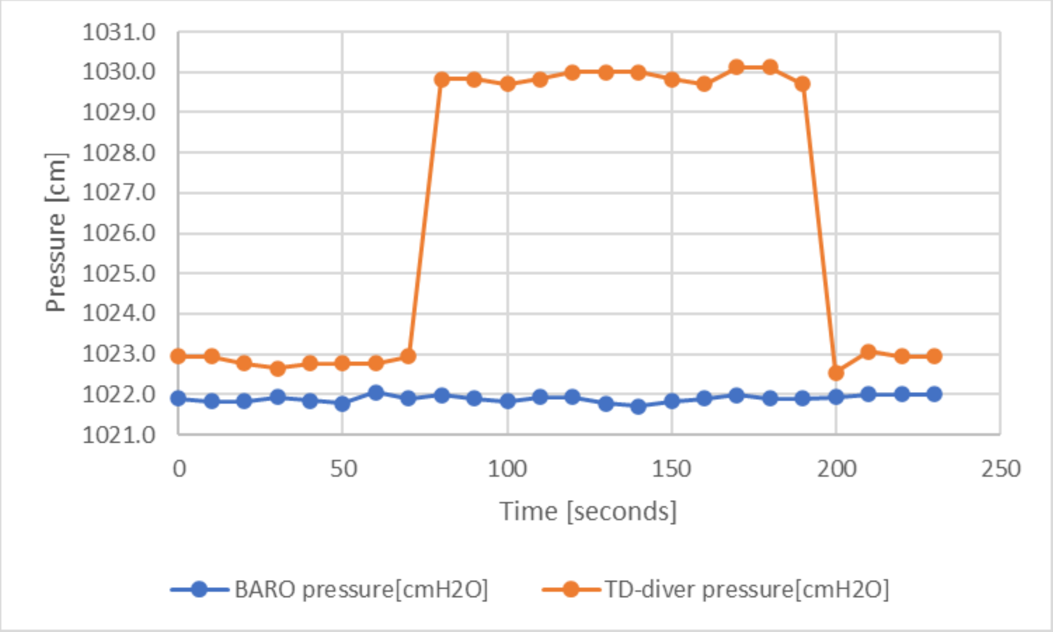


Figure 7.12: The measured pressure by the two divers.

As you can see there is a difference in pressure between the two divers before and after entering the glass. This is related to the accuracy of the divers and this difference will be neglected.

3.4. The water column can be calculated by subtracting the values of the BARO diver from the TD diver. The results graph is depicted in Figure 7.13.

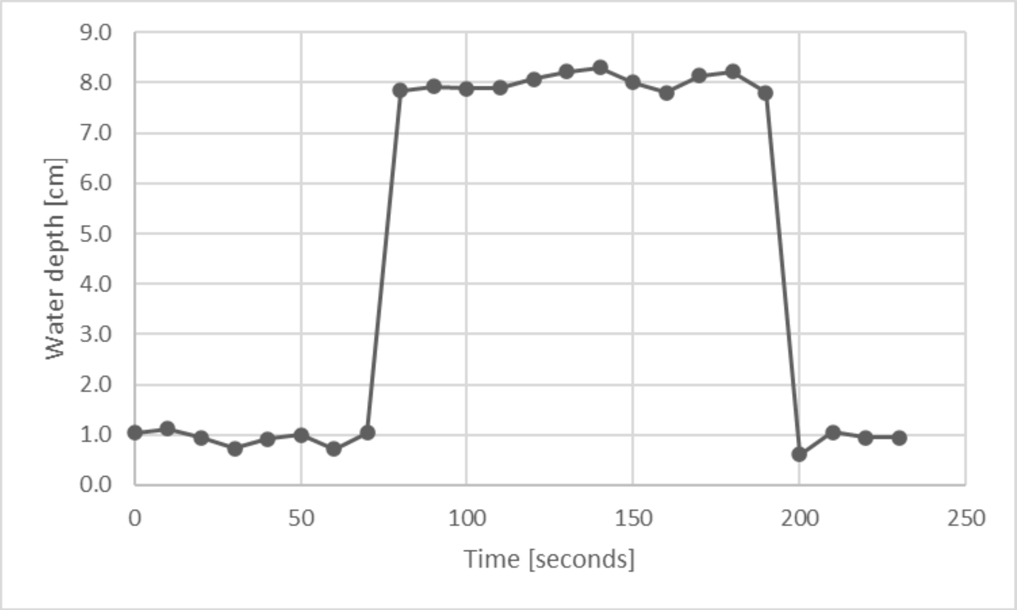


Figure 7.13: The difference between the TD-diver and the BARO-diver.

4. Now also add the manual measurements of the water column to the Excel sheet. This step needs extra care. The TD-diver measures the water column on top of the diver, while the manual measurements give the measuring depth (see *Figure 7.9*). You can compute the water column from your manual measurements by subtracting the manual measuring depth from the cable length.
5. Now compare the manual measurements of the water column with the measurements from the diver. Are there any differences? In case of a deviation between manual and automatic measurements, make sure that this deviation is reasonably constant. For instance, if you measure a difference of 5 cm at the start of the test and also during the test, this can be explained by an error in measuring the cable length. This is not a problem for further interpretation of the test results.
6. Now calculate for each timestep the drawdown in both boreholes. The drawdown is the change in the water column compared to the level before extracting.
7. Now plot the drawdown values in the pumping well and observation well in one graph. An example of the drawdown values in two nearby piezometers is given in Figure 7.14.

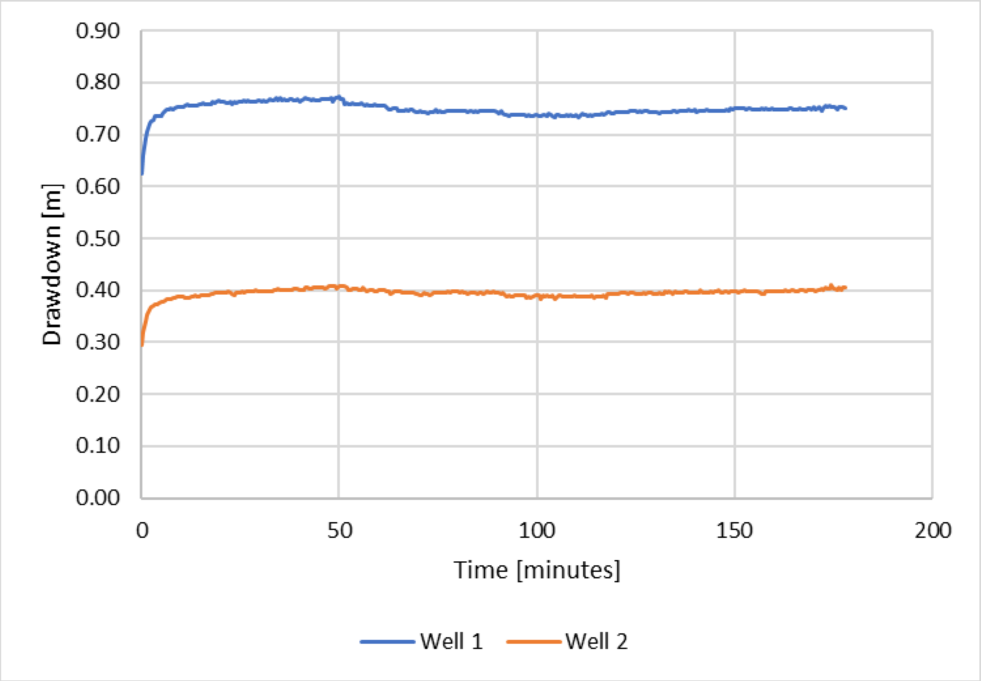


Figure 7.14: Plotting the drawdown in both wells.

8. First you will calculate *KD* using Thiem's method (see equation 7.1). For this formula, you will choose one moment. For the formula to be applicable, a steady state should have been reached. In reality, this is probably not the case. However, if the drawdown lines of both wells are parallel, you can assume a steady state has been reached.
    8.1. To check this, plot on the y-axis the drawdown, and on the x-axis the time. Adjust the scale of the x-axis to a logarithmic scale. Figure 7.15 shows an example where the two lines are parallel. Based on this you can assume that steady-state has been reached.

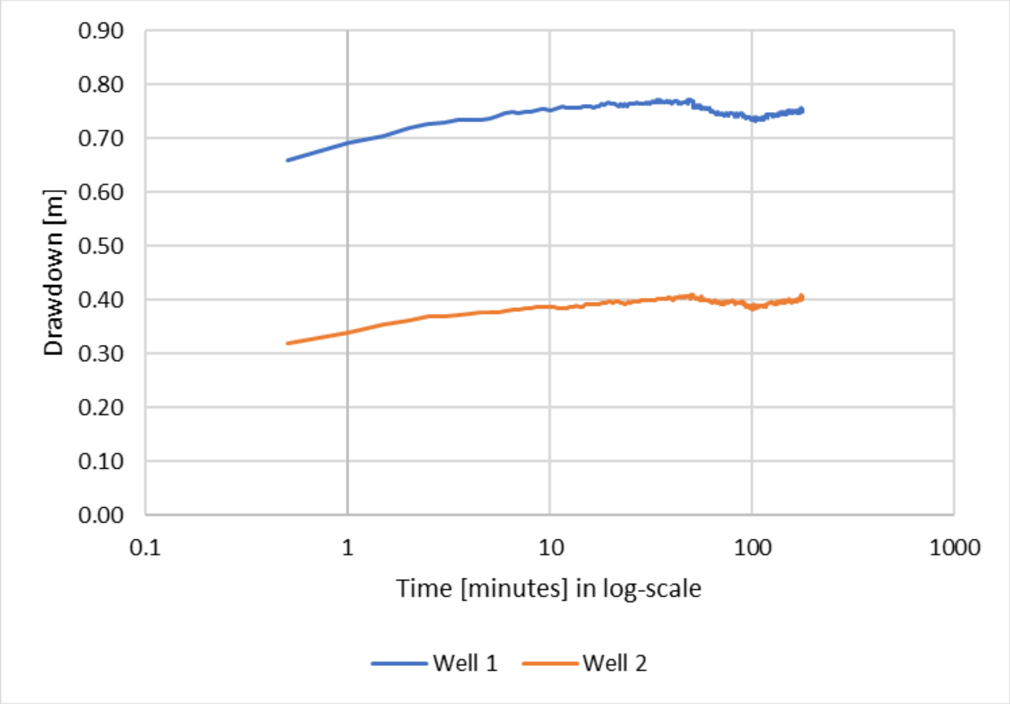


Figure 7.15: Plot the drawdown on a semi-log scale

8.2. Now choose the values of the steady state drawdown for both the pumping well and the observational well. It does not matter which timesteps are taken, as long as both are within the period where both lines run parallel to each other.

8.3. Compute the hydraulic conductivity using equations 7.1 and 7.2.

9. As was mentioned before the flow has probably not reached a steady-state. Therefore, you will also calculate *KD* using Theis's method. In addition, this method also enables you to calculate the dimensionless aquifer storage coefficient *S*. The calculation is not as straightforward as in the previous steps. For this example, the results of a different pumping test will be used. An Excel file will be provided to assist you. The steps are as follows:

9.1. Make a table in Excel with the time and drawdown values. Make sure to convert the time values into minutes and the drawdown values into meters.

9.2. Calculate for each timestep t/r^2

9.3. Plot a graph with the drawdown values on the y-axis and t/r^2 on the x-axis. See Figure 7.16 for an example.

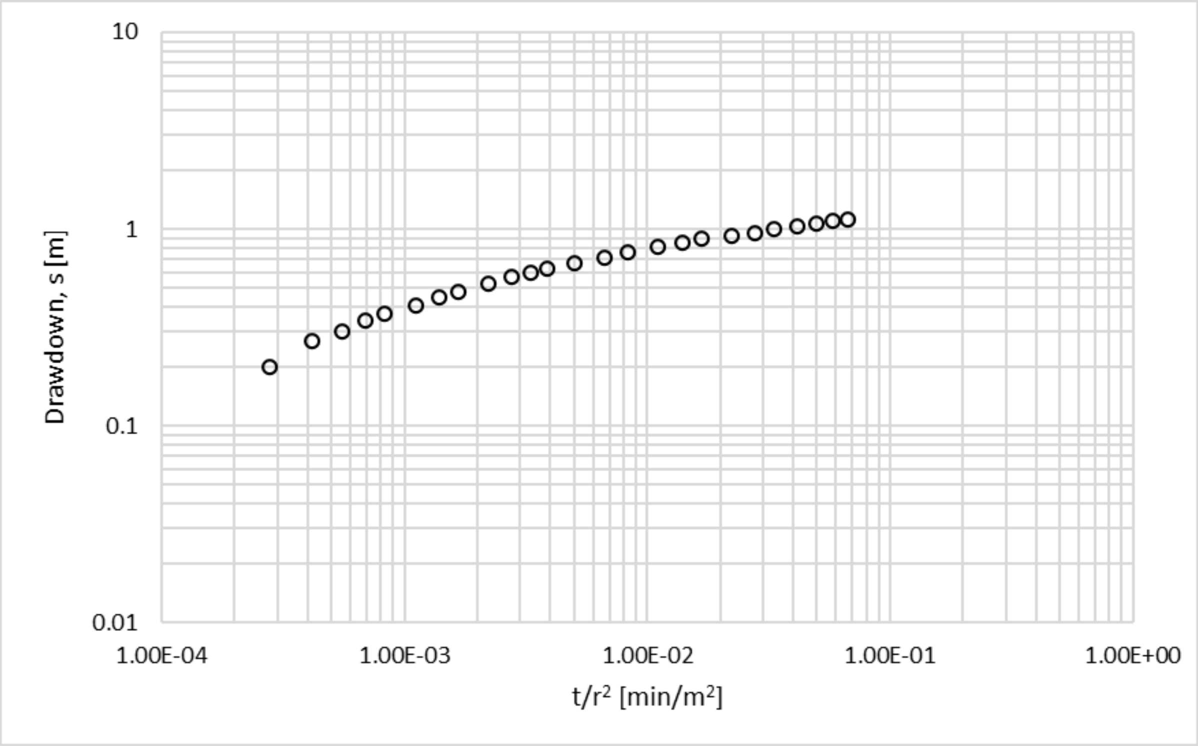


Figure 7.16: Example of drawdown values plotted versus t/r^2

9.4. Now you will place the graph with the pumping test results on top of the Theis curve, which is shown in Figure 7.4. Try to adjust the location of the data graph so that all the points line up on the Theis curve. Figure 7.17 shows an example.

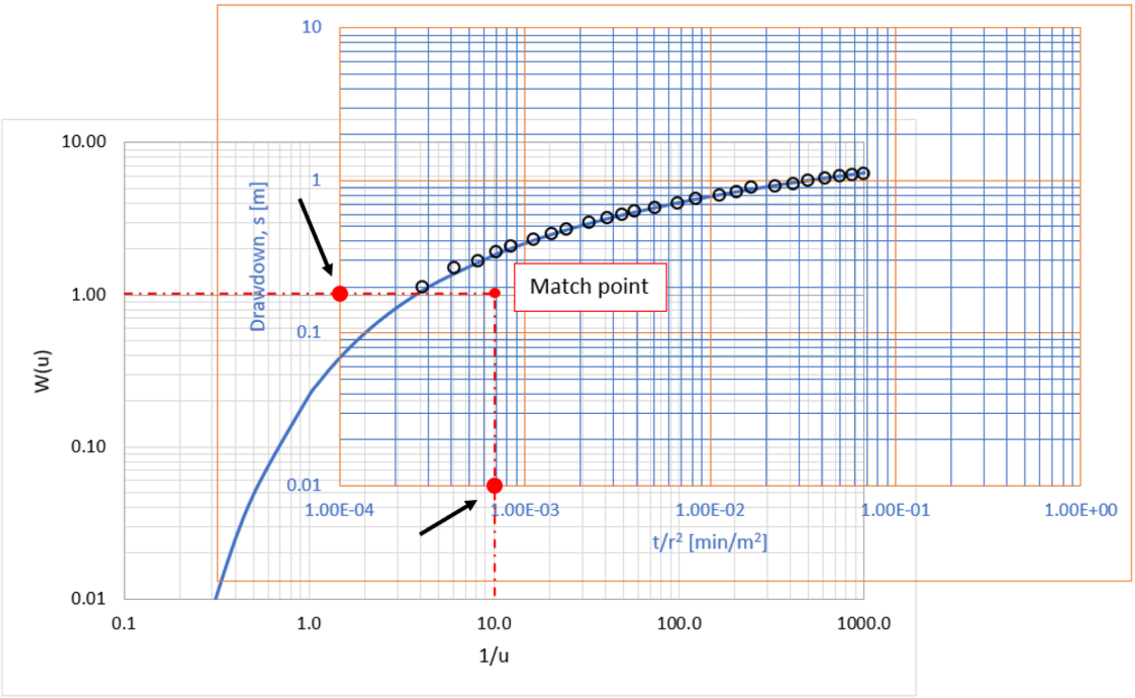


Figure 7.17: Fitting the pumping test results on top of the Theis curve and finding the match point

9.5. After you have adjusted the graph, you can define the match point. For this example, this point will be chosen on $W(u) = 1$ and $1/u = 10$.

9.6. Read from the upper graph the values of the drawdown s and t/r^2 that are located at the match point. You now have values for $W(u)$, $1/u$, s, and t/r^2.

9.7. Now you can calculate KD and S using equations 7.3 and 7.4.

An example of the data processing is given in a separate Excel.

7.5 Reflective questions

1. Look at the borehole description given in Appendix B: Borehole description at HUNRE. Does the calculated value for the hydraulic conductivity k match with the theoretical values shown in Table 7.1?

It could very well be that there is a difference. The values given in Table 7.1 are only indicative. You would expect them to be in the same order of magnitude, but this is not guaranteed.

2. If you did have two observation wells, and you could take the head loss in the pumping well into account, how would this change the results?

If you would take into account the head loss in the well, the hydraulic conductivity would be a bit higher.

3. Did the aquifer reach a steady state? If not, how will this influence your computations?

Technically you never reached steady-state as this requires an infinite amount of time, but we can assume steady-state if no significant change in head can be observed. Check the student data to assess this. If a steady state has not been reached, the actual hydraulic conductivity will probably be a bit lower than the one computed.

4. You assumed a confined aquifer, but in reality, there will be some leakage. How does this influence your results?

The hydraulic conductivity will be a bit lower in reality than the one computed.

7.6 References

Kruseman, G. P., De Ridder, N. A., & Verweij, J. M. (1970). *Analysis and evaluation of pumping test data* (Vol. 11, p. 200). Wageningen, The Netherlands: International institute for land reclamation and improvement.

Theis, C. V. (1935). The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage. *Eos, Transactions American Geophysical Union*, 16(2), 519-524.

Thiem G. (1906). Hydrologische methoden (dissertation). J.M. Gebhardt's Verlag.

8. Inverse auger hole test

8.1 Introduction

8.1.1 Hydraulic conductivity of the upper soil

The ability of soil to transport water is called the hydraulic conductivity. A high hydraulic conductivity means water can flow through the soil easily. The hydraulic conductivity is an often-used parameter, important for many applications. For example, when modeling an aquifer, the hydraulic conductivity determines the behavior of the aquifer.

The soil in an aquifer, however, is usually quite different than the soil close to the surface. The upper soil layer is influenced by the weather, plants, animals, human interference, and many other aspects. Thus, the hydraulic conductivity of this upper soil layer is also quite different than the hydraulic conductivity of deeper layers. For example, it is a very important parameter when designing horizontal drainage systems, irrigation systems, groundwater abstraction structures, and recharge systems. Thus, we would like to measure this hydraulic conductivity. For this, an inverse auger hole test can be used.

You are going to perform an inverse auger hole test. A small but deep hole is dug by hand and filled with water. The water level in the hole will drop, and by measuring this drop you can compute the hydraulic conductivity. This concept is shown in Figure 8.1.

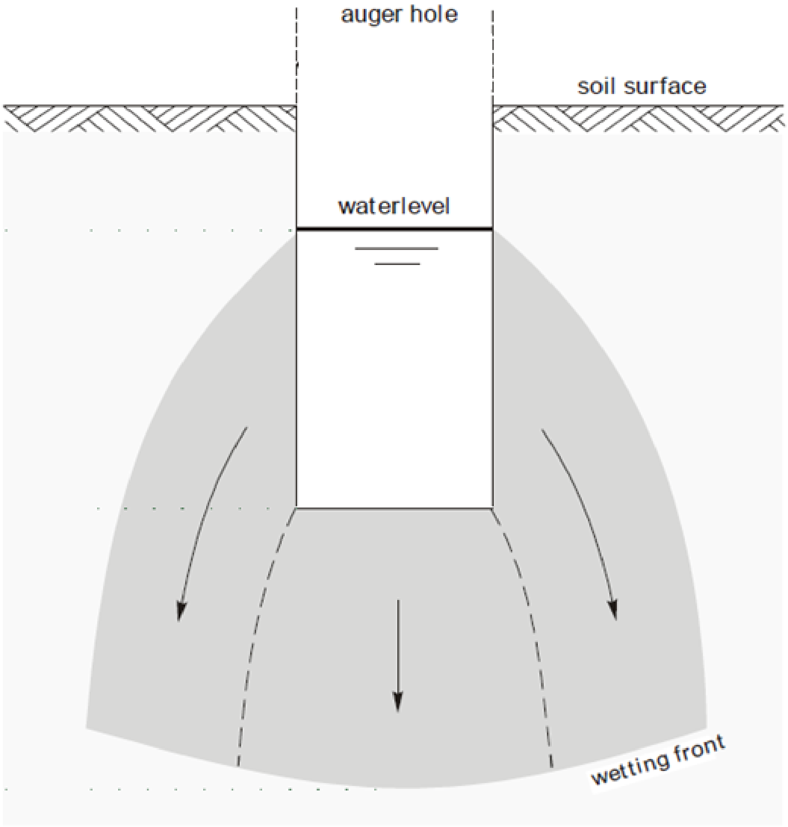


Figure 8.1: Infiltration from a water-filled auger hole into the soil (Nijland & Oosterbaan, 1994)

8.1.2 Learning goals

With this experiment, you will learn how to perform an inverse auger hole test and compute the hydraulic conductivity based on the collected data. You will also learn the underlying theory which is used to process the data and compute the hydraulic conductivity.

You will learn how to use an auger and a hand water level meter.

8.2 Theory

When a hole is dug in the soil and this hole is filled with water, the water will infiltrate into the soil. This infiltration will be both vertically and horizontally. The higher the hydraulic conductivity, the quicker the water will infiltrate. At the start of the infiltration, the water will flow relatively quickly since the surrounding soil is still unsaturated, and the extra suction causes the water to infiltrate quicker. However, over time the soil surrounding the hole will be saturated and the infiltration rate will reach a constant value. Once the soil is fully saturated, the infiltration rate can be used to compute the hydraulic conductivity. The hydraulic conductivity of the saturated layer is computed according to equation 8.1.

$$k_{sat} = 1.15\, r \, \frac{\log\left(z_1 + \frac{1}{2}r\right) - \log\left(z_2 + \frac{1}{2}r\right)}{t_2 - t_1} \tag{8.1}$$

where:

k_{sat}	hydraulic conductivity of saturated soil
r	radius of the borehole
z_1	water level at time t_1
z_2	water level at time t_2

8.3 Experiment

The equipment and materials needed for this experiment can be seen in Table 8.1. Figure 8.2 shows the boring device, including the handle. The three different augers used in this experiment are also shown in Figure 8.3. A spatula can be seen in Figure 8.4. A record sheet for this experiment can be found in Appendix E: Record sheets.

Table 8.1: The needed equipment and materials to perform an inverse auger hole test

Equipment/material	**Quantity**	**Purpose**
Handle	1	Used for attaching the augers and drilling by hand.
Edelman auger for clay	1	Penetrating clay soils.
Edelman auger for coarse sand	1	Penetrating sandy soils.
Spiral auger	1	Penetrating hard soils.
Spatula	1	For pulling sticky soil out of the auger.
Measuring tape	1	Measure the depth of the borehole.
Hand water level meter	1	Measuring water level inside the borehole.
Small wooden board	1	Used to read the water level from a fixed reference level.
Bucket	1	Filling the borehole with water.
Stopwatch	1	Keep track of time during the experiment.

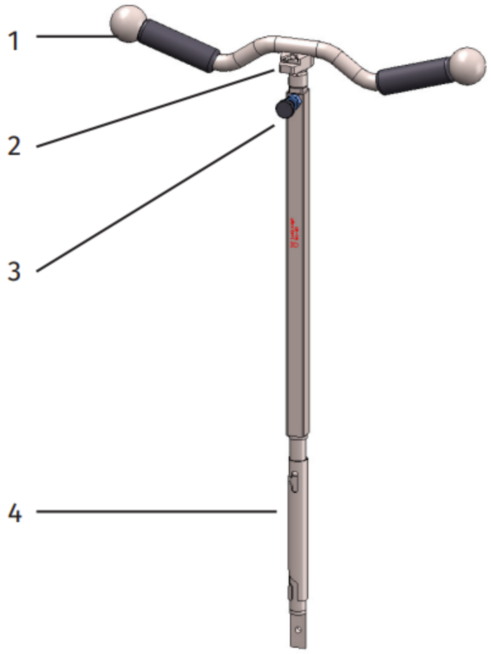


Figure 8.2: 1) Handle, 2) adjustable ratchet, 3) halt knob to adjust the height, 4) coupling sleeve (Eijkelkamp, 2022)

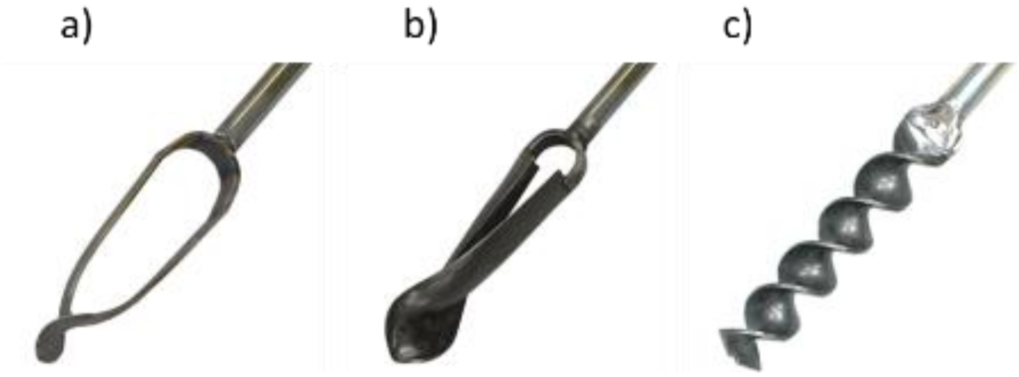


Figure 8.3: a) Edelman auger for clay, b) Edelman auger for coarse sand, c) Spiral auger (Eijkelkamp, 2022)

Figure 8.4: Spatula

In this experiment the hydraulic conductivity will be accessed at two different depths: 25cm and 50cm. The test will also be performed at two different locations: on a plowed field (agriculture) and in undisturbed soil. So, in total four boreholes will be dug. Table 8.2 shows an overview. The two types of soil can be seen in Figure 8.5.

Table 8.2: Overview of the four different boreholes

Test	Land type	Depth (cm)
1	Agricultural plowed field	25
2	Agricultural plowed field	50
3	Grass field	25
4	Grass field	50

Figure 8.5: Left: agricultural ploughed field. Right: grass field

First read through all the steps before doing anything.

1. The first step is to drill a hole into the ground at the desired depth. This can be a quite challenging task. Clay or sandy clay is relatively easy to extract using a hand auger. For the extraction of coarse sand, a specific auger is required.
2. To make a borehole, attach the handle to the desired auger. Often you will find clay or sandy clay in the first layer, so start with the Edelman auger for clay. The auger can be attached to the auger using the coupling sleeve.

3. Now place the auger on the surface and start turning the handle clockwise while pressing firmly on the soil, as shown in Figure 8.6. After one rotation you can rotate back in a counterclockwise direction. Repeat this step until you think that the auger is completely filled with soil. Now pull the auger out of the ground. Be careful to lift with your legs, not with your back.

Figure 8.6: Drilling a borehole using the auger and handle.

4. While excavating a hole it is wise to keep track of the materials that have been extracted. A nice way of presenting the different soils is to lay the excavated soil in order of excavation on the surface, as shown in Figure 8.7. The spatula can be used to remove sticky soil from the auger.

Figure 8.7: Presenting the different soil layers during the excavation of a borehole

5. During digging stop every once in a while, to measure the depth of the hole with the measuring tape. Ask yourself if you have already reached the desired depth or if you need to dig deeper.
6. When the borehole has reached the desired depth, take a photograph of the excavated soil. This makes it possible to better explain the results of the test after coming back from the field.
7. Note the exact depth of the borehole. The depth may deviate from the values in Table 8.2.
8. During the test the water level will be measured using a hand water level meter. For this, you need to make sure that the water depth during the test is measured relative to the same reference level. For this, a simple piece of wood can be used, as shown in Figure 8.8.

Figure 8.8: Measuring the water depth using a piece of wood, so that the reference level is always constant

9. Now assign tasks to each member in the field: one will measure the time, one will write down the measurements, and one will fill the borehole.
10. Fill the hole with water in one go using the bucket, as shown in Figure 8.9. It is important that your filling is almost instantaneous. The amount of water to add to the borehole depends on which layers you are interested in. Fill the 25cm deep borehole completely. Fill the borehole with a 50 cm depth half-full. Directly after the borehole is filled a timer will start. The water level is measured at an interval of 10 seconds.

Figure 8.9: Filling the hole with water.

11. At first the water level will go down very fast. As time progresses the water level will go down more slowly. The frequency of measurements can therefore be decreased over time, but this has to be carefully recorded.
12. Perform the test until the water inside the borehole has completely been infiltrated.
13. After completion of the test the soil around the borehole is completely saturated. For a reliable estimate of the hydraulic conductivity, the test should now be performed again.

8.4 Data processing

1. During the experiment you measured the depth from a fixed reference on the surface to the water level inside the borehole. Convert these values to the actual water depths inside the hole. Figure 8.10 shows an overview of the measurements.

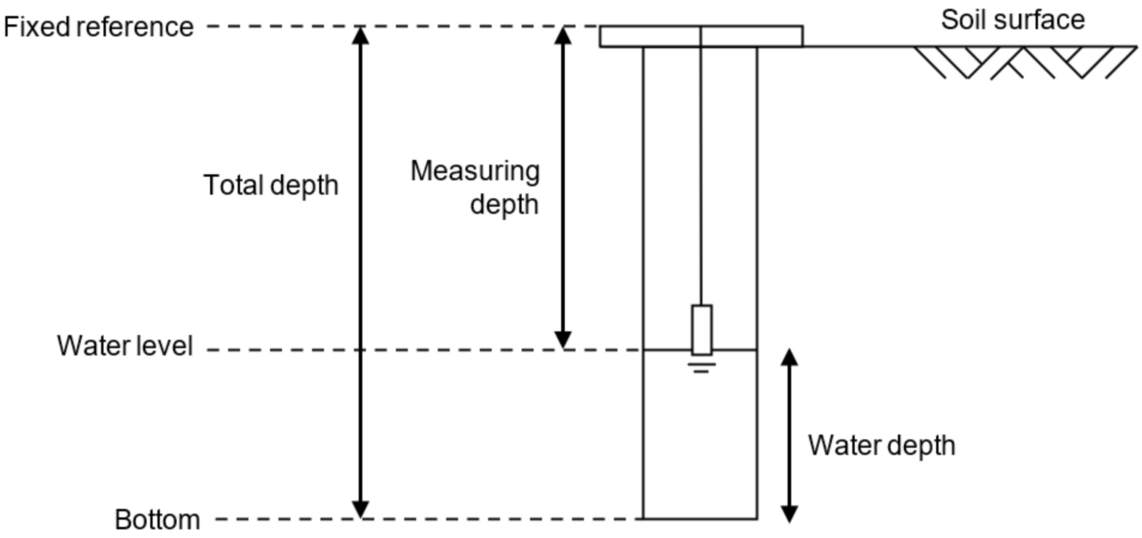


Figure 8.10: Measurements for the inversed auger-hole method

2. Export the measured water depths to Excel and graph the results over time like in Figure 8.11.

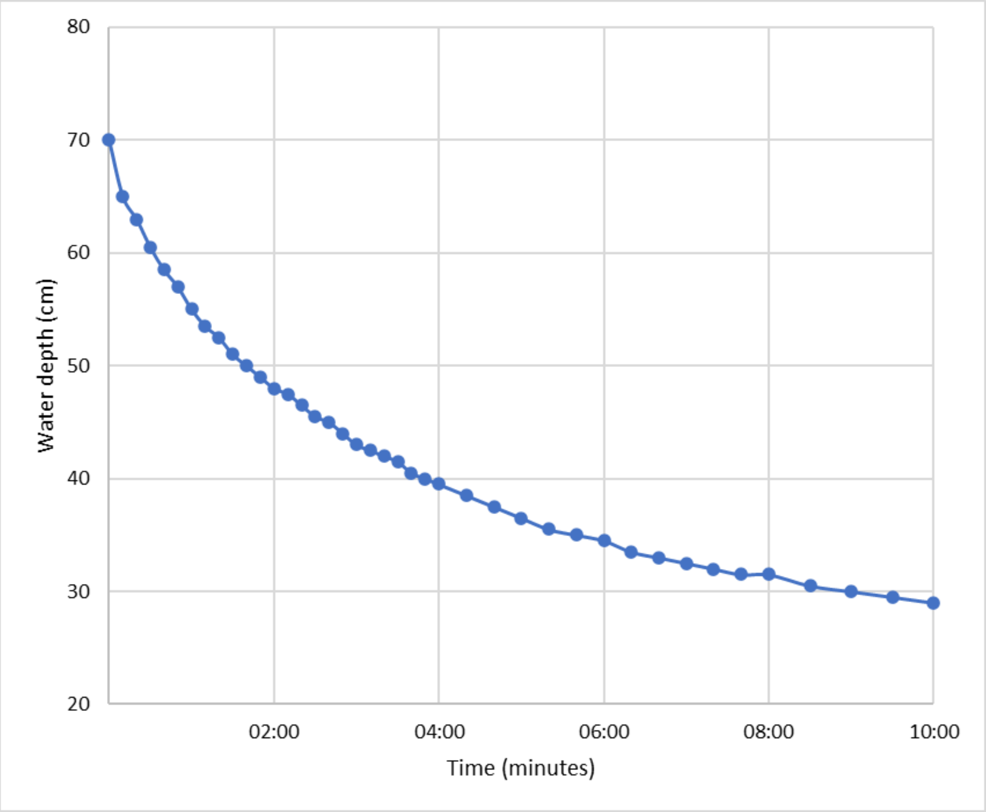


Figure 8.11: Example of the inverse auger hole method field results.

3. Now transform the time into seconds and plot the time on the x-axis on a log scale. Based on this graph the steady-state water level drop can be determined. When you can draw a straight line through the points, the saturated conductivity has reached a constant value, as shown in Figure 8.12. This value is close to the real value of the conductivity directly around the borehole.

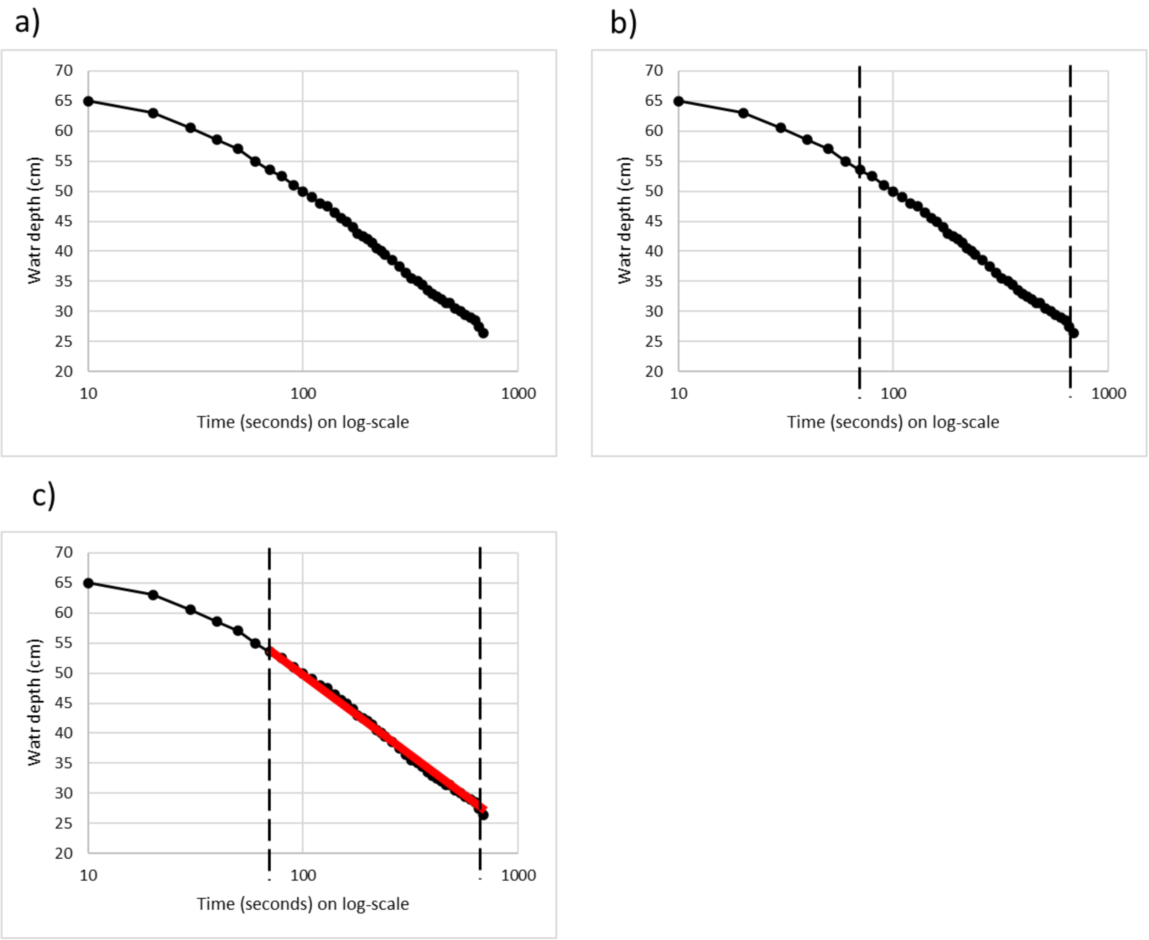


Figure 8.12: a) Transforming the dataset on a semi-log scale. b) finding a region where the points line up in a straight line. c) presenting the points with a straight line.

4. Now you can compute the hydraulic conductivity according to equation 8.1.

An example of the data processing can be found in a separate Excel. An example can also be found below.

After 80 seconds, the infiltration has reached a steady state and is constant. At that time, the water depth is 0.525 m. After 690 seconds, the water depth decreased to 0.265 m. The radius of the borehole is 6 cm. The hydraulic conductivity is then:

$$k_{sat} = 1.15\, r \frac{\log\left(z_1 + \frac{1}{2}r\right) - \log\left(z_2 + \frac{1}{2}r\right)}{t_2 - t_1}$$

$$k_{sat} = 1.15 \cdot 0.06 \frac{\log\left(0.525 + \frac{1}{2} \cdot 0.06\right) - \log\left(0.265 + \frac{1}{2} \cdot 0.06\right)}{690 - 80}$$

$$k_{sat} = 3{,}10 \cdot 10^{-5}\ m/s = 2.68\ m/day$$

So the hydraulic conductivity of the saturated soil is 2.68 m/day.

8.5 Reflective questions

1. You have performed the test at four locations. Two of the experiments were done inside the soil of a plowed field and two were performed on grassland. Can you explain the difference in hydraulic conductivity for the 25cm deep boreholes?

The experiments done in the plowed field will probably have a much higher conductivity, as the water infiltrates much quicker. This is because the soil is plowed regularly.

2. Now can you explain the difference in hydraulic conductivity between the two 50cm deep boreholes? Can you explain these differences based on the soil profile you have created?

Plowing is always only 20 cm into the soil, so it has nothing to do with plowing. Depending on the soil, students may find a higher or lower conductivity.

3. What value for the hydraulic conductivity would you choose when building a hydrological model? Why?

For a hydrological model, we are interested in the interaction between groundwater and the surface. The hydraulic conductivity measured at the top 25 cm will likely not be representative of the deeper soil, since this top layer is influenced by many factors. Thus, the hydraulic conductivity measured at 50 cm is more suitable, since it is a better indicator of the interaction between groundwater and the surface.

8.6 References

Eijkelkamp (2022), *Handleiding 01.11SE Ergonomische Handboorset*. Retrieved from https://www.royaleijkelkamp.com/media/tvhhqo5d/m-0111sen-ergonomische-handboorset-copy.pdf

Nijland, R. J. O. H. J., & Oosterbaan, R. (1994). Determining the saturated hydraulic conductivity. *Drainage Principles and Applications*, 16, 37.

9. Double ring infiltration test

9.1 Introduction

9.1.1 Infiltration

Infiltration is the process by which water on the ground surface enters the soil. It is relevant for irrigation, drainage, improving crop yield, water availability, and minimizing erosion. When constructing a hydrological model, infiltration is often an important component. However, the rate at which infiltration occurs depends on many factors and can differ greatly depending on not only the soil itself but also on the state of the soil.

Because of the importance of infiltration in so many applications, and its temporal and spatial variability, being able to measure the infiltration is crucial for a water manager. You are going to perform the double ring infiltration test to assess the infiltration rate of the soil. With this infiltration test, the vertical hydraulic conductivity of a soil layer in the unsaturated zone can be determined.

The double ring infiltration test uses, as its name suggests, two metal rings with different diameters. The rings are pushed partially into the soil and are then filled with water. Measuring the water level change over time gives an estimate of the infiltration rate. This is also referred to as the falling head method.

9.1.2 Learning goals

You are going to learn how to perform a double ring infiltration test. You will learn the underlying theory, and use the data gathered during this test to assess the infiltration capacity of the soil. You will learn how to install and use the two rings.

9.2 Theory

Water on the ground surface wants to enter the soil under the force of gravity. If the soil is dry, suction also causes the water to infiltrate into the soil. This process of infiltration occurs for example after a rain event. The infiltration rate depends on the soil characteristics. For example, water infiltrates much slower in clay than in sand. The state of the soil also matters. Water will generally infiltrate faster into dry soil than into wet soil.

In a double ring infiltration test, two rings are placed partially in the soil: the smaller ring within the larger one. They are then both filled with water. The water in the rings will infiltrate into the soil. The water will flow vertically downwards, but at the sides of the wetting front, the water will also flow laterally a bit. This is because the soil next to the rings is dry. We are only interested in vertical infiltration, since usually, for example during a rain event, the entire soil is wet equally. There are usually no large differences on a small spatial scale, like an agricultural field. Therefore, infiltration is usually only vertically, so for a double ring infiltration test we are interested only in this vertical infiltration.

This is also the reason two rings are used. The water from the outer ring will infiltrate vertically and horizontally. The water in the inner ring can only infiltrate vertically since the water infiltrating from the outer ring blocks the water from the inner ring from flowing horizontally. This is illustrated in Figure 9.1.

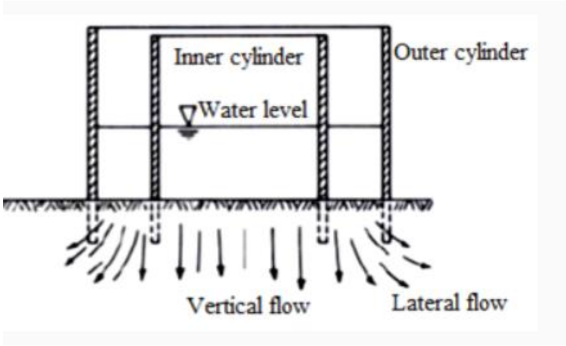


Figure 9.1: Schematization of the setup (Tiwari, Raghuwanshi, & Gorantiwar, 2014).

By monitoring the water height in the inner ring, the infiltration rate can be determined. If the soil is initially unsaturated, the infiltration rate will be higher due to suction forces. As the soil gets more saturated, the infiltration rate slows down and becomes constant. This constant infiltration rate is a good indicator of the permeability of the soil. The infiltration rate is computed according to equation 9.1.

$$v = \frac{\Delta h}{\Delta t} \tag{9.1}$$

where:

v	infiltration rate
Δh	drop in water level in the inner ring
Δt	time it took for this water level drop

To reiterate: only the water level in the inner ring is monitored during a double ring infiltration test. The outer ring's only purpose is to assure only vertical infiltration in the inner ring. Sometimes only a single ring is used for simplicity; the results from such an experiment will in general not be as accurate as the one with two rings. The whole system of rings, accessories, and water level meter is called a double ring infiltrometer.

9.3 Experiment

The equipment and materials needed for this experiment can be seen in Table 9.1. A record sheet for this experiment can be found in Appendix E: Record sheets.

Table 9.1: The equipment and materials needed for the double ring infiltration test

Equipment/material	Quantity	Purpose
14 cm diameter ring	1	Functions as the inner ring
28 cm diameter ring	1	Functions as the outer ring
Measuring line/staff gauge	1	Measuring the water level lowering
Stopwatch	1	Measuring time
Bucket	2	Filling the rings with water
Shovel/knife	1	Make excavation slots
Steel hammer	1	For hammering down the rings
Wooden plank	1	To aid in hammering down the rings

First read through all the steps before doing anything.

1. Get the rings at least 3 to 5 centimeters into the ground. Start with the inner ring, then do the outer ring. The exact method for this step is site dependent and some creativity may be required. Use the following guidelines, also shown in Figure 9.2.
   a. First try to rotate the ring into the ground.
   b. Subsequently hammer it into the ground using a hammer and a piece of wood.
   c. Alternate hammering with small excavations. For this, use a trowel to create slots at the outer side of the ring. Hammer it a little further and ensure that no water is leaking through the slots. You can compact the soil using the trowel. It is also possible to refill the slots with some clay.

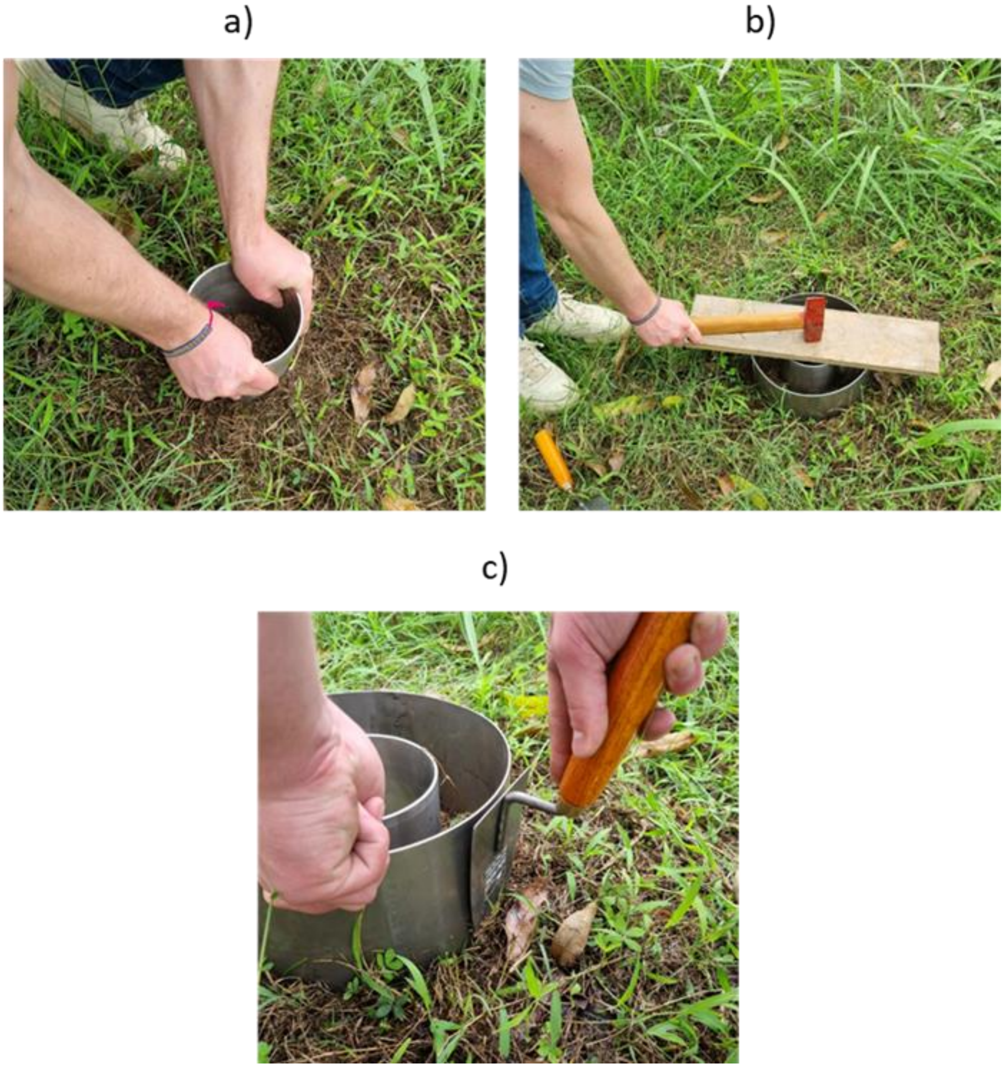


Figure 9.2: Inserting the rings into the ground using various methods.

2. Fill the two rings simultaneously with water up to 10 centimeters and start the stopwatch. The filling of the rings can be seen in Figure 9.3.

Figure 9.3: Filling the rings with water.

3. Measure the water level in the inner ring after a certain time. Make sure that the water level is measured with the top of the ring as a reference point and not the ground level, as shown in Figure 9.4. In this way, the subsidence is canceled out.

Figure 9.4: Measuring the water depth

4. Repeat step 3 multiple times. Come up with a proper time interval. For example, start with measuring every minute. If there are hardly any changes, increase the time step. This of course depends on the soil type. Also, refill the water in the outer ring if needed (the water level in the outer ring will lower a bit faster due to lateral flow), as shown in Figure 9.5. Try to keep the water level in the outer ring somewhat equal to the water level in the inner ring.

Figure 9.5: Refilling the outer ring of water.

9.4 Data processing

1. Make sure you have all the data from your experiment in a table. One column should contain the timestamps, another column has the measured water level at the corresponding timestamp.
2. Convert this table to a graph and find from which timestamp, the infiltration has reached a more or less constant rate.
3. Compute the infiltration rate according to equation 9.1

An example of the data processing is given below. This example can also be found in a separate Excel.

The data is presented in Table 9.2.

Table 9.2: The water level in the inner ring measured over a certain period

Time [hr]	**Water level [cm]**
00:00	18,5
00:11	18,0
00:34	17,5
00:54	17,0
01:10	16,0
02:48	13,2
04:45	10,0
06:45	7,0

The table can then be converted into a graph, as shown in Figure 9.6.

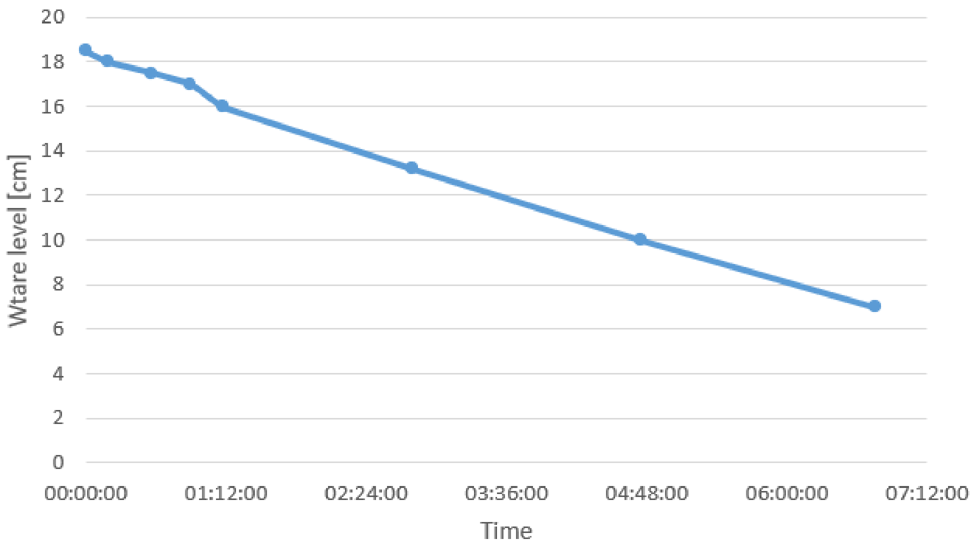


Figure 9.6: Example of water level measurements inside the inner ring

The infiltration is constant after the 54 minutes timestamp. At this time, the water level is 17.0 cm. At the end of the experiment, at the 6 hours and 45 minutes timestamp, the water level is 7.0 cm. The drop in water level is 17.0 – 7.0 = 10.0 cm. The time difference is 06:45 – 00:54 = 05:51, so 5 hours and 51 minutes or 5.85 hours. The infiltration rate is computed according to equation 9.1.

$$v = \frac{\Delta h}{\Delta t} = \frac{10.0\ cm}{5.85\ h} = 1.71\ cm/h$$

So the infiltration rate is 1.71 cm/h, or 0.41 m/day.

9.5 Reflective questions

1. Does the water level inside the ring influence the infiltration rate?

Yes, the water in the ring adds pressure, causing the water to infiltrate quicker. The infiltration rate is thus higher than it really should be.

2. What would be the difference between a falling head test (the one you just performed) and a constant head test (using a Mariotte bottle)?

In a constant head test, the water level stays constant. With a falling head test, the water level drops, as does the pressure on the infiltrating water. Thus theoretically, the infiltration rate will not be truly constant during a falling head test. With a constant head test, the infiltration rate will be more constant.

It should be noted that this effect, and thus also the differences between a constant head test and a falling head test, are not that significant, especially since the rings during a double ring infiltration test are only filled with a small amount of water.

3. Does the determined value of the infiltration rate match with the soil type?

Check student data and compare it to the described soil

4. How do the tests at different locations compare?

Students should find that coarser soils have a higher infiltration capacity. The initial wetness of the soil does not matter, since the soil is saturated during the experiment, and only after full saturation has been reached the infiltration rate is measured.

9.6 References

Tiwari, Raghuwanshi, Gorantiwar (2014). *Irrigation Engineering*. Retrieved from http://ecoursesonline.iasri.res.in/mod/page/view.php?id=1994

10. Soil sampling

10.1 Introduction

10.1.1 Soil sampling with Kopecki rings

The upper soil layer is only a small part of the total hydrological cycle, but it is one of the most important ones. From this upper soil layer, water infiltrates into the ground or evaporates into the air. We are therefore often interested in the properties of the upper soil layer. To assess these properties, we need to take a soil sample and study this sample in the lab. Taking a soil sample is not as easy and straightforward as it may seem; special rings called Kopecki rings are needed, and the process of taking the samples with these rings is quite meticulous.

10.1.2 Learning goals

In this experiment, you will learn how to use Kopecki rings to take a soil sample. You will learn how to analyze a soil sample to compute the water content, the porosity, and the dry bulk density of the sample. You will also learn the underlying theory on which sampling and data processing is based.

10.2 Theory

For this experiment, we will use Kopecki rings to capture undisturbed soil samples, which have an inner volume of exactly 100 cm^3.

10.2.1 Porosity

Soil consists of particles. These particles can differ quite a lot in size. Some particles are too small to be visible to the naked eye, like clay particles. Somewhat larger particles like sand, are visible to the naked eye. The larger particles, like gravel, are orders of magnitude larger than clay particles and clearly visible.

These particles do not fit together perfectly, there is some space between them. This space is either filled with air or with water. These spaces between particles are called pores. Porosity is the volume of the pores within a certain volume of soil. It is computed according to equation 10.1.

$$n = \frac{V_{pores}}{V_{total}} \tag{10.1}$$

where:

n	porosity
V_{pores}	volume of the pores
V_{total}	volume of the soil including pores

Sand has a porosity between 0.3 - 0.4, while clay may have a porosity of 0.5. Figure 10.1 shows the concept of pores, soil, air, and water.

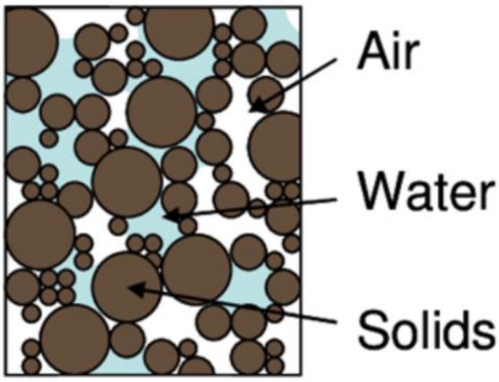


Figure 10.1: Soil particles with space between them, called pores. These pores are filled with water or air. (Veenstra, White, & Schaefer, 2005)

10.2.2 Dry bulk density

Pores can be filled with either air or water. If all the pores are completely filled with water, the soil will be denser than when the pores are completely filled with air. The density of the soil when all the pores are filled with air is called the dry bulk density of the soil.

The dry bulk density of a soil partially depends on the porosity; soils with a larger porosity usually have a lower dry bulk density, since they contain more air. But porosity is not the only factor. The make-up of the soil is also relevant. For example, soil that contains a lot of organic matter usually has a low dry bulk density. Most soils have a dry bulk density of between 1.0 - 1.6 g/cm^3, denser than water.

The dry bulk density can be computed according to equation 10.2.

$$\rho = \frac{m_{dry\ soil}}{V_{total}} \tag{10.2}$$

where:

ρ	dry bulk density
$m_{dry\ soil}$	volume of the pores

10.2.3 Water content

In nature, the soil is seldom completely dry. There will be always a little bit of moisture in the pores of the soil. Even plants cannot suck away this tiny amount of water. The amount of water in the pores of a soil is called the water content. Farmers like to know the water content of their soil so that they know when they have to irrigate. The volumetric water content of the soil is computed according to equation 10.3, and it considers the volume of water together with the volume of the soil (including the pores).

$$\phi = \frac{V_{water}}{V_{total}} \tag{10.3}$$

where:

ϕ	volumetric water content
V_{water}	volume of water in the soil

In addition, the gravimetric water content is also used. This is defined according to equation 10.4.

$$w = \frac{m_{water}}{m_{dry\ soil}} \tag{10.4}$$

where:

w	gravimetric water content
m_{water}	mass of water in the soil

Note that we can compute the volumetric water content if we know the gravimetric water content and the dry bulk density, and vice-versa, according to equation 10.5.

$$\phi = w \cdot \rho \tag{10.5}$$

10.3 Experiment

This experiment can be divided into two parts: in the field, you will gather soil samples of the upper soil layer using the Kopecki rings. The second part of the experiment will be done at HUNRE, where you will analyze the soil samples. A record sheet for this experiment can be found in Appendix E: Record sheets.

10.3.1 The field activities

The equipment and materials needed to perform this experiment can be seen in Table 10.1.

Table 10.1: The equipment and materials needed for taking a soil sample in the field

Equipment/material	Quantity	Purpose
Kopecki rings	4	Capturing of a soil sample
Steel hammer	1	Hammering down the Kopecki ring inside the soil
Small plank	1	To assist in hammering the Kopecki ring
Trowel	1	Erase soil around the sample
Scissors	1	Cutting away small roots

First read through all the steps before doing anything.

1. Remove about 5 cm from the top layer using a trowel. Try to disturb the soil below as little as possible. See also Figure 10.2.

Figure 10.2: Removing the topsoil layer.

2. Use a hammer and a small plank to hammer down the ring into the soil, as shown in Figure 10.3. Try to do this as straight and evenly as possible. Never wiggle the ring or hit it at one specific side.

Figure 10.3: Hammering the ring into the soil.

3. While hammering the ring into the ground, you can remove some of the soil around the ring to make it easier, as shown in Figure 10.4. Do not remove soil that is lower than the bottom of the ring, or you will risk disturbing the soil sample. Repeat the process of hammering and removing soil until the ring is completely filled with soil.

Figure 10.4: Removing some of the soil around the ring.

4. Once the ring is completely filled, you will have to make sure the top of the soil sample is nice and even. This is quite tricky to do since you have to disturb the soil sample as little as possible. First, you have to get rid of any excess soil above the top of the ring. Place your knife on the ring, making a cut into any soil that is above the top of the ring. Repeat this until you have made a grid of cuts across the top of the ring, as depicted in Figure 10.5. The cuts will have loosened the soil that is above the top of the ring. Gently sweep this excess soil away. Any roots sticking out can be snipped off with a pair of scissors.

Figure 10.5: Carefully cutting a grid into the soil that is sticking out above the top of the ring.

5. Once the top of the soil sample is contained within the ring, you can put the lid on, as shown in Figure 10.6.

Figure 10.6: Putting the lid on the ring, after having removed excess soil.

6. Clear away the remaining soil around the ring with the trowel. Now remove the soil below the bottom of the ring. Using the trowel, cut horizontally below the ring with sufficient distance between the cut and the ring, as shown in Figure 10.7

Figure 10.7: Cutting horizontally below the ring.

7. Very carefully lift the sample out of the ground and turn it over. Remove any excess soil using the same method as in step 4.
8. Once the bottom side is also trimmed, you can put a lid on this side as well. Put tape around the sample for securing the lids. On the tape write a number to identify the sample. In a log, write down the exact location, time, date, and person who took the sample.

10.3.2 The lab experiment

After capturing, the soil will be analyzed in the lab. The equipment and materials needed for this can be seen in Table 10.2.

Table 10.2: The equipment and materials needed for testing the soil sample in the lab

Equipment/material	Quantity	Purpose
Oven	1	Drying the soil samples.
Aluminum bowls	4	For placing the soil samples inside the oven
Sink	1	Saturating the soil samples with water

1. Take an aluminum bowl or some aluminum foil, just something you can place the sample on and that is ovenproof. Weigh this aluminum bowl or foil.
2. Carefully remove the lids from the rings and place the ring with the soil sample on the aluminum.
3. Make sure the sample remains undisturbed. Weight the sample, as shown in Figure 10.8, and compute the mass of the sample, including the ring.

Figure 10.8: Weighing the soil sample.

4. You are going to fully saturate the soil sample. You cannot just pour water over the sample; air would get trapped within the pores and the sample would not be able to be fully saturated. Therefore, you are going to saturate the sample from below. Place the sample in a bowl or box with edges at least as high as the ring. It does not matter what material the bowl or box is made of. Pour water into the bowl or box until the water level is 1 cm. The water will enter the sample from below. After some time, a couple of hours or so, you can increase the water level again to 2 cm. Again, after some time, increase to 3 cm, and finally

increase to 4 cm. The water level should be just below the edge of the soil sample, as shown in Figure 10.9. The capillary forces will make sure the sample will be fully saturated. This whole process may take a full 24 hours.

Figure 10.9: Saturating the soil sample from below.

5. When the soil is fully saturated, carefully take the sample out of the bowl or box with water. Dry off the outside of the ring, so that you do not measure any extra water. Put it on the aluminum and weigh the fully saturated sample, as shown in Figure 10.10.

Figure 10.10: Weighing the soil sample after it has been fully saturated.

6. Put the sample together with the aluminum in the oven for 24 hours at 105 °C, as shown in Figure 10.11. This will remove all moisture from the sample. Because the soil will be very dry, the sample will be very brittle and fragile. The aluminum will catch any particles that fall off.

Figure 10.11: Putting the saturated soil samples in a 105 °C oven to dry for 24 hours.

7. After 24 hours in the oven, take the sample from the oven and weigh it again, as shown in Figure 10.12. Be careful since the sample and the ring will obviously be hot.

Figure 10.12: Weighing the sample after it has dried in the oven.

8. Remove the soil sample from the ring and dry it completely. Weigh the ring, as shown in Figure 10.13. Remember to also weigh the aluminum if needed.

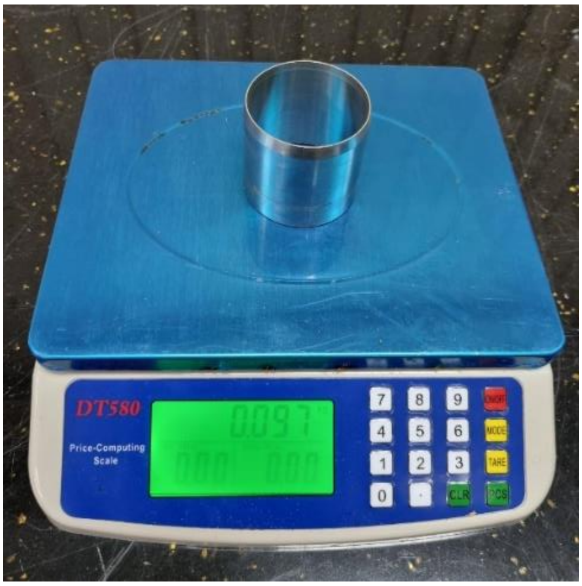


Figure 10.13: Weighing the ring.

10.4 Data processing

This can be performed during the lab part. You do not have to wait until you have measured everything to make a start. Pay close attention to the units.

1. Compute the dry bulk density of the soil using equation 2.
2. Compute the porosity of the soil sample according to equation 1.
3. Compute the volumetric soil moisture content according to equation 3.
4. Compute the gravimetric soil moisture content using equation 5.

An example of the data processing is given below. This example can also be found in a separate Excel.

The volume of the Kopecki ring is by definition 100 cm^2. We assume the density of water is 1.0 g/cm^3. The mass of the soil sample is 161 g. After saturating the soil sample, the sample has a mass of 189 g. After drying the sample in the oven for 24 hours at 105 °C the sample has a mass of 145 g. Thus, the dry bulk density of the sample is:

$$\rho = \frac{m_{dry\ soil}}{V_{total}} = \frac{145}{100} = 1.45\ \mathrm{g/cm^3}$$

The water in the saturated sample has a mass of 189 – 145 = 44 g, which equals 44 cm^3. The porosity of the sample is thus:

$$n = \frac{V_{pores}}{V_{total}} = \frac{44}{100} = 0.44$$

In the initial soil sample there was 161 – 145 = 16 g of water present. This equals to 16 cm³ of water. The volumetric water content of the sample thus is:

$$\phi = \frac{V_{water}}{V_{total}} = \frac{16}{100} = 0.16$$

The gravimetric water content of the soil is thus:

$$w = \frac{\phi}{\rho} = \frac{0.16}{1.45} = 0.11\ \mathrm{cm}^3/\mathrm{g}$$

Note that students should carefully pay attention to what mass they are measuring. The mass of the Kopecki rings and aluminum should always be kept in mind.

10.5 Reflective questions

1. If the soil contains a lot of organic matter, we dry the soil sample at 70 °C for 48 hours. Why is that?

As to not burn the organic material, which would reduce the mass of the dry soil. Because the drying temperature is lower, the duration of drying has to be increased to ensure completely dry soil.

2. It is important not to disturb the soil when taking a sample. Do you think you were able to do this? If not, how will this have influenced the results?

If done right, you can take a sample without disturbing the soil too much. Depends on how the students think the experiment went.

3. Macropores are very hard to measure using this method and thus often ignored. Therefore, how does the actual average porosity of the soil compare to the measured soil porosity?

The actual porosity of the soil will be a bit higher since the macropores are not taken into account.

10.6 References

Veenstra, M., White, D. J., & Schaefer, V. R. (2005). Rapid field testing techniques for determining soil density and water content. In *Proceedings of the 2005 Mid-Continent Transportation Research Symposium*. Ames, IA. Iowa State University (pp. 1-13).

11. Measuring precipitation and evaporation

This manual contains instructions for two separate experiments: measuring precipitation and measuring evaporation. Since they are both very simple and since you need the precipitation data for the evaporation experiment, these are grouped.

11.1 Introduction

11.1.1 Precipitation and evaporation

Precipitation and evaporation are some of the most important processes in hydrology and have long been the focus of scientific research. They are relevant for many different fields within water management, like flood control, irrigation, erosion, cloud formation, aridification, the energy balance, etc. Also, for any hydrological system precipitation and evaporation are some of the most important parameters. Even the simplest models often incorporate them, since they are so essential.

It may thus come as no surprise that many efforts have been made to measure these two fluxes. A wide range of techniques and methods have been developed over time, ranging from simple and easy to perform to incredibly complex and requiring state-of-the-art technology.

11.1.2 Learning goals

In this experiment, you will learn two simple techniques to measure precipitation and evaporation. There are many kinds of evaporation, but in this experiment, the focus will be on open-water evaporation. There are also multiple kinds of precipitation, but we focus on rainfall, by far the most common form of evaporation, especially in Vietnam. You will learn how to measure the open water evaporation using an evaporation bucket. You will learn how to measure the rainfall using a bottle and funnel. You will also learn how to process the data from these two experiments to compute the evaporation and rainfall.

11.2 Theory

11.2.1 Evaporation

Measuring the actual evaporation for an open water body is pretty straightforward. A container or bucket with a surface area of about 1 m^2 is placed on the ground. The container is filled with water up to a height of 20 cm. Every morning the water level is measured. The drop in water level divided by the time interval gives the rate of open water evaporation. Of course, precipitation also needs to be taken into account

11.2.2 Rainfall

Measuring rainfall cannot be done using a bucket, because you want to exclude the effects of evaporation. The most common method for measuring rainfall is to use a funnel and bottle, as shown in Figure 11.1. Theoretically, a larger funnel will lead to a smaller measurement error. A common size for the area of the funnel is 100 - 200 cm^2. To minimize the effects of wind, the rims of the funnel need to be sharp. You also need to make sure that there is no loss from splashing during heavy rain. You can make the precipitation collector using a plastic water bottle and place the funnel on top. The water level inside the bottle should be measured every morning.

Figure 11.1: Measuring the rainfall

In order to calculate the precipitation, equation 11.1 can be used.

$$P = \frac{V_{bottle}}{A_{funnel} * \Delta t} \tag{11.1}$$

where:

P	precipitation
V_{bottle}	volume of the bottle
A_{funnel}	area of the opening of the funnel
Δt	duration of the experiment

If a measuring cup is not available, the volume of the bottle can be computed using equation 11.2.

$$V_{bottle} = \Delta h_{bottle} * A_{bottle} \tag{11.2}$$

where:

A_{bottle}	cross-sectional area of the bottle
Δh_{bottle}	change in water height in the bottle

11.3 Experiment

The equipment and materials needed to perform this experiment can be found in Table 11.1. A record sheet for this experiment can be found in Appendix E: Record sheets.

Table 11.1: The equipment and materials needed to measure open water evaporation and the precipitation

Equipment/material	Quantity	Purpose
Bottle	1	Measuring rainwater
Funnel	1	Collecting rainwater into the bottle
Container	1	Measuring open-water evaporation
Measuring tape	1	Measuring depths and diameters

First read through all the steps carefully before doing anything.

1. Place a bucket or container outside. Preferably the material of the bucket or container is not very heat conductive. The bucket should be exposed to the sun.
2. Measure the area of the bucket or container.
3. Fill it with about 20 cm of water. Ideally, the water is somewhere between 20 – 25 °C.
4. Place a bottle with a funnel inserted into the opening outside. Do not place the bottle with the funnel next to a building; an open area is best.
5. Measure the area of the opening of the funnel and the cross-sectional area of the bottle.
6. Every day at 08:00 you measure the water depth in the bucket and the bottle.

11.4 Data processing

1. Compute the daily precipitation using equations 11.1 and 11.2.
2. Compute the daily evaporation, taking into account the precipitation of the previous day.

An example of the data processing can be seen below. This example can also be found in an Excel file.

The funnel has an area of 0.3 m^3 and the bottle has an area of 0.015 m^2. The measured water depths in the evaporation bucket and the bottle can be seen in Table 11.2.

Table 11.2: The measured water depth in the evaporation bucket and the bottle (rain meter). Each measurement is done at 08:00 on the corresponding day.

What	Day 1	Day 2	Day 3	Day 4	Day 5
Water depth rain meter [mm]	0	51	77	104	104
Water depth in evaporation bucket [mm]	150	145	144	142	137

To compute the rainfall on day 1, the difference in water height in the bottle between day 1 and day 2 has to be computed. This difference is 51 – 0 = 51 mm. Multiplying by the cross-sectional area of the bottle, the added volume of the bottle can be found, according to equation 11.2:

$$V_{bottle} = \Delta h_{bottle} * A_{bottle} = 0.051 \cdot 0.015 = 0.000765\, m^3 = 0.765\, l.$$

Dividing this volume by the area of the funnel will give the precipitation, according to equation 11.1.

$$P = \frac{V_{bottle}}{A_{funnel} * \Delta t} = \frac{0.000765}{0.3 \cdot 1} = 0.00255\, m/day = 2.55\, mm/day$$

So, on day 1, the precipitation was 2.55 mm. This can be repeated for the other days.

For the evaporation on day 1, this can simply be computed as the difference in water level between day 1 and day 2 in the evaporation bucket plus the rainfall of day 1. Thus, the evaporation for day 1 is 150 – 145 + 2.55 = 7.55 mm/day. This can be repeated for all other days. The results can be seen in Table 11.3.

Table 11.3: The measured precipitation and evaporation per day. Note how you cannot measure the evaporation and precipitation of day 5, since that would require measurements on day 6.

What	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**
Precipitation [mm]	2.55	1.3	1.35	0	-
Evaporation [mm]	7.55	2.3	3.35	5	-

11.5 Reflective questions

1. Do you think the measured open water evaporation is comparable to the open water evaporation from a sinkhole? Why/why not?

Not entirely. The sinkhole is quite deep into the ground and thus sheltered from the wind. This will cause the open water evaporation of the sinkhole to be a bit lower than the open water evaporation from the evaporation bucket.

Also, if the evaporation bucket is placed in the sun it will heat up, increasing the evaporation rate. The heat capacity of the water in the evaporation bucket will also be lower since there is simply less of it, thus it will heat up quicker than the water in the sinkhole. This again will cause the open water evaporation from the sinkhole to be a bit lower than the open water evaporation from the evaporation bucket.

2. Why is it preferred to measure the volume in the rain meter with a measuring cup instead of with the area?

Using a measuring cup is much more accurate. The cross-sectional area of a bottle is hard to measure and usually not constant. The bottom of a bottle often is also different. In short, the bottle is not a perfect cylinder, although this is assumed with this method. Therefore, a measuring cup is preferred.

3. In the dry season it can still rain, but this is usually a very small amount. Is that a problem?

A small amount of rain may not be measured very accurately, because some of the water will stay on the funnel instead of flowing into the bottle. For small amounts of rain, this can lead to significant errors. Also, small rain events often have small rain droplets, and these are more susceptible to the wind.

12. Integral assignment

12.1 Introduction

The experiments described in this manual all measure certain aspects of the hydrological cycle. But in water management, we are rarely interested in just a single component of a system. To understand a system, every component of the system needs to be taken into account.

12.2 Assignment

This is not an experiment, but an assignment. The assignment considers the northern sinkhole, shown in Figure 12.1. Your assignment is:

Make a water balance of the sinkhole and describe how you would measure its components.

Think about the different contributions and explain how you would measure them. Note that this is a theoretical question, so no real experiments have to be performed, only a written explanation is expected. Support your answer with sketches. Try to combine the knowledge and experience from the fieldwork to identify the fluxes and how you would measure them.

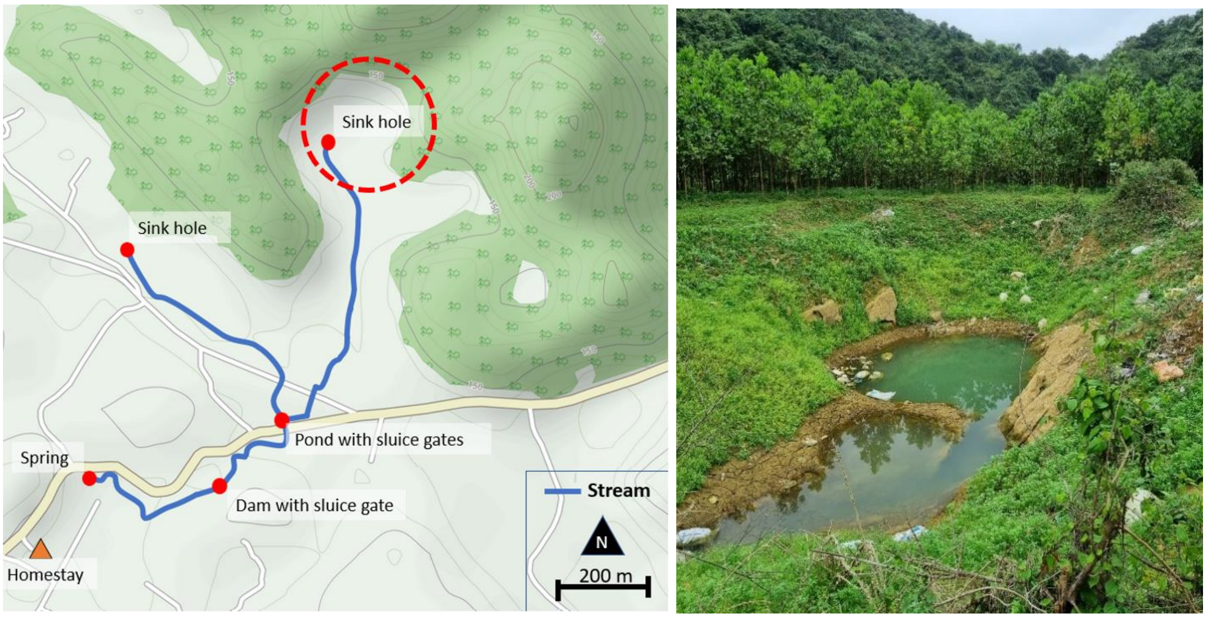


Figure 12.1: The sinkhole of interest

Below is given what would more or less be expected of the students. Other answers are possible as long as they are based on solid arguments.

Each of the flow components can be categorized as an incoming or outgoing flux. The components either add water to the system or remove water from the system, as shown in Figure 12.2.

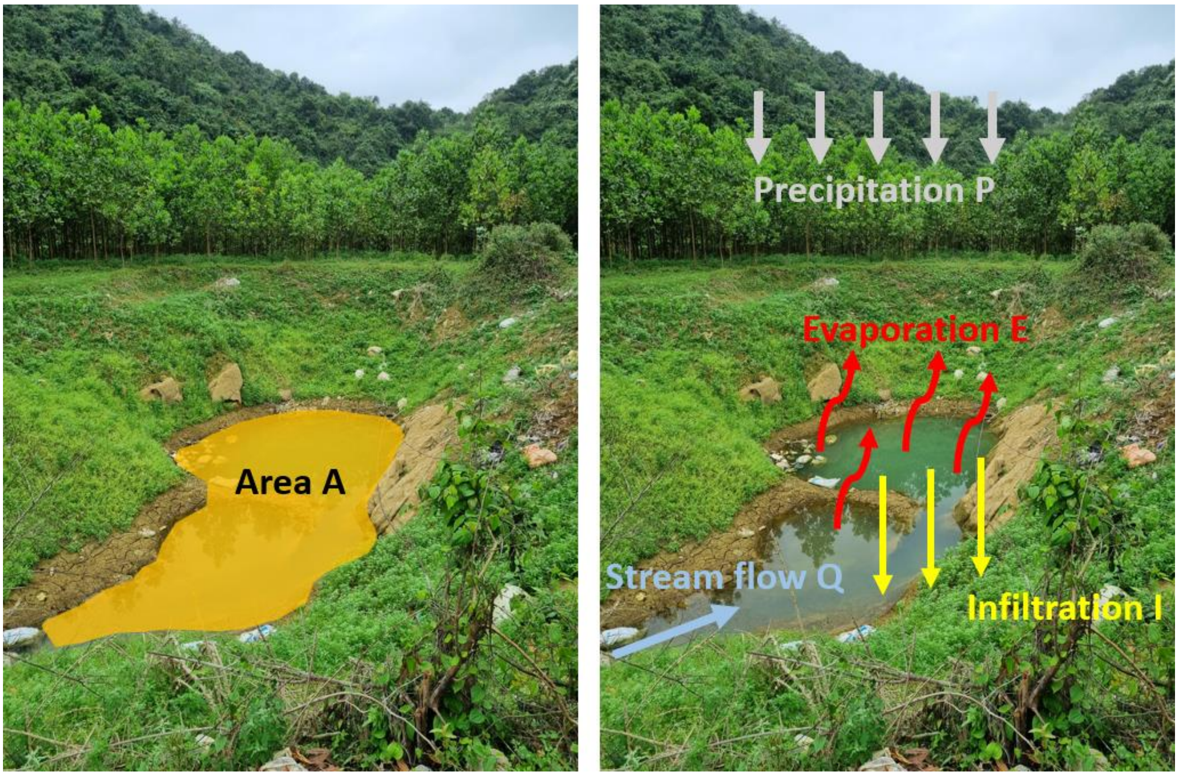


Figure 12.2: The different fluxes of the sinkhole

Equation 12.1 gives a complete water balance for an arbitrary surface water body.

$$\frac{dS_w}{dt} = (P - E_o - L)A_w + Q_s + Q_r + Q_{g,w} + Q \qquad (12.1)$$

where:

S_w	Storage of water in the sinkhole
t	time
E_o	open water evaporation
L	infiltration
Q_s	overland flow to the surface water
Q_r	subsurface flow to the surface water
Q_{gw}	groundwater flow to the surface water
Q	discharge
A	area of the surface water
P	precipitation

We now assume the following

- We will neglect the change in water storage inside the sinkhole. In other words, we assume that the water level inside the sinkhole stays constant.
- We will neglect inflow to the sinkhole coming directly from groundwater or the subsurface.
- We assume there is no direct overland flow to the sinkhole.

Equation 12.1 will thus simplify as follows.

$$\frac{dS_w}{dt} = (P - E_o - L)A_w + Q_s + Q_r + Q_{g,w} + Q$$

$$0 = (P - E_o - L)A_w + 0 + 0 + 0 + Q$$

$$-Q = (\mathrm{P} - E_o - L)A_w$$

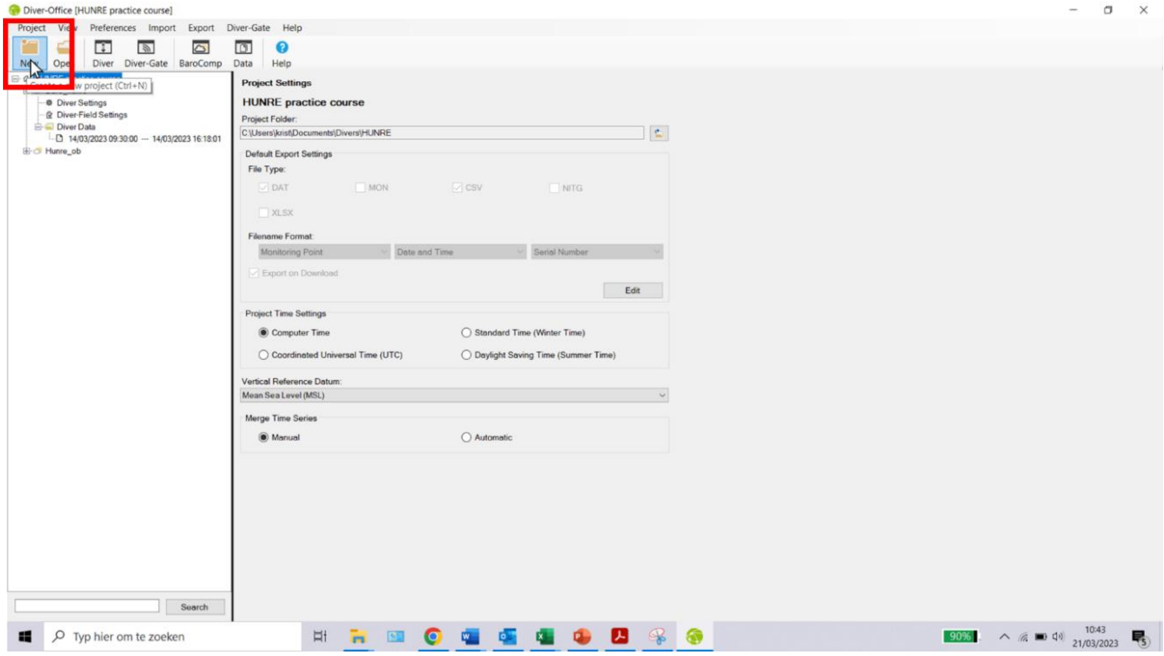
$$0 = \frac{Q}{A_w} + P - E_o - L$$

The discharge from the stream Q can best be measured using a V-notched weir. The precipitation can be measured using a rain meter (bottle and funnel). The evaporation can be measured using an evaporation bucket and the precipitation data. Seepage could be measured using a seepage meter, but this is quite tricky. Since all other parameters in the equation are known, the seepage can also be deducted; it is the only unknown.

Appendix A: Diver Manual

a. Setting up the diver

1. Download the Diver-Office program from the website of Van Essen Instruments: https://www.vanessen.com/products/software/diver-office/
2. Open the program and create a new project:



Project Settings

HUNRE practice course

Project Folder: C:\Users\krist\Documents\Divers\HUNRE

Default Export Settings

File Type: ☑ DAT ☐ MON ☑ CSV ☐ NITG ☐ XLSX

Filename Format: Monitoring Point | Date and Time | Serial Number

☑ Export on Download

Project Time Settings

● Computer Time ○ Standard Time (Winter Time)

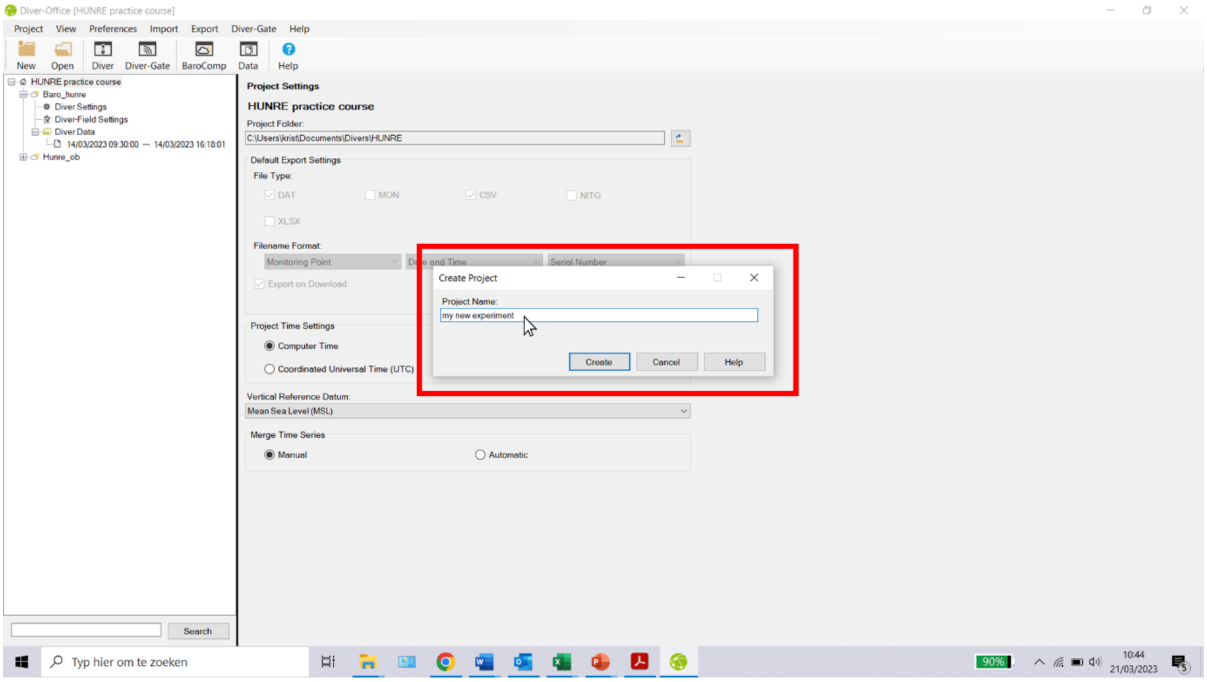
○ Coordinated Universal Time (UTC) ○ Daylight Saving Time (Summer Time)

Vertical Reference Datum: Mean Sea Level (MSL)

Merge Time Series

● Manual ○ Automatic

3. Give a name to your new project:

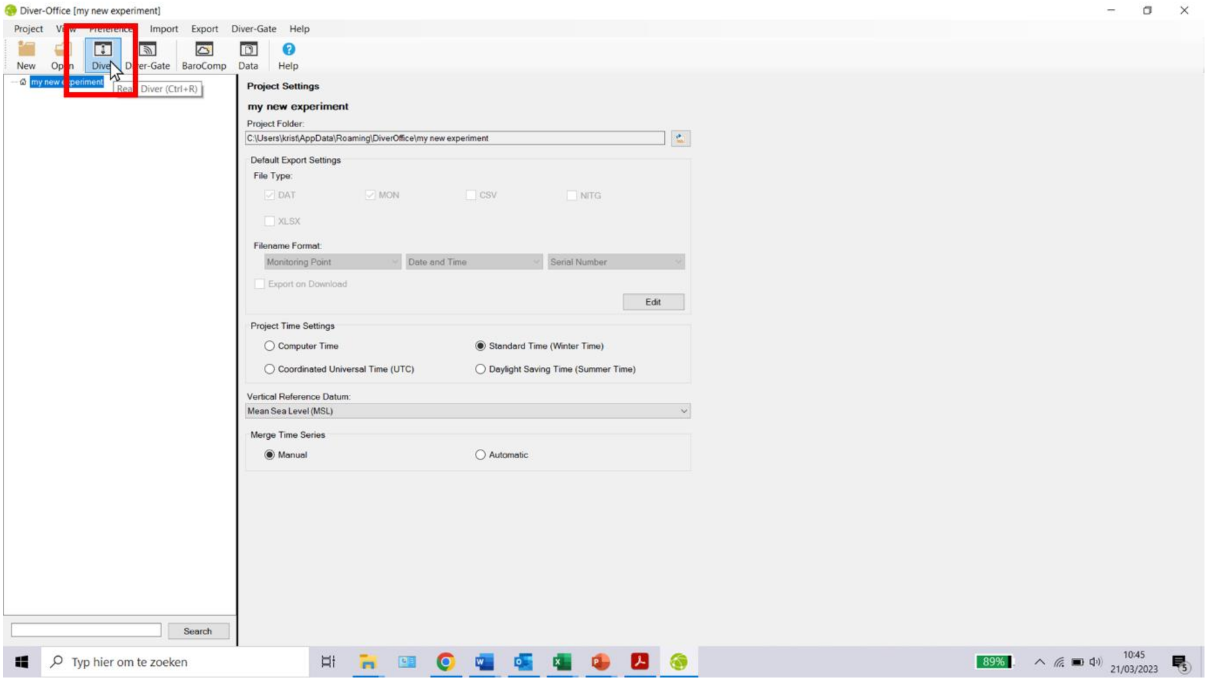


Create Project

Project Name: my new experiment

4. Attach the USB Reading Unit to your PC and press the Diver into the unit:

5. Inside Diver-Office click on “Diver” to read out the diver



Project Settings

my new experiment

Project Folder: C:\Users\krist\AppData\Roaming\DiverOffice\my new experiment

Default Export Settings

File Type: ☑ DAT ☑ MON ☐ CSV ☐ NITG ☐ XLSX

Filename Format: Monitoring Point | Date and Time | Serial Number

☐ Export on Download

Project Time Settings

○ Computer Time ● Standard Time (Winter Time)

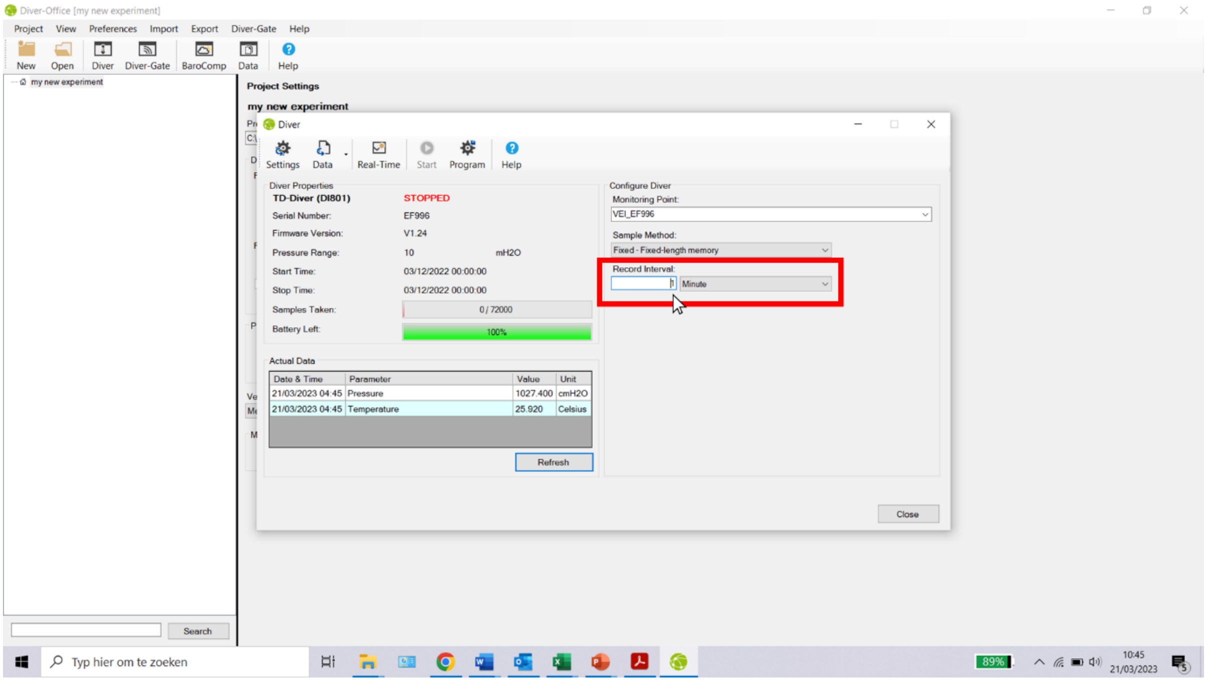
○ Coordinated Universal Time (UTC) ○ Daylight Saving Time (Summer Time)

Vertical Reference Datum: Mean Sea Level (MSL)

Merge Time Series

● Manual ○ Automatic

6. Now a pop-up screen shows up in which you can change the settings of the diver. Make sure the record interval is set to 1 minute.



Diver Properties

TD-Diver (DI801) STOPPED

Serial Number: EF996

Firmware Version: V1.24

Pressure Range: 10 mH2O

Start Time: 03/12/2022 00:00:00

Stop Time: 03/12/2022 00:00:00

Samples Taken: 0 / 72000

Battery Left: 100%

Actual Data

Date & Time	Parameter	Value	Unit
21/03/2023 04:45	Pressure	1027.400	cmH2O
21/03/2023 04:45	Temperature	25.920	Celsius

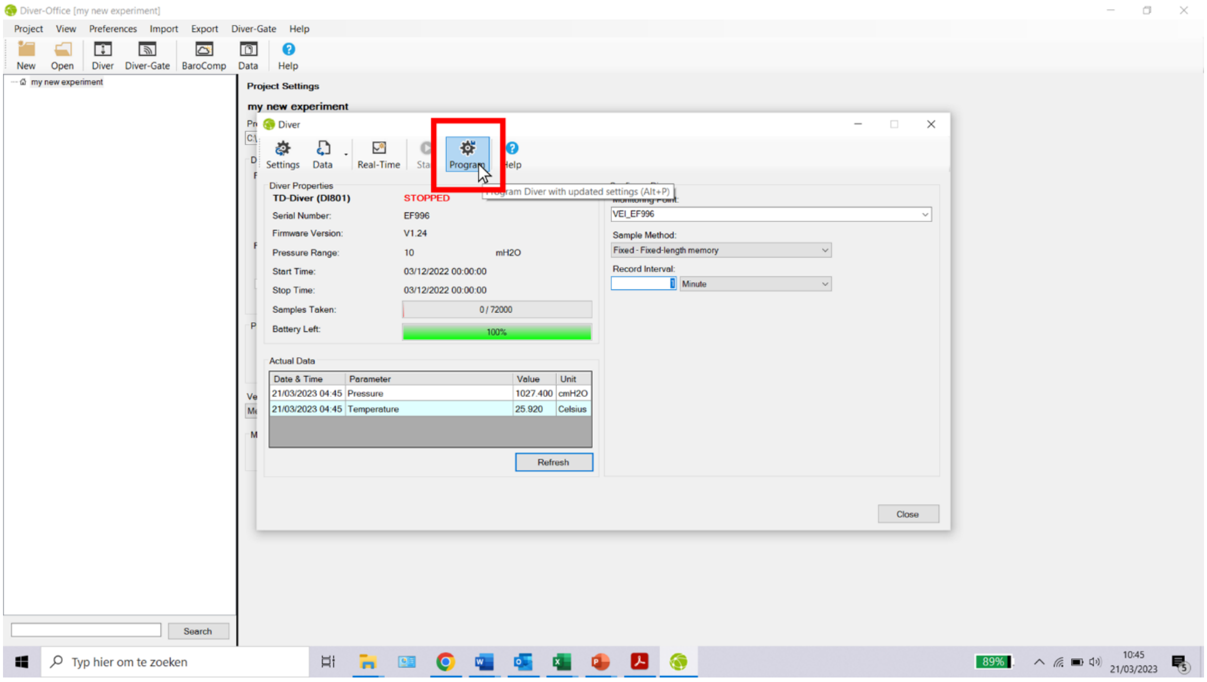
Configure Diver

Monitoring Point: VEI_EF996

Sample Method: Fixed - Fixed-length memory

Record Interval: 1 Minute

7. To apply your changes click on "Program".



Diver Properties

TD-Diver (DI801) STOPPED

Serial Number: EF996

Firmware Version: V1.24

Pressure Range: 10 mH2O

Start Time: 03/12/2022 00:00:00

Stop Time: 03/12/2022 00:00:00

Samples Taken: 0 / 72000

Battery Left: 100%

Actual Data

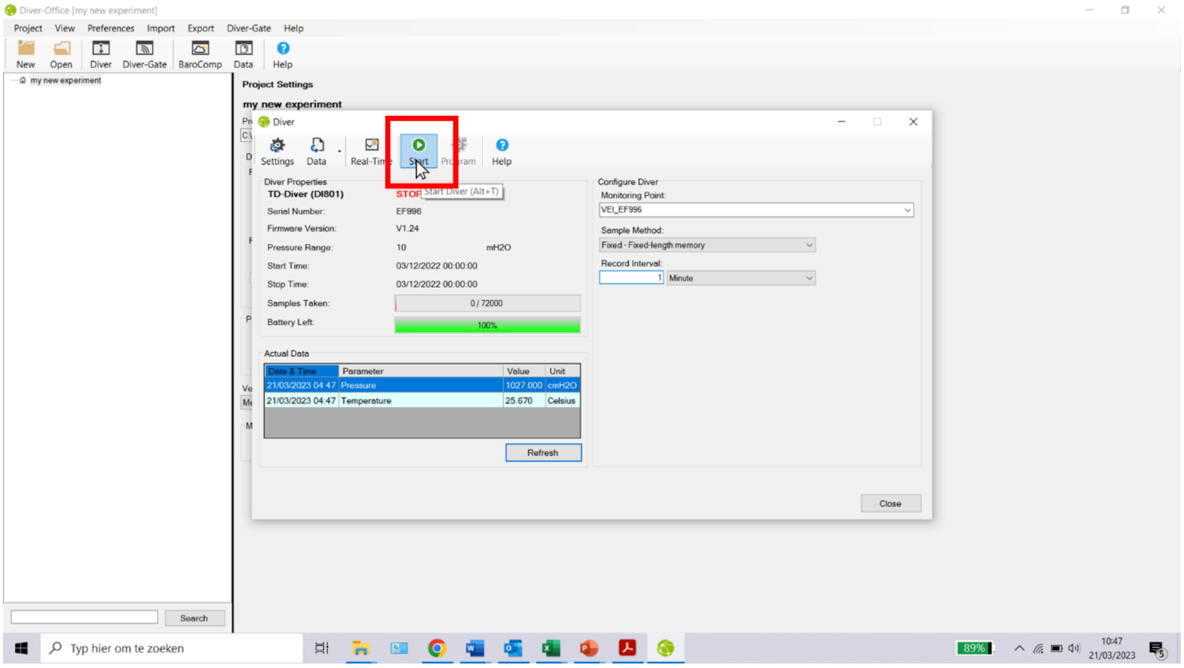
Date & Time	Parameter	Value	Unit
21/03/2023 04:45	Pressure	1027.400	cmH2O
21/03/2023 04:45	Temperature	25.920	Celsius

Monitoring Point: VEI_EF996

Sample Method: Fixed - Fixed-length memory

Record Interval: 1 Minute

8. For the diver to make measurements you need to click on “Start”.



Diver Properties

TD-Diver (DI801) STOP

Serial Number: EF996

Firmware Version: V1.24

Pressure Range: 10 mH2O

Start Time: 03/12/2022 00:00:00

Stop Time: 03/12/2022 00:00:00

Samples Taken: 0 / 72000

Battery Left: 100%

Configure Diver

Monitoring Point: VEI_EF996

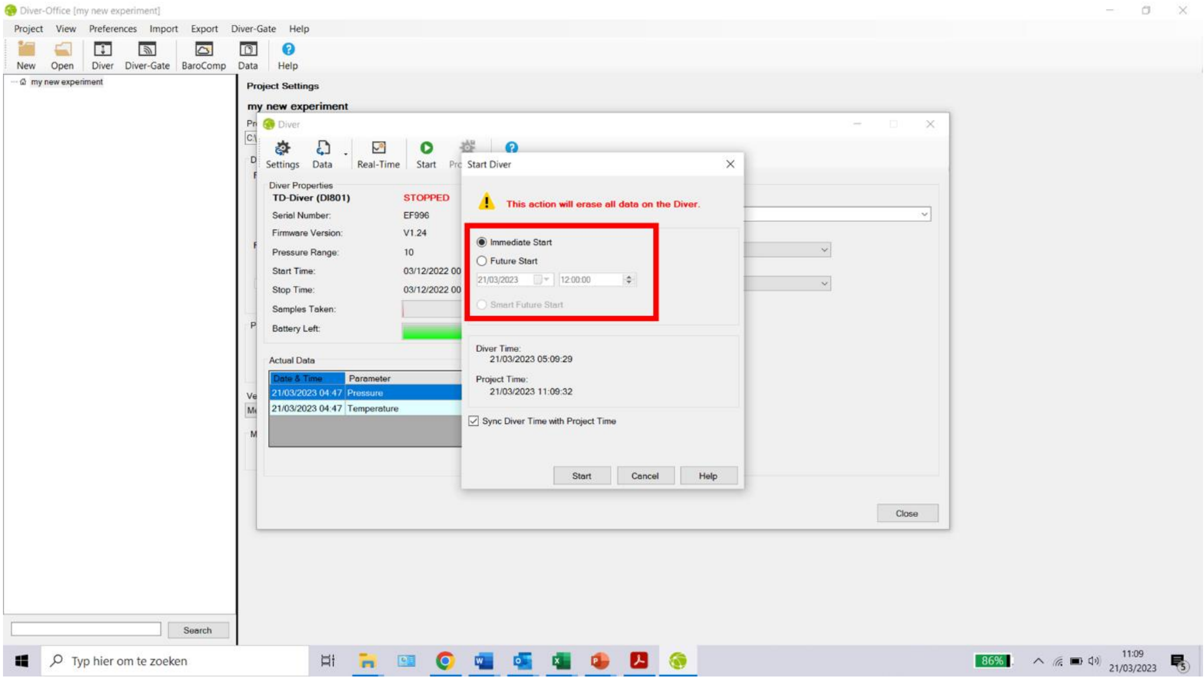
Sample Method: Fixed - Fixed-length memory

Record Interval: 1 Minute

Actual Data

Date & Time	Parameter	Value	Unit
21/03/2023 04:47	Pressure	1027.000	cmH2O
21/03/2023 04:47	Temperature	25.670	Celsius

9. In the following screen you can either choose to begin measuring immediately or to start at a specific date and time.



Diver Properties

TD-Diver (DI801) STOPPED

Serial Number: EF996

Firmware Version: V1.24

Pressure Range: 10

Start Time: 03/12/2022 00

Stop Time: 03/12/2022 00

Start Diver

This action will erase all data on the Diver.

● Immediate Start

○ Future Start

21/03/2023 12:00:00

○ Smart Future Start

Diver Time:
21/03/2023 05:09:29

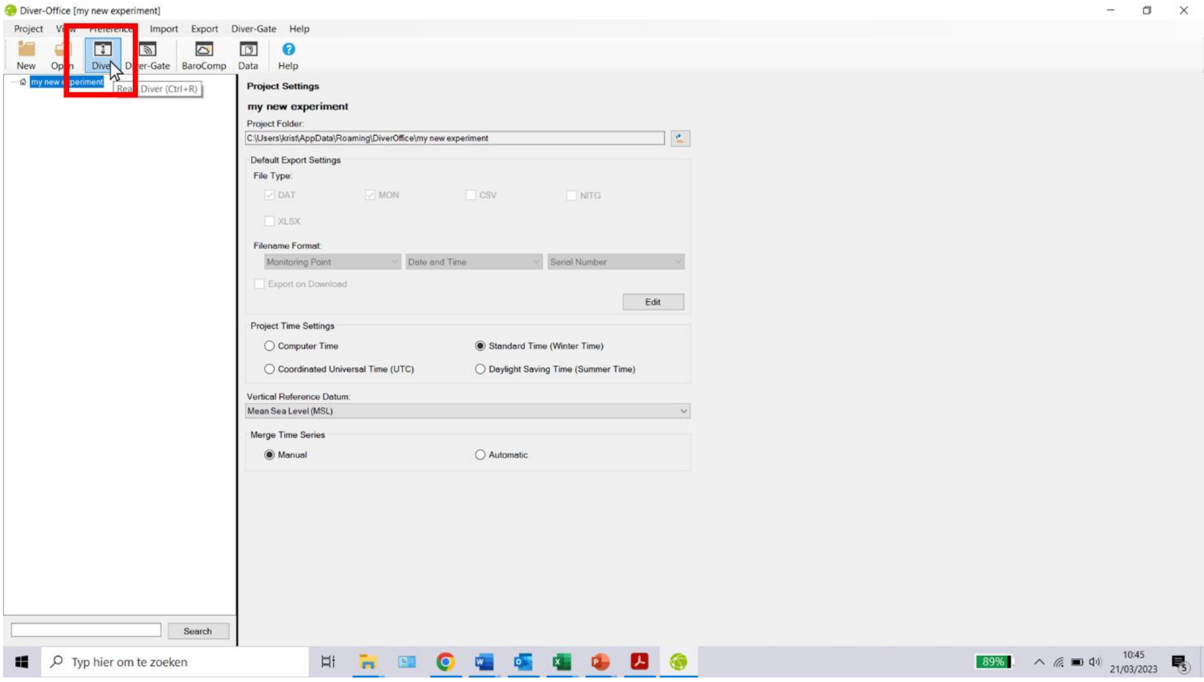
Project Time:
21/03/2023 11:09:32

☑ Sync Diver Time with Project Time

10. The diver is now ready to use.

b. Download data from the diver after measurements

1. Open your project inside Diver-Office and attach the diver again to your PC using the USB connector.
2. Inside Diver-Office click on “Diver” to read out the diver



Project Settings

my new experiment

Project Folder: C:\Users\krist\AppData\Roaming\DiverOffice\my new experiment

Default Export Settings

File Type: ☑ DAT ☑ MON ☐ CSV ☐ NITG ☐ XLSX

Filename Format: Monitoring Point, Date and Time, Serial Number

☐ Export on Download

Project Time Settings

○ Computer Time ● Standard Time (Winter Time)

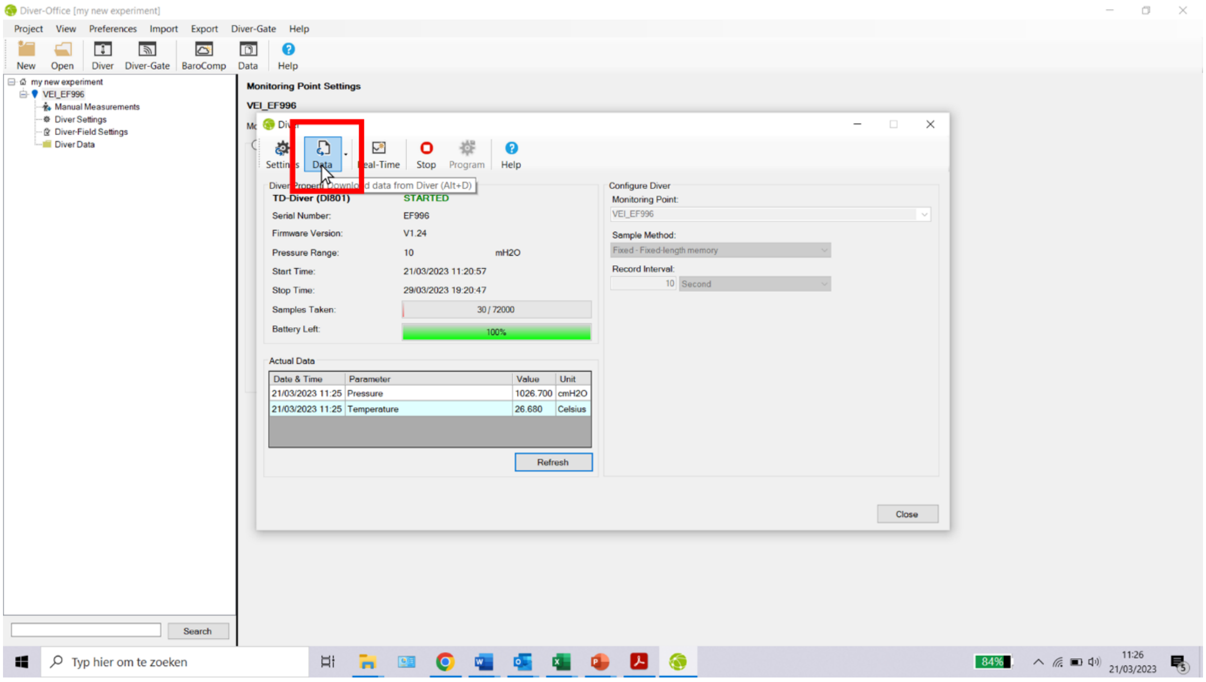
○ Coordinated Universal Time (UTC) ○ Daylight Saving Time (Summer Time)

Vertical Reference Datum: Mean Sea Level (MSL)

Merge Time Series

● Manual ○ Automatic

3. Now in the pop-up screen click on “Data” to download the data from the diver.



Monitoring Point Settings

VEI_EF996

Diver Properties

TD-Diver (DI801) STARTED

Serial Number: EF996

Firmware Version: V1.24

Pressure Range: 10 mH2O

Start Time: 21/03/2023 11:20:57

Stop Time: 29/03/2023 19:20:47

Samples Taken: 30 / 72000

Battery Left: 100%

Actual Data

Date & Time	Parameter	Value	Unit
21/03/2023 11:25	Pressure	1026.700	cmH2O
21/03/2023 11:25	Temperature	26.680	Celsius

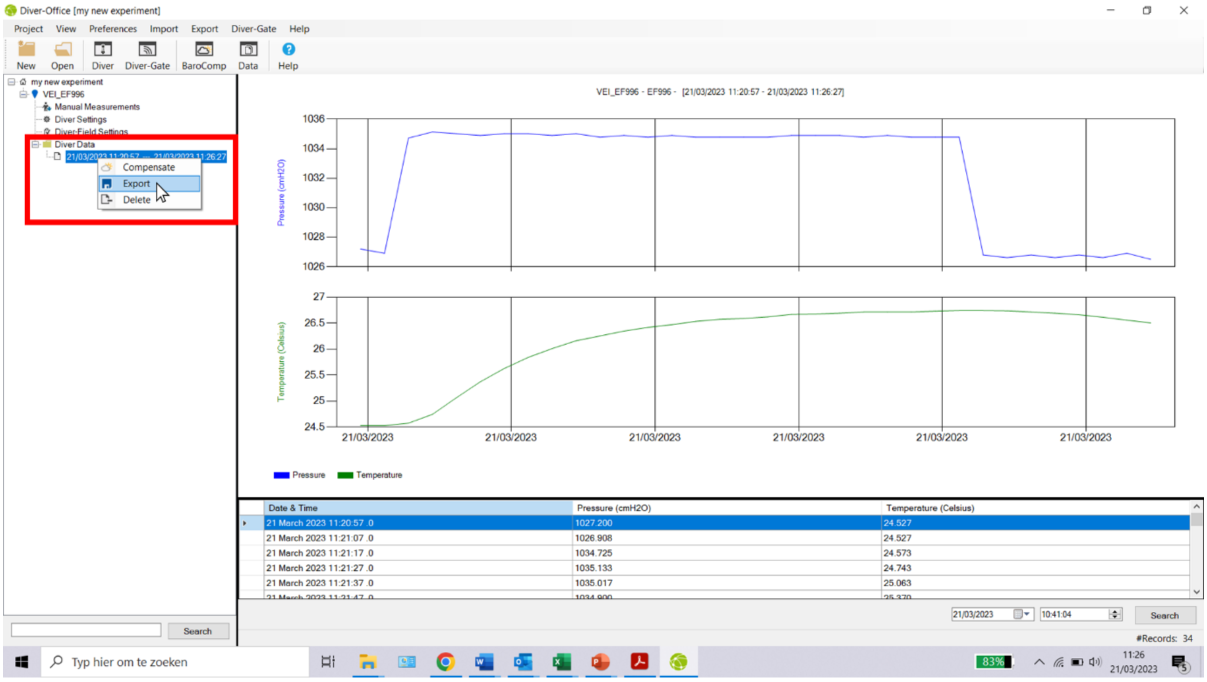
Configure Diver

Monitoring Point: VEI_EF996

Sample Method: Fixed - Fixed-length memory

Record Interval: 10 Second

4. In the following screen the measurements are presented in graphs. On the left side, you will find a folder called “Diver Data”. Inside this folder, you can find the measurements. Right-click on the measurement file and click on Export.

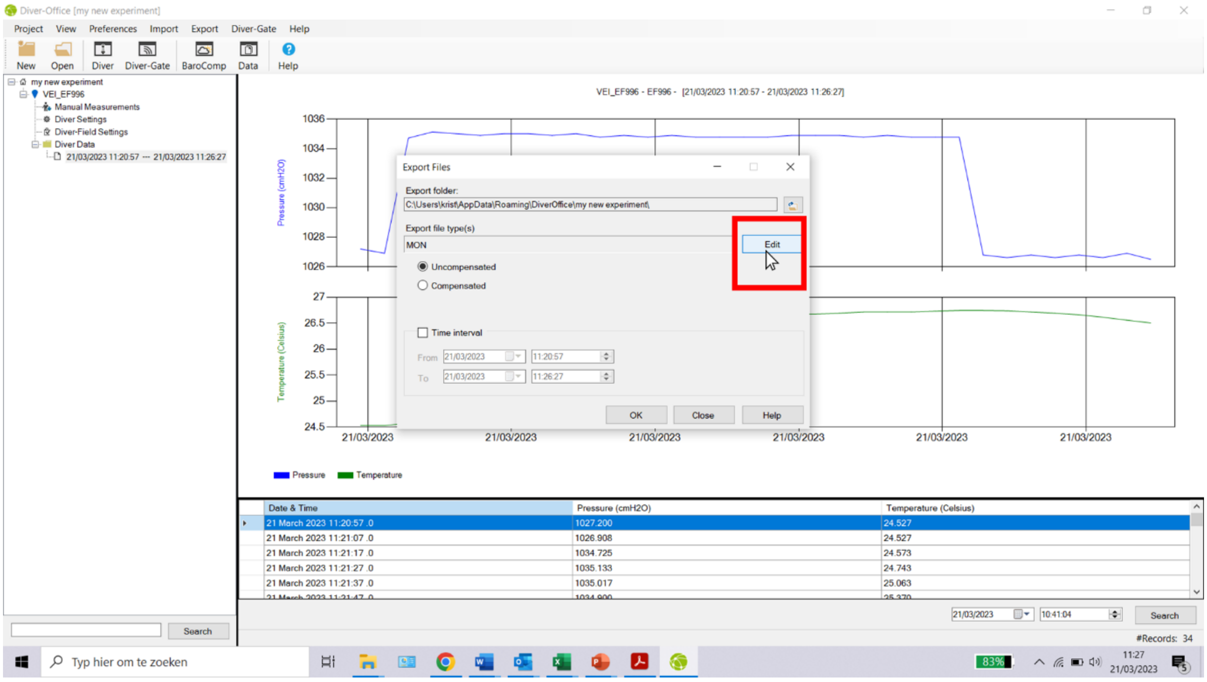


Date & Time	Pressure (cmH2O)	Temperature (Celsius)
21 March 2023 11:20:57 .0	1027.200	24.527
21 March 2023 11:21:07 .0	1026.908	24.527
21 March 2023 11:21:17 .0	1034.725	24.573
21 March 2023 11:21:27 .0	1035.133	24.743
21 March 2023 11:21:37 .0	1035.017	25.063

21/03/2023 10:41:04 Search

#Records: 34

5. Inside the pop-up screen you need to make sure the file type is set to CSV. Click on Edit to adjust the file type.



Export folder: C:\Users\krist\AppData\Roaming\DiverOffice\my new experiment\

Export file type(s): MON

● Uncompensated

○ Compensated

☐ Time interval

From 21/03/2023 11:20:57

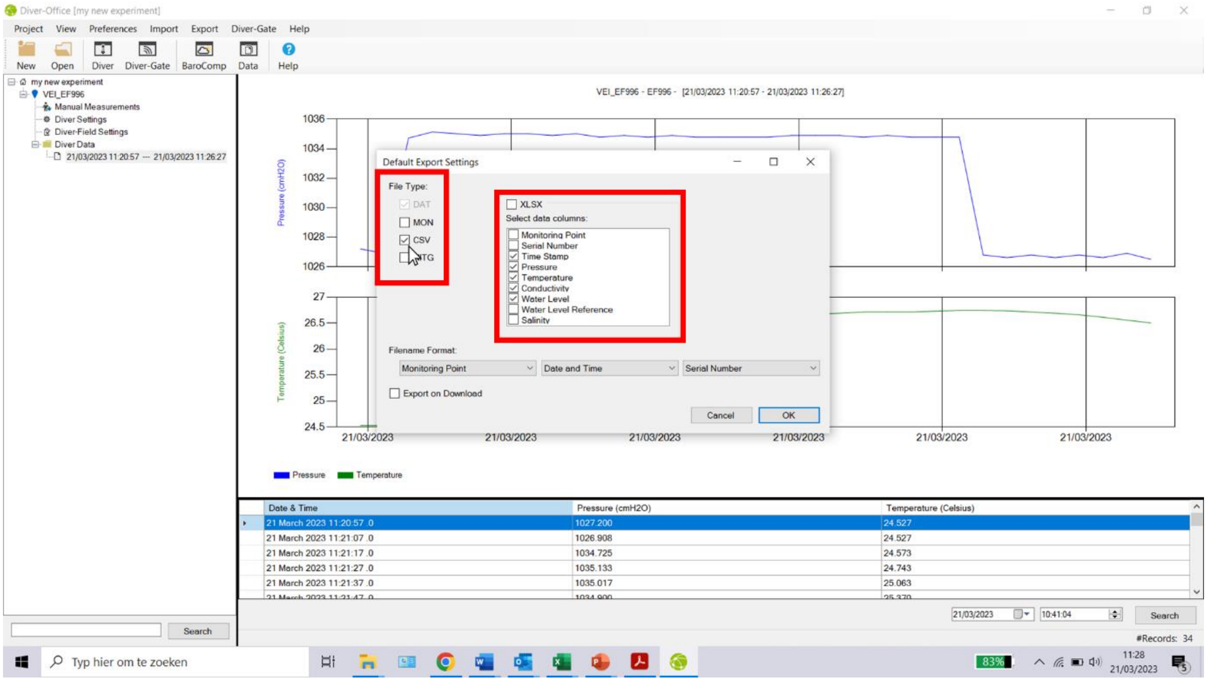
To 21/03/2023 11:26:27

Date & Time	Pressure (cmH2O)	Temperature (Celsius)
21 March 2023 11:20:57 .0	1027.200	24.527
21 March 2023 11:21:07 .0	1026.908	24.527
21 March 2023 11:21:17 .0	1034.725	24.573
21 March 2023 11:21:27 .0	1035.133	24.743
21 March 2023 11:21:37 .0	1035.017	25.063

21/03/2023 10:41:04 Search

#Records: 34

6. Change the Export Settings according to the image below.



Default Export Settings

File Type:
☑ DAT
☐ MON
☑ CSV
☐ MTG

☐ XLSX

Select data columns:
☐ Monitoring Point
☐ Serial Number
☑ Time Stamp
☑ Pressure
☑ Temperature
☑ Conductivity
☑ Water Level
☐ Water Level Reference
☐ Salinity

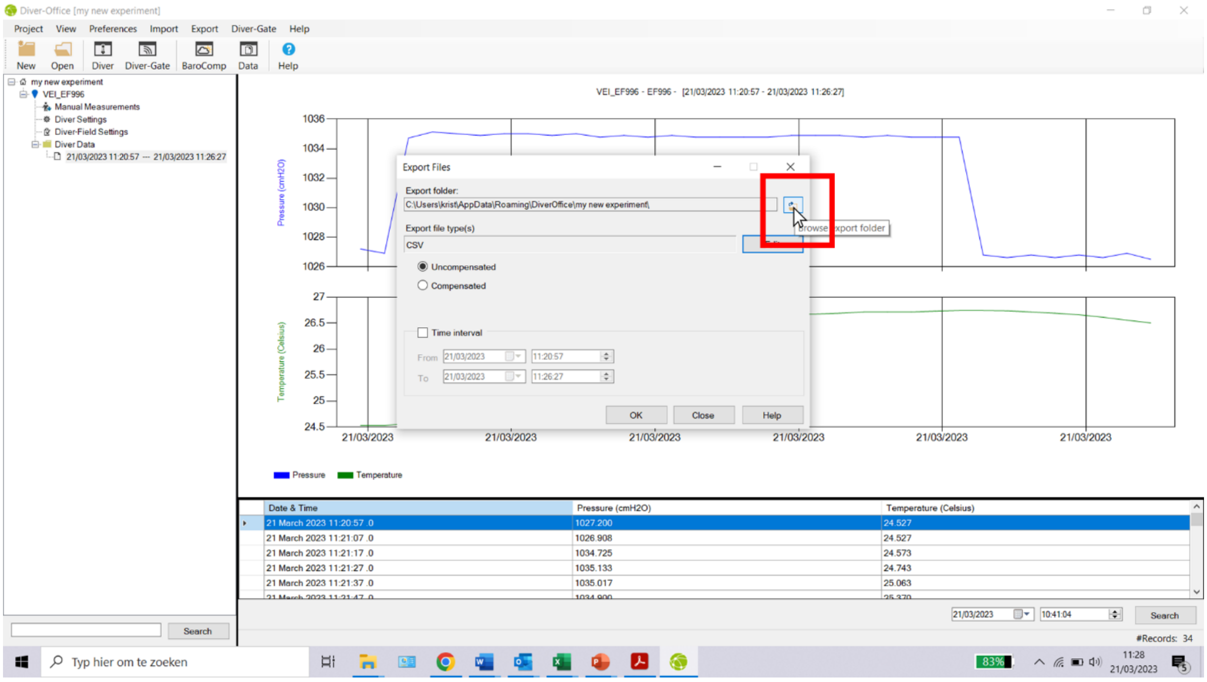
Filename Format: Monitoring Point | Date and Time | Serial Number

☐ Export on Download

Cancel | OK

Date & Time	Pressure (cmH2O)	Temperature (Celsius)
21 March 2023 11:20:57 .0	1027.200	24.527
21 March 2023 11:21:07 .0	1026.908	24.527
21 March 2023 11:21:17 .0	1034.725	24.573
21 March 2023 11:21:27 .0	1035.133	24.743
21 March 2023 11:21:37 .0	1035.017	25.063

7. Adjust the Export folder to your desired location and press OK.



Export Files

Export folder: C:\Users\krist\AppData\Roaming\DiverOffice\my new experiment\

Export file type(s): CSV

● Uncompensated
○ Compensated

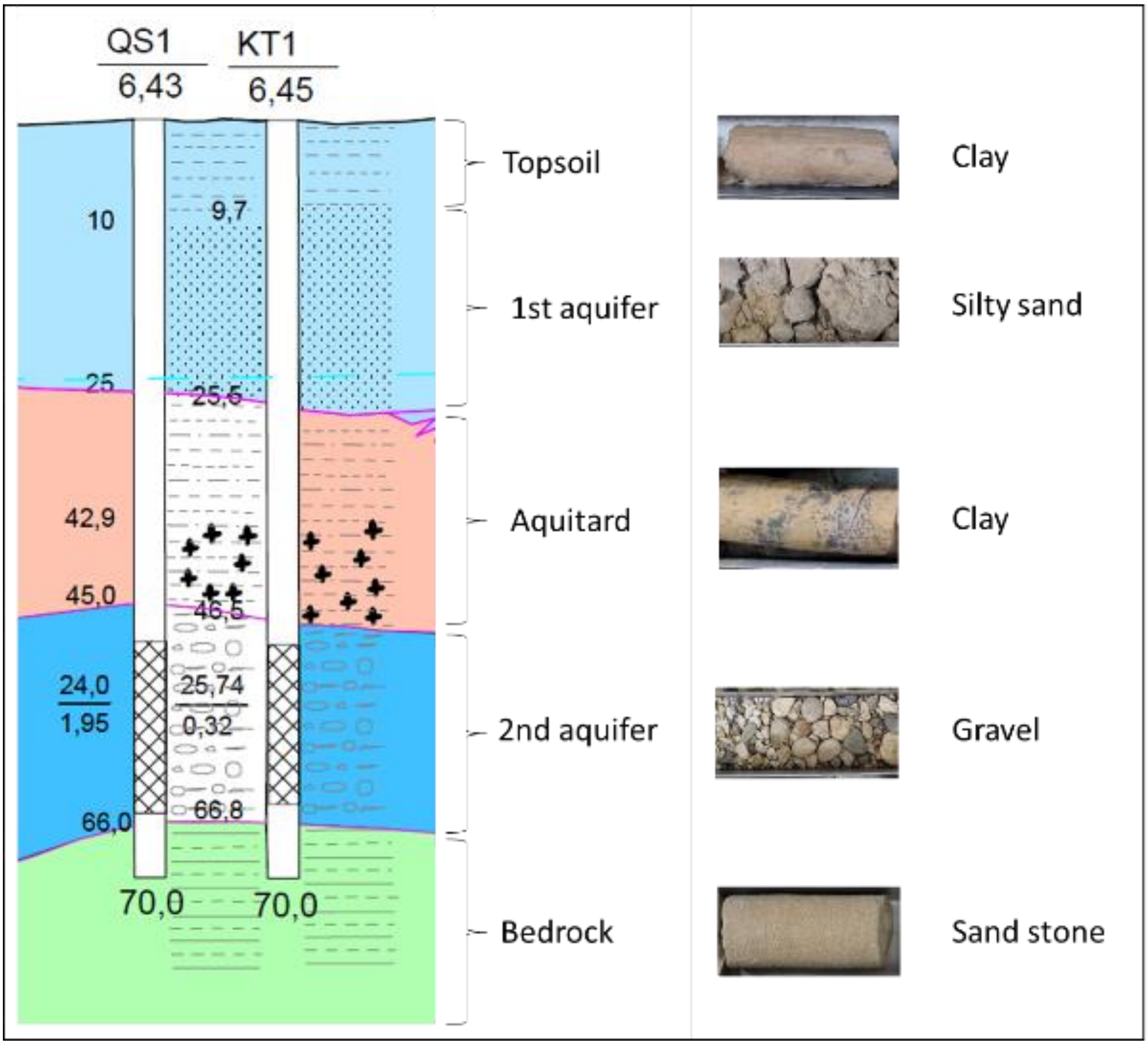
☐ Time interval
From 21/03/2023 11:20:57
To 21/03/2023 11:26:27

OK | Close | Help

Date & Time	Pressure (cmH2O)	Temperature (Celsius)
21 March 2023 11:20:57 .0	1027.200	24.527
21 March 2023 11:21:07 .0	1026.908	24.527
21 March 2023 11:21:17 .0	1034.725	24.573
21 March 2023 11:21:27 .0	1035.133	24.743
21 March 2023 11:21:37 .0	1035.017	25.063

8. The diver measurements are now stored on your PC and can be opened using Excel.

Appendix B: Borehole description at HUNRE



Appendix C: Macroinvertebrate biomonitoring

SITE INFORMATION TABLE	
River name:	Date (dd/mm/yr):
Site name:	Collector's name:
GPS co-ord Lat(S): Long(E):	School/organisation:
Site description: e.g. downstream of industry	Notes: e.g. weather, impacts, flow, etc.
pH: Water temp: °C Dissolved oxygen: mg/l Water clarity: info at www.minisass.org	

GPS co-ordinates as degrees, minutes, seconds (e.g. 29°30'25" S / 30°45'10" E) **OR** as decimal degrees (e.g. 29.50694°S / 30.75277°E) If you don't have a GPS, upload your results at **www.minisass.org**, find your site on the map, click to upload your result and the co-ordinates are saved for you!

Scoring

1. On the table, circle the sensitivity scores of the identified organisms.
2. Add up all of the sensitivity scores.
3. Divide the total of the sensitivity scores by the number of groups identified.
4. The result is the **average score**, which can be interpreted into an ecological category given below.

Interpret the miniSASS score:

Although an ideal sample site has rocky, sandy, and vegetation habitats, not all habitats are always present at a site. If your river had no rocky habitats that were sampled, use the **sandy type** category to interpret your scores.

GROUPS	SENSITIVITY SCORE
Flat worms	3
Worms	2
Leeches	2
Crabs or shrimps	6
Stoneflies	17
Minnow mayflies	5
Other mayflies	11
Damselflies	4
Dragonflies	6
Bugs or beetles	5
Caddisflies (cased & uncased)	9
True flies	2
Snails	4
TOTAL SCORE	
NUMBER OF GROUPS	
AVERAGE SCORE (miniSASS Score)	
Average Score = Total Score ÷ Number of groups	

Ecological category (Condition)		River Category	
		Sandy Type	Rocky Type
🟦	**NATURAL CONDITION** (Unchanged/untouched – Blue)	> 6.9	> 7.2
🟩	**GOOD CONDITION** (Few modifications – Green)	5.9 to 6.8	6.2 to 7.2
🟧	**FAIR CONDITION** (Some modifications – Orange)	5.4 to 5.8	5.7 to 6.1
🟥	**POOR CONDITION** (Lots of modifications – Red)	4.8 to 5.3	5.3 to 5.6
🟪	**VERY POOR CONDITION** (Critically modified – Purple)	< 4.8	< 5.3

Now, upload your results at www.miniSASS.org or use the miniSASS App (download from the miniSASS website) or send a scan of this page to info@minisass.org!

miniSASS is used to monitor the health of a river and measure the general quality of the water in that river. It uses the make-up of macro-invertebrates (small animals) living in rivers and is based on the sensitivity of the various animals to water quality.

NOTE: miniSASS does NOT measure the contamination of the water by bacteria and viruses and thus does not tell us if the river water is fit to drink.

Equipment list

- Net (see www.minisass.org)
- white container / tray / ice-cream box
- magnifying glass
- pencil
- shoes/gumboots
- hand wash / soap

www.minisass.org
Version 3.0 – September 2015

Method

The best sites have rocks in moving water (**rocky type** rivers). Not all sites have rocks, but may be largely sandy (**sandy type** rivers).

1. Whilst holding a small net in the current, **disturb** the stones, vegetation, sand etc. with your feet or hands.
2. You can also lift stones out of the current and gently **pick** organisms off with your fingers or forceps.
3. Do this for about **5 minutes** whilst **ranging across the river to different habitats** (biotopes).
4. Rinse the net and turn the contents into a plastic tray. **Identify** each group of organisms using the identification guide (see insert: start with the dichotomous key, then use the identification guide for more information).
5. Fill in the site information and **mark** the identified organisms off on the scoring sheet (back page).
6. **Add up** the sensitivity scores and determine the **average score**.
7. Interpret your miniSASS score.
8. Remember: **WASH** your hands when done!

https://www.youtube.com/channel/UCub24hwrLi52WR9C24uTbaQ

Don't have a net? Make your own – it is easy!

Take any piece of wire, for example an old clothes hanger, and bend it into the shape of a net. Then tie the netting (which can be any porous material) to the wire with a piece of string. Alternatively cut the bottom out of an ice cream container and staple netting to the bottom. Now you have a net!!

Macroinvertebrates

What are they?

Macroinvertebrates are animals that have no backbone and you can see them with the naked eye.

Why are they used for biomonitoring?

- Different macroinvertebrates have different sensitivities to water quality conditions. More sensitive "nunus" will disappear from a river system where water quality has declined. On the score sheet, the higher the score, the more sensitive the "nunus" are.
- They are generally easy to collect and identify.
- They are relatively sedentary which allows the source of pollution to be detected.
- They indicate the water quality conditions at a site, providing an overall measure of the "health" of a river.
- They provide a picture of recent events affecting water quality at a site.

Why is water quality monitoring & management important in South Africa?

Fresh water is essential for life on earth. Water is also used in all spheres of human life, namely agriculture, industry, biodiversity conservation, sanitation and hydration.

However due to the amount of rainfall South Africa receives, it is classified as a water-stressed country. This means that if we do not monitor, manage and conserve our current water resources, we will be placing them and the population under tremendous stress in the future!

Get ready to put your crab on the map!

Load your site at: www.miniSASS.org

Glossary

Biomonitoring: the monitoring of biodiversity using biological organisms

Biodiversity: diversity within species, between species and of ecosystems

Conservation: the maintenance of environmental quality and functioning

Ecosystem: a complete community of living organisms and the non-living materials of their surroundings

Sedentary: inactive, motionless, not moving

River safety

Take special care in polluted waters. Beware of dangerous animals (crocs/hippos!) and fast flowing waters. Wear protective gear when necessary and wash your hands regularly with soap and clean water wherever possible!!

What can you do?

As the general public, we play a part in making a difference to managing freshwater resources in our communities. miniSASS has the potential to be a powerful 'red flag' indicator to identify aquatic pollution sources. By using miniSASS we can actively take an interest in the management of the health of freshwater bodies in our community.

Your interest and knowledge can be enhanced by adopting a local river in your community and monitoring it over time, identifying sources of pollution and taking local action to make a difference. You could also encourage more members of the community to take positive action towards monitoring and conserving water.

Contribute to the picture of river quality in South Africa

Download miniSASS resources and upload data at

www.minisass.org or use the miniSASS App

For queries, comments or assistance email info@minisass.org

Also available from Share-Net: www.sharenet.org.za Tel (033) 3303931

History of the miniSASS tool

South Africa is a world leader in biomonitoring techniques using macro-invertebrates. The most successful of these is the South African Scoring System version 5 (SASS5). miniSASS is based on SASS and uses the presence of macro-invertebrates to indicate "river health". Where SASS5 contains over 90 different macroinvertebrate taxa, miniSASS uses 13 taxa, allowing for simpler identification and understanding. miniSASS provides similar indications of "river health" status as the more comprehensive SASS5 assessment, providing a good method to generate useful biomonitoring data. miniSASS Version 1 was developed using roughly 2 000 SASS4 data records. miniSASS Version 2 was based on over 6 000 SASS5 records, making it more robust & more widely applicable in Southern Africa. Version 3 has updated Ecological Categories to be more closely aligned with SASS5 results.

Key words for further reading

macroinvertebrate, benthic, water quality, conservation, biodiversity, river health, aquatic pollution, SASS, taxa, invertebrate classification, ecological monitoring

Additional resources and partners

WATER RESEARCH COMMISSION
www.wrc.org.za

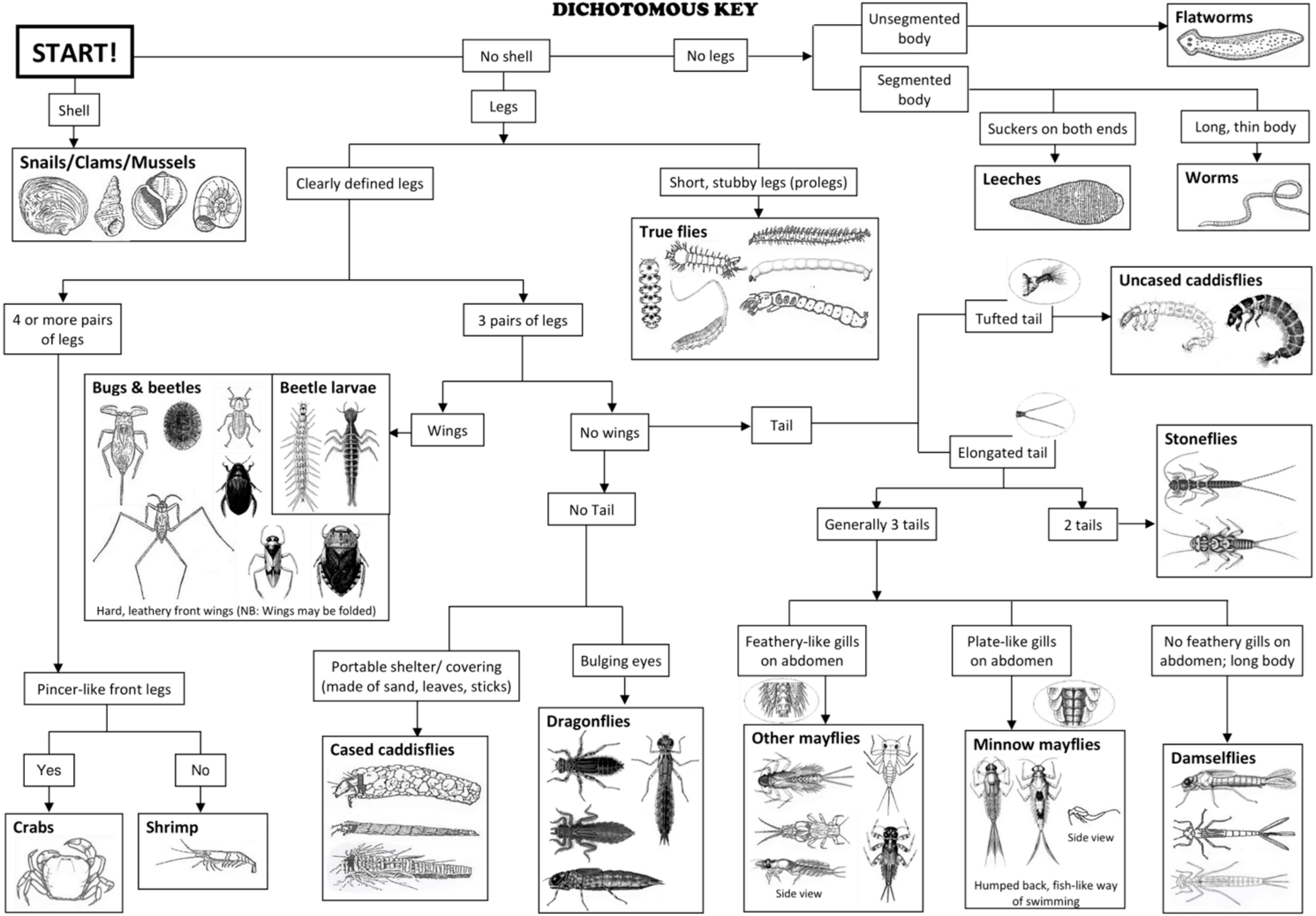
WESSA
PEOPLE CARING FOR THE EARTH
www.wessa.org.za

GroundTruth
Water, Wetlands and Environmental Engineering
www.groundtruth.co.za

water & sanitation
Department:
Water and Sanitation
REPUBLIC OF SOUTH AFRICA
www.dwa.gov.za

science & technology
Department:
Science and Technology
REPUBLIC OF SOUTH AFRICA
www.dst.gov.za

DICHOTOMOUS KEY



Appendix D: Water quality standards

Table D.1. Limit values for parameters if the water is to be used in any way without cleaning first ((Ministry of Science and Technology, 2023)

Parameter	**Unit**	**Value limit**
Nitrite (NO_2-N)	mg/l	0.05
Ammonium (NH_4-N)	mg/l	0.3
Chloride (Cl^-)	mg/l	250
Fluoride (F^-)	mg/l	1
Cyanide (CN^-)	mg/l	0.01
Arsenic (As)	mg/l	0.01
Cadmium (Cd)	mg/l	0.005
Lead (plumbum)(Pb)	mg/l	0.02
Chromium (6+)(Cr^{6+})	mg/l	0.01
Total Chromium (Cr)	mg/l	0.05
Copper (Cuprum)(Cu)	mg/l	0.1
Zinc (Zincum)(Zn)	mg/l	0.5
Nickel (Ni)	mg/l	0.1
Manganese (Mn)	mg/l	0.1
Mercury (Hydragyrum)(Hg)	mg/l	0.001
Iron (Ferrum) (Fe)	mg/l	0.5
Antimony (Sb)	mg/l	0.02
Anionic surfactants	mg/l	0.1
Total phenol	mg/l	0.005
Aldrin ($C_{12}H_8Cl_6$)	µ/l	0.1
Lindane ($C_6H_6Cl_6$)	µ/l	0.02
Dieldrin ($C_{12}H_8Cl_6O$)	µ/l	0.1
Total Dichlorodiphenyltrichloroethane (DDT_s) ($C_{14}H_9Cl_5$)	µ/l	1.0
Heptachlor & Heptachlorepoxide ($C_{10}H_5Cl_7$ & $C_{10}H_5Cl_7O$)	µ/l	0.2
Total oil and grease (oils & grease)	mg/l	5.0
Polychlorinated biphenyls (PCBs)	mg/l	0.0005
Tetrachloroethylene (PCE) (C_2Cl_4)	mg/l	0.04
1,4-Dioxane ($C_4H_8O_2$)	mg/l	0.05
Carbon tetrachloride (CCl_4)	mg/l	0.004
1,2 Dichloroethane ($C_2H_4Cl_2$)	mg/l	0.03
Methylene chloride (CH_2Cl_2)	mg/l	0.02
Benzene (C_6H_6)	mg/l	0.01
Chloroform ($CHCl_3$)	mg/l	0.08
Formaldehyde (CH_2O)	mg/l	0.5
Bis (2-ethylhexyl)phthalate	mg/l	0.008

DEHP ($C_{24}H_{38}O_4$)		
Hexachlorobenzene (C_6Cl_6)	µ/l	0.04
Organophosphorus plant protection chemicals	µ/l	0.5
Total radioactivity α	Bq/l	0.1
Total radioactivity β	Bq/l	1.0
E. coli	MPN or CFU/100 ml	20

Table D.2. Limit values of parameters in surface water for classification of water quality in rivers, streams, canals, and ditches for aquatic habitat protection ((Ministry of Science and Technology, 2023)

Parameter	**pH**	6.5 – 8.5	6.0 – 8.5	6.0 – 8.5	< 6.0 or > 8.5
	BOD5 (mg/l)	≤ 4	≤ 6	≤ 10	> 10
	COD (mg/l)	≤ 10	≤ 15	≤ 20	> 20
	TOC (mg/l)	≤ 4	≤ 6	≤ 8	> 8
	TSS (mg/l)	≤ 25	≤ 100	> 100 and no floating filth	> 100 and floating filth
	DO (mg/l)	≥ 6.0	≥ 5.0	≥ 4.0	≥ 2.0
	Total phosphorus (TP) (mg/L)	≤ 0.1	≤ 0.3	≤ 0.5	> 0.5
	Total nitrogen (TN) (mg/L)	≤ 0.6	≤ 1.5	≤ 2.0	> 2.0
	Total coliform (MPN or CFU/100 ml)	≤ 1000	≤ 5000	≤ 7500	> 7500
	Coliform heat resistant (MPN or CFU/100 ml)	≤ 200	≤ 1000	≤ 1500	> 1500
Water quality classification level		A	B	C	D

Appendix E: Record sheets

Every test has a record sheet. On these record sheets, the data collected during an experiment can be written. Afterward, you can copy the collected data from the field to a digital version of the record sheet (Excel). Always do this the same day; papers can get lost or damaged easily, or data can become unreadable.

Before you do any experiment, you should first have a proper look at the corresponding record sheet, and make sure you understand what data needs to be filled in and where. Determine beforehand how often you will have to do an experiment. Bring enough copies of each record sheet, and keep in mind that often an experiment will go wrong a couple of times before you will do it right, so you will need more record sheets than the number of times you plan to do an experiment.

Some record sheets have room for multiple iterations of an experiment. Be sure to always carefully note the date, time, location, and people conducting the experiment. This is crucial information that you often will need when processing the data.

Table of contents – record sheets

Record sheet velocity area method E.2

Record sheet pumping test E.3

Record sheet inverse auger hole test E.4

Record sheet double ring infiltration test E.5

Record sheet cross-sectional area for gulp injection E.6

Record sheet gulp injection E..7

Record sheet constant rate injection E.8

Record sheet soil sampling E.9

Record sheet water quality E.10

Record sheet discharge measurement with a weir E.11

Record sheet seepage test E.12

Record sheet precipitation and evaporation E.13

Record sheet velocity area method

Date	
Time	
Location	
Name(s)	
Group	

Segment nr.	Distance from bank [m]	Water depth [m]	Flow velocity [m/s]
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			

Drawing of the cross-section

Record sheet pumping test

Date			
Time			
Location			
Name(s)			
Group			
Initial water level	m	**Distance between two wells**	m
Discharge	m^3/hour	**Thickness of the aquifer**	m

Time cum. [min]	**ΔT [min]**	**Water level in pumping well [m]**	**ΔH in pumping well [m]**	**Water level in observation well [m]**	**ΔH in observation well [m]**
5	5				
10	5				
15	5				
20	5				
25	5				
30	5				
45	15				
60	15				
75	15				
90	15				
120	30				
150	30				
180	30				
210	30				
240	30				
300	60				
360	60				
420	60				
480	60				

Time cum. [min]	**Discharge [m/h]**	**Time cum. [min]**	**Discharge [m^3/h]**
5		240	
30		300	
60		360	
120		420	
180		480	

Record sheet inverse auger hole test

Date	
Time	
Location	
Name	
Group	
Total depth of the hole [cm]	
Diameter of the hole [cm]	

Time from t=0 [s]	**Measuring depth [cm]**	**Time from t=0 [s]**	**Measuring depth [cm]**
00:00		00:00	
00:10		00:10	
00:20		00:20	
00:30		00:30	
00:40		00:40	
00:50		00:50	
01:00		01:00	

Record sheet double ring infiltration test

Date	
Time	
Location	
Name(s)	
Group	

Time from t=0 [hh:mm:ss]	**Water level inside the inner ring [cm]**	**Time from t=0 [hh:mm:ss]**	**Water level inside the inner ring [cm]**
00:00:00		00:00:00	
00:01:00		00:01:00	
00:02:00		00:02:00	
00:05:00		00:05:00	
00:10:00		00:10:00	

Record sheet cross-sectional area for gulp injection

Date	
Time	
Location	
Name(s)	
Group	
Distance downstream [m]	

Distance from bank [m]	**Water depth [m]**	**Distance from bank [m]**	**Water depth [m]**
0.0		3.1	
0.1		3.2	
0.2		3.3	
0.3		3.4	
0.4		3.5	
0.5		3.6	
0.6		3.7	
0.7		3.8	
0.8		3.9	
0.9		4.0	
1.0		4.1	
1.1		4.2	
1.2		4.3	
1.3		4.4	
1.4		4.5	
1.5		4.6	
1.6		4.7	
1.7		4.8	
1.8		4.9	
1.9		5.0	
2.0		3.1	
2.1		3.2	
2.2		3.3	
2.3		3.4	
2.4		3.5	
2.5		3.6	
2.6		3.7	
2.7		3.8	
2.8		3.9	
2.9		4.0	
3.0		Computed area [m^2]	

Record sheet gulp injection

Date		**Distance downstream**	m
Time		**Mass of salt used**	g
Location		**Natural EC**	µS/cm
Group		**Natural concentration**	mg/L

Time	**EC [µS/cm]**	**Time**	**EC [µS/cm]**	**Time**	**EC [µS/cm]**	**Time**	**EC [µS/cm]**
00:00		03:00		06:00		09:00	
00:05		03:05		06:05		09:05	
00:10		03:10		06:10		09:10	
00:15		03:15		06:15		09:15	
00:20		03:20		06:20		09:20	
00:25		03:25		06:25		09:25	
00:30		03:30		06:30		09:30	
00:35		03:35		06:35		09:35	
00:40		03:40		06:40		09:40	
00:45		03:45		06:45		09:45	
00:50		03:50		06:50		09:50	
00:55		03:55		06:55		09:55	
01:00		04:00		07:00		10:00	
01:05		04:05		07:05		10:05	
01:10		04:10		07:10		10:10	
01:15		04:15		07:15		10:15	
01:20		04:20		07:20		10:20	
01:25		04:25		07:25		10:25	
01:30		04:30		07:30		10:30	
01:35		04:35		07:35		10:35	
01:40		04:40		07:40		10:40	
01:45		04:45		07:45		10:45	
01:50		04:50		07:50		10:50	
01:55		04:55		07:55		10:55	
02:00		05:00		08:00		11:00	
02:05		05:05		08:05		11:05	
02:10		05:10		08:10		11:10	
02:15		05:15		08:15		11:15	
02:20		05:20		08:20		11:20	
02:25		05:25		08:25		11:25	
02:30		05:30		08:30		11:30	
02:35		05:35		08:35		11:35	
02:40		05:40		08:40		11:40	
02:45		05:45		08:45		11:45	
02:50		05:50		08:50		11:50	
02:55		05:55		08:55		11:55	

Record sheet constant rate injection

Date	
Time	
Location	
Name(s)	
Group	

What	**Value**	**Unit**
Natural EC of the stream		µS/cm
Natural salt concentration of the stream		mg/l
Concentration of the solute		g/l
Increased constant EC level		µS/cm
Increased constant concentration level		mg/l
Discharge of Mariotte bottles		l/s
Discharge of the river		l/s

What	**Value**	**Unit**
Natural EC of the stream		µS/cm
Natural salt concentration of the stream		mg/l
Concentration of the solute		g/l
Increased constant EC level		µS/cm
Increased constant concentration level		mg/l
Discharge of Mariotte bottles		l/s
Discharge of the river		l/s

What	**Value**	**Unit**
Natural EC of the stream		µS/cm
Natural salt concentration of the stream		mg/l
Concentration of the solute		g/l
Increased constant EC level		µS/cm
Increased constant concentration level		mg/l
Discharge of Mariotte bottles		l/s
Discharge of the river		l/s

Record sheet soil sampling

Date	
Time	
Location	
Name(s)	
Group	

What	**Value**	**Unit**
Volume of the ring		cm^3
Density of water		g/cm^3
Mass of the aluminum bowl or foil		g
Mass of Kopecki ring		g
Mass of soil sample		g
Mass of saturated soil sample		g
Mass of dry soil sample		g
Dry bulk density of the soil		g/cm^3
Porosity		-
Volumetric water content		-
Gravimetric water content		-

What	**Value**	**Unit**
Volume of the ring		cm^3
Density of water		g/cm^3
Mass of the aluminum bowl or foil		g
Mass of Kopecki ring		g
Mass of soil sample		g
Mass of saturated soil sample		g
Mass of dry soil sample		g
Dry bulk density of the soil		g/cm^3
Porosity		-
Volumetric water content		-
Gravimetric water content		-

Record sheet water quality

Date		**Location**	
Time		**Group**	

Parameter	**Instrument**	**Unit**	**Loc. 1**	**Loc. 2**	**Loc. 3**	**Loc. 4**	**Loc. 5**	**Loc. 6**	**Loc. 7**	**Loc. 8**
EC	EC meter									
Temperature	EC meter									
pH	pH-probe									
DO	DO-probe									
Ammonia	Test strip									
Phosphate	Test strip									
Nitrate Nitrogen	Test strip									
Nitrite	Test strip									
Turbidity	Turbidity meter									
Turbidity	Transparency tube									
Ecological category	Biomonitoring									

Measurement location	**Coordinates**	**Time**	**Measurement location**	**Coordinates**	**Time**
Loc. 1			Loc. 5		
Loc. 2			Loc. 6		
Loc. 3			Loc. 7		
Loc. 4			Loc. 8		

Record sheet discharge measurement with a weir

Date	
Time	
Location	
Name(s)	
Group	

What	Value	Unit
Volume in jar/measuring cup		l
Time to fill jar/measuring cup		s
Discharge		l/s

What	Value	Unit
Volume in jar/measuring cup		l
Time to fill jar/measuring cup		s
Discharge		l/s

What	Value	Unit
Volume in jar/measuring cup		l
Time to fill jar/measuring cup		s
Discharge		l/s

What	Value	Unit
Water height above the weir		cm
Discharge with weir method		l/s
Average discharge with cup		l/s

Record sheet seepage test

Date	
Time	
Location	
Name(s)	
Group	

What	Value	Unit
Water depth		m
Water depth in piezometer		m
Difference in water depth		m

What	Value	Unit
Water depth		m
Water depth in piezometer		m
Difference in water depth		m

What	Value	Unit
Volume in bag at the start		l
Volume in the bag at the end		l
Change in volume		l
Duration of experiment		h
Seepage/infiltration		l/h
Area of bucket		m^2
Seepage/infiltration		mm/h

What	Value	Unit
Volume in bag at the start		l
Volume in the bag at the end		l
Change in volume		l
Duration of experiment		h
Seepage/infiltration		l/h
Area of bucket		m^2
Seepage/infiltration		mm/h

Record sheet precipitation and evaporation

Date	
Time	
Location	
Name(s)	
Group	

What	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**
Water depth rain meter [mm]					
Precipitation [mm]					
Water depth in evaporation bucket [mm]					
Evaporation [mm]					

What	**Value**	**Unit**
Area of funnel		m^2
Cross-sectional area of bottle		m^2
Total evaporation		mm
Total precipitation		mm

What	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**
Water depth rain meter [mm]					
Precipitation [mm]					
Water depth in evaporation bucket [mm]					
Evaporation [mm]					

What	**Value**	**Unit**
Area of funnel		m^2
Cross-sectional area of bottle		m^2
Total evaporation		mm
Total precipitation		mm