Determining groundwater velocity with DTS at the Máximakanaal and in the Horstermeerpolder

by

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Abstract

A suggested approach for determining groundwater flow in unconsolidated aquifers is tested. Performing a heat pulse response test by using a heat- and fibre-optic cable should result in a vertical profile of groundwater velocities. These cables are installed by using direct push ensuring the direct contact between cable and aquifer. The suggested approach is tested with two case studies. The first case study near the Máximakanaal was meant to determine if the canal is leaking. This experiment failed during the installation which was discovered after analyzing the results. The mistakes that were made during this case study have been analyzed and are discussed. The second case study was not performed by the author of this thesis. Nonetheless, the measurements of this case study enabled the completion of retrieving groundwater velocities from distributed temperature sensing and reviewing the approach.

Contents

1 Introduction

Determining groundwater velocities can be a devious process. Methods based on Darcy's Law are prone to inaccuracies in case of low hydraulic gradients or inaccurate determination of these gradients [Labaky et al., 2009]. Other methods rely on costly tracers or devices to determine groundwater velocity. The method used in this report makes use of measurements by using a fiber optic cable in combination with a Distributed Temperature Sensing (DTS) system. The method is based on previous research [des Tombe et al., 2019] and is developed as a tool for analyising data when using DTS.

The aim of this report is to determine groundwater velocity by using DTS. A project site next to the Máximakanaal in The Netherlands has been used for measurements. The reason why this location was chosen is explained in chapter 3.1. However, while analysing the results it was discovered this test failed. To be able to test the method of des Tombe et al., (2019) and retrieve groundwater velocities this report made use of data from a different experiment at the Horstermeerpolder. In addition to the determination of groundwater velocities, an evaluation of the failed experiment and its difficulties will be discussed. Here the focus lays on the detection of faulty measurements. How to detect these in an early stage, before putting effort in the full analysis of the data, and before the measuring experiment has finished. This will be discussed in chapter 3.

The report is set out as follows. Chapter 2 treats the methodology, it is explained how DTS works, which assumptions are made and presents the general set-up for DTS measurements that are performed. Chapter 3 entails the experiment at the Máximakanaal. It contains the reason why the experiment was performed, a more detailed set-up and most importantly the lessons learned from the failed experiment at the Máximakanaal. Chapter 4 shortly introduces the data that is used for determining groundwater velocity and how it was obtained. Chapter 5 presents the results of the measurements at the Horstermeerpolder after which chapter 6 concludes the findings on the measurements and method used. Finally chapter 7 presents some recommendations to improve results of this study.

2 Methodology

2.1 Theory on DTS

Distributed Temperature Sensing (DTS) determines the temperature based on the back scattering of light. The medium through which light is sent, an optic fibre cable, scatters light differently for different temperatures. This is due to the Bloch oscillation of the medium. The scattered light is defined by Raman scattering, which consists of three spectral components: Rayleigh scattering, Stokes and Anti-Stokes [Ukil et al., 2011]. The Stokes signal does not depend on the Bloch oscillations of the medium, it is insensitive to temperature changes, whereas the Anti-Stokes signal does depend on it and therefore is sensitive to temperature changes. The ratio of these signals result in combination with parameters γ, α_d and C, into a (local) temperature measurement [Ukil et al., 2011]. To have an accurate temperature estimation these parameters should be calibrated.

2.2 Calculation of the specific discharge

To calculate the specific discharge from the previously measured temperature a couple of parameters need to be derived. Des Tombe et al., (2019) showed that the required parameters reduce to timescale A, $\frac{r}{B}$, temperature asymptote $T(t_\infty)$ and an autoregressive parameter α with the assumptions presented below.

- The vertical depth profile consists of many horizontal layers.
- Vertical transfer of water and heat is neglected.
- Temperature of water and solids are at an instantaneous equilibrium.
- Specific discharge is steady and uniform in each layer.
- The flow is not altered by the installed heating cable and fibre optic cable.

To derive these parameters the normalised calibrated temperature of the whole vertical depth profile is fitted to the physical processes of water and heat transfer. The steps taken for the derivation have been described by des Tombe et al., 2019. The processes of water and heat transfer come forth from rewriting the governing equation for temperature distribution in a single layer (formula 1, [Hopmans et al., 2002]). The specific discharge can be extracted by taking a couple of steps. First the governing equation is solved for a point source at the origin for solute transport [Hunt, 1983]. After this solution [Zubair and Chaudhry, 1996] and [Diao et al., 2004] did this for heat transfer which leads to formula 2.

$$D_x \frac{d^2T}{dx^2} + D_y \frac{d^2T}{dy^2} - q\frac{\rho_w c_w}{\rho c}\frac{dT}{dx} = \frac{dT}{dt} \tag{1}$$

$$T = \frac{p}{4\pi\rho c\sqrt{D_x D_y}} \exp{(\frac{x}{B})} W(\frac{A}{t}, \frac{r}{B})) \tag{2}$$

where

$$A = \frac{r^2}{4D_x} \tag{3}$$

$$B = 2D_x \frac{\rho c}{q\rho_w c_w} \tag{4}$$

$$r = \sqrt{x^2 + \frac{D_x}{D_y}y^2} \tag{5}$$

Here p is a point source of a certain power, ρc volumetric heat capacity of saturated soil, $\rho_w c_w$ volumetric heat capacity of water, D_x, D_y thermal dispersion coefficients and x, t are location and time parameters.
To retrieve the specific discharge equation 4 can be rewritten into equation **??**. However, to obtain the specific discharge several parameters are needed. These come from fitting the normalised temperature to the physical processes. The calibrated temperature is normalised by subtracting the background temperature.

The physical processes consist of groundwater flow and heat transfer and can, when summarized, be described by formula 7. Where K_0 is the modified Bessel function of the second kind and order 0 and $W(\frac{A}{t}, \frac{r}{B})$ the Hantush Well function. These fitted parameters can then be used inside the explicit formula 6 to estimate the specific discharge [des Tombe et al., 2019].

$$q = \frac{1}{\rho_w c_w}\left(\left[\frac{\frac{r}{B}}{\sqrt{A}}\right]^2 \frac{\beta_x \rho c}{2} + \frac{\frac{r}{B}}{\sqrt{A}}\sqrt{\kappa\rho c + \left[\frac{1}{2}\frac{\frac{r}{B}}{\sqrt{A}}\beta_x \rho c\right]^2}\right) \tag{6}$$

$$T(t, t_0) = \begin{cases} \frac{T(t_\infty)}{2K_0(r/B)} W(\frac{A}{t}, \frac{r}{B}) & 0 < t \leq t_0 \\ \frac{T(t_\infty)}{2K_0(r/B)} [W(\frac{A}{t}, \frac{r}{B}) - W(\frac{A}{t-t_0}, \frac{r}{B})] & t > t_0 \end{cases} \tag{7}$$

The values for $\rho_w c_w$, $\kappa\rho c$ and $\beta_x \rho c$ are estimations and come from the research of des Tombe et al., 2019.

2.3 General set-up

To acquire the necessary data for calculating the specific discharge, DTS measurements have been taken. As has been mentioned in the introduction two experiments have been performed. The experiment at the Máximakanaal failed after which data of the experiment at the Horstemeerpolder has been used for further results. Since the set-up for both experiments are quite similar a general set-up for a DTS system is discussed in this section. When discussing the individual experiments details such as which DTS system is used are presented.

The set-up of both experiments have: a DTS system, computer, fibre optic cable, a calibration bath and since both of the experiments made use of active heating a heating cable (see section 2.4). To be able to make use of and protect the equipment a local power supply (generator), a place to protect the equipment from weather and security measures were required. Both of the experiments make use of a double-ended system. This means that a signal that is send through the optic fibre cable is first in one direction followed by a signal in the opposite direction. This improves the measurements because near distortions (e.g. a splice) the obtained signals are of better quality.

2.3.1 Installation

The fibre optic cable is pushed into the soil together with the heating cable via direct push. The fibre optic cable that comes out of the soil is directed to the location of the DTS system where a large part of cable is set in a calibration bath, this happens for both cable directions. Then the DTS system is installed, for which the fibre optic cable is spliced (precision weld) at each end to a connector. A thermometer installed in the calibration bath is connected to the DTS system as well. The DTS system is connected to a computer which saves all data while the measurements takes place and enabled in one case the remote viewing of data. A rough sketch of the set-up can be seen in figure 1. Note that the optic fibre cable is drawn straight, while in reality the cable is twisted and has an unknown position with regard to the heating cable. The same goes for the heating cable [Bakker et al., 2015].

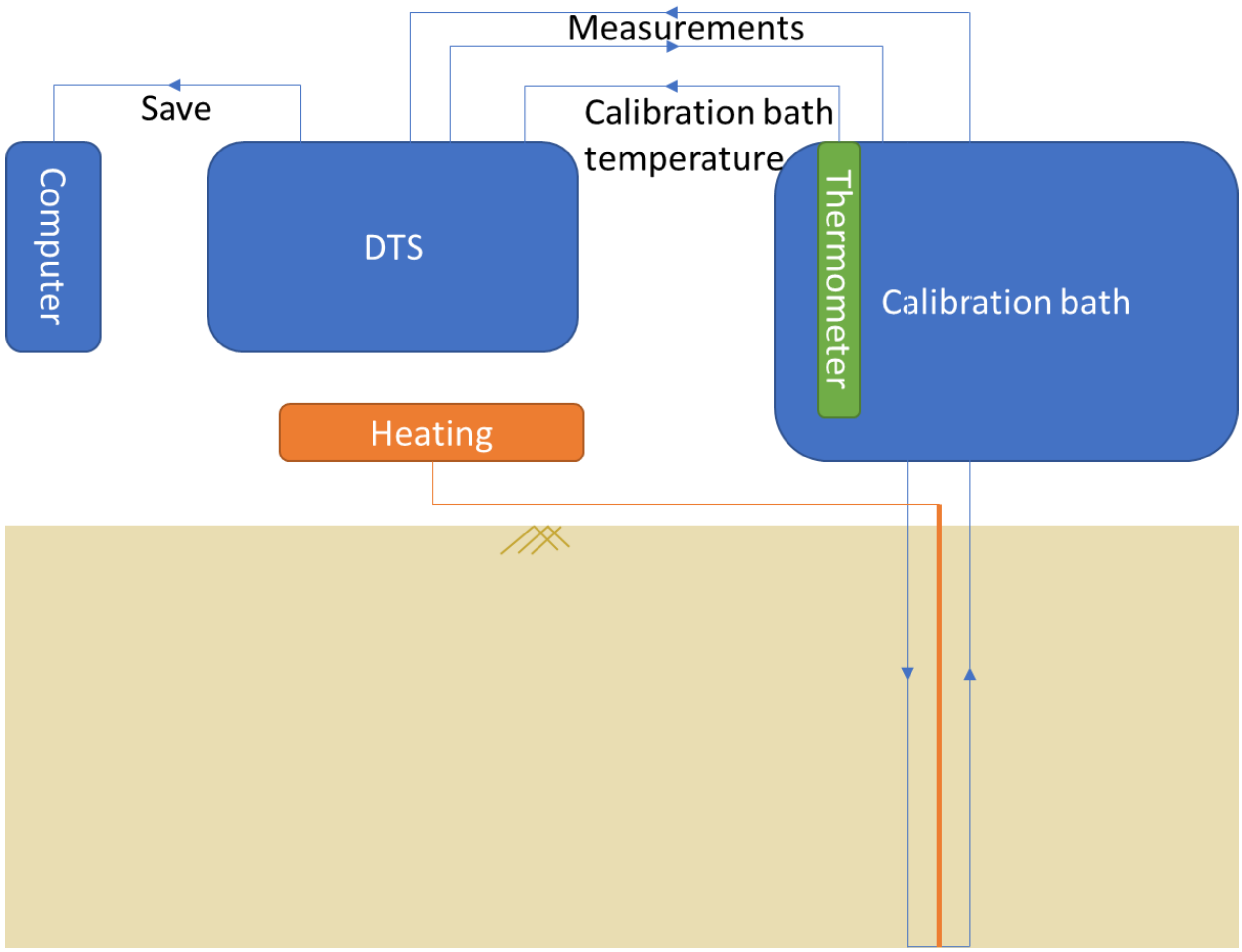


Figure 1: General set-up of double ended DTS system

2.4 Measurements

Once the set-up is finished the measurements can start. As mentioned before both of the experiments concern active heating tests. An active test can be described in two phases: 1) the soil is actively heated for a period 2) the heating stops and the soil temperature slowly returns to its natural equilibrium. Both phases are measured continuously and each individual phase takes up to 5-7 days.

2.4.1 Calibration

To retrieve accurate temperature measurements the known temperature of a part of the cable is used, for example the calibration bath. The temperature of the optic fibre cable inside the calibration bath is known due to the thermometer(s). The calibration process sets the amount of measured scattered light per temperature. Therefore accurate temperatures along the rest of the optic fibre cable can be obtained. A splice distorts the scattering of light which induces errors in the measurements after a splice, these measurements should not be used.

2.4.2 Fitting

The heating and cooling of the soil follow the physics of formula 7, however not all parameters are known. Due to groundwater flow the heating at certain horizontal layers is slower or faster, which is the other way around in the cooling phase. Formula 7 is fitted to the measured temperature per horizontal layer by adjusting the parameters A, $\frac{r}{B}$ and $T(t_{\infty})$. These fitted parameters can then be used to calculate the specific discharge with formula 6.

3 Lessons learned: measurements at the Máximakanaal

This chapter contains the lessons learned from the measurements at the Máximakanaal. The reason why these measurements were done and the specific set-up details are presented first. Thereafter, the results, experiences and lessons learned will be discussed.

3.1 Experiment

The aim of the research is to check if there is a leak in the Máximakanaal. A difference in the sum of discharges in the river before and after the canal could not be explained. A possible explanation can be a leaky clay layer. After construction of the canal the contractor forgot to apply a clay layer which lead to leaking [Huismans, 2015]. Rijkswaterstaat thinks this clay layer could be the cause of the problems again. To check if the canal is leaking two locations for the measurements had been appointed. One where the contractor applied a clay layer after construction and one where there is no clay layer. If the canal is leaking while the clay layer is intact there should be a significant difference in groundwater flow from the canal towards the land for each point. Hence the need to determine the groundwater velocities.

3.1.1 Set-up & measurements

The general set-up for the measurements has been discussed in section 2.3. For this experiment an ORYX OX4-SR (DTS system) is used, the fiber optic cable is heavily reinforced with a steel wire mesh and a wide steelwire, and the calibration bath consisted of a large bucket filled with river water. The cables were installed as deep as possible, which varied per location (respectively -23 m and -24 m w.r.t. NAP).

The measuring period was about two weeks. One week of heating, one week of cooling. During this time there was limited access to the data via a remote desktop by which individual files could be downloaded. After the measuring period finished the equipment was moved to the second location and the process was repeated.

3.2 Results, experiences and lessons learned

3.2.1 Cable shortening

During the set-up a team with different experiences worked together. Most of them had worked with optic fibre cable before but did not know about DTS. This general nescience did not work favourably for the experiment. During cable installment a part of the fibre cable was shortened 'for easier handling'. Long parts of fibre optic cable might seem redundant but this is far from true. Extra cable should go in the calibration bath, this will make the calibration process easier, faster and more accurate.

Take home message: Before the experiment set-up is installed make sure that at least one person knows what the following steps of the experiment will be. In this case nobody knew, this resulted in the optic fibre being shorted and the calibration bath being hard to find in the data. To find the calibration bath the method described in the section below can be used.

3.2.2 Checking signals

The measurements are taken over a relatively long period (9-14 days) if a component does not work this induces time delay. Therefore, it is important to check if everything works accordingly. During the set-up the optic fibre cable was checked upon by pointing a flashlight on one side of the cable, the other side of the cable lighted up and it was concluded the cable was good to go. Assuming that this was the most critical component the heating cable was left alone. This was a mistake.

A few days after the start of the measurements the preliminary results were checked to confirm that everything worked accordingly. A quick plot of the temperature at the start of the measurements versus a plot of the temperature at the end of the heating period showed a clear increase in temperature (see figure 2).

Therefore it was concluded that everything was working accordingly. This was a mistake as well.

The two mistakes above are related. The heating cable did not work. This was verified afterwards by checking the resistance in the cable. The visible heating in figure 2 came from a day & night pattern induced by calibrating on the internal reference temperature, this happens automatically for the ORYX OX4-SR. Therefore the temperature check was wrong.

> How does a day & night pattern arise?
> The DTS system has an internal coil with 50 m of optic fibre spun around it. The DTS system measures the temperature of the coil (with a 'normal' thermometer) and assumes that the temperature of this 50 m of optic fibre is the same. That way the DTS system determines what temperature a certain reflection of scattered light represents. However, the outside of this optic fibre does not have the same temperature as the inside. Figure 3 gives a little insight. The faster cooling and heating of the outer layer of optic fibres induce an error in the measurements in the form of a day and night pattern.

Take home message: When checking if the temperature works, try to check the cable after installation, see if it actually becomes warm. Otherwise, first calibrate. Locate the area where the optic fibre is in the soil and plot the temperature over time for an x value in this reach. During the heating and cooling period an image such as figure 7 should be seen. The figure can, due to incorrect calibration or a wrongly chosen x value, take strange shapes (e.g. figure 4). Try multiple calibrations and/or multiple values along the cable.

Another way of checking if heating works is to plot the variance of the temperature. If the heating cable works, the part of the optic fibre in the soil is not constant. An example of this case, where the heating is not working is shown in figure 5. It shows the variance over length at the end of the heating period (t = t2). As can be seen the variance is constant and about zero. Figure 6 shows an example of a test with a working heating cable, also at the end of the heating period. Here (between $120m < x < 24m$) the cable in the soil shows a varying variance. This implies that the heat is not constant which point to a working heating element. This method can also be used to find the calibration bath.

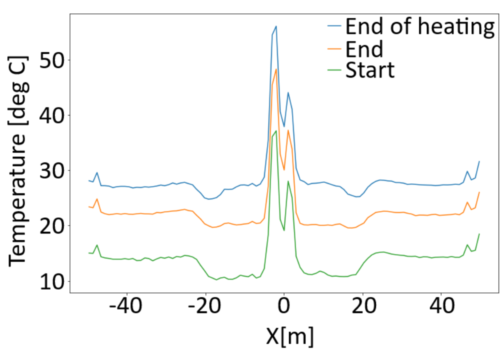


Figure 2: Temperature over distance

Figure 3: Cable spun around a coil

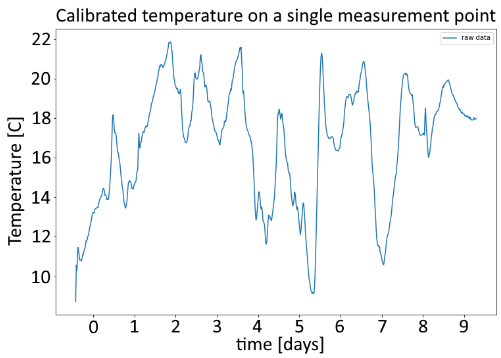


Figure 4: Wrong calibration or wrong choice of x

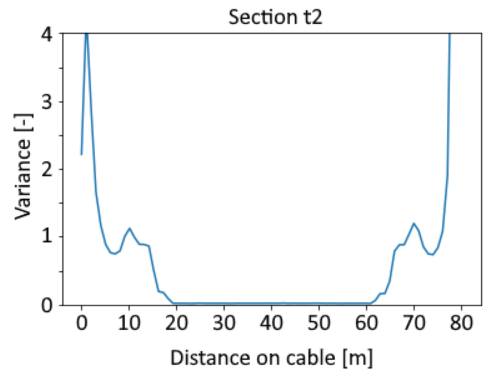


Figure 5: Variance of temperature with broken heating

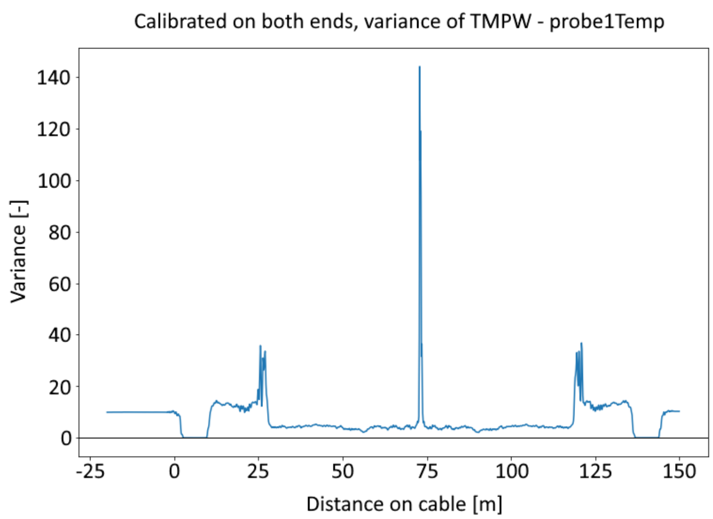


Figure 6: figure
Variance of temperature with working heating

3.3 Technical summary

During the experiment set-up multiple companies worked together, however none of them knew the experiment in detail. Therefore no one took responsibility for the required checks (working heating cable, working fibre optic cable) and materials. The checks were not performed because they were deemed unnecessary and the optic fibre cable was shortened for easier handling. This impaired measuring results due to worsened calibration capacity. Furthermore, the required equipment to perform the necessary checks was not on site. After installation it was too easily concluded that the set-up was working correctly.

4 New data

Due to the failed experiment at the Máximakanaal the groundwater velocities at the canal can not be determined. To complete the process of retrieving groundwater velocities from DTS measurements the remainder of this report makes use of data from an experiment done at the Horstermeerpolder. The Horstermeerpolder is far away from the Máximakanaal and the groundwater velocities retrieved are not comparable. The goal assessing if the canal is leaky is therefore not achieved.

The experiment at the Horstermeerpolder has a similar set-up as the one at the Máximakanaal. However, the goal is different. [des Tombe et al., 2019] created a method for determining the specific discharge. They wanted to verify if this method was still accurate for large depths (up to 45 meters) and if vertical differences in groundwater velocities could be measured. The optic fibre cable and heating cable were installed to a depth of almost -50 m with respect to NAP (see figure 9). The DTS system used is a more modern system than the experiment at the Máximakanaal, made by Sylixa. The precision and accuracy of the measurements are significantly better. The calibration bath was larger and isolated, theoretically resulting in reduced temperature fluctuations. Besides these improvements the optic fibre cable had a splice in the point of the probing device, resulting in unusable measurements near the splice due to distortions of the signal.

The remainder of this report makes use of the measurements retrieved from the experiment at the Horstermeerpolder.

5 Results

This chapter presents the results. Firstly an overview of the location and soil properties are presented with the measurements, secondly these measurements are calibrated which result in usable temperatures, thirdly the model (physical processes of water and heat transfer) is fitted to the calibrated temperatures and finally the specific discharge is estimated.

5.1 Measurements

5.1.1 Location and soil properties

Figures 8 and 9 show the location of the probing and soil characteristics of the experiment. As can been seen in figure 8 the measurements have been taken in a polder.

5.1.2 Data

The measurements result in initial temperatures. An example is shown in figure 7. The temperature response on the heating cable is clearly visible but the scale and absolute temperatures are off, besides this a day and night pattern can be recognised. In order to retrieve reliable temperatures the measurements have to be calibrated.

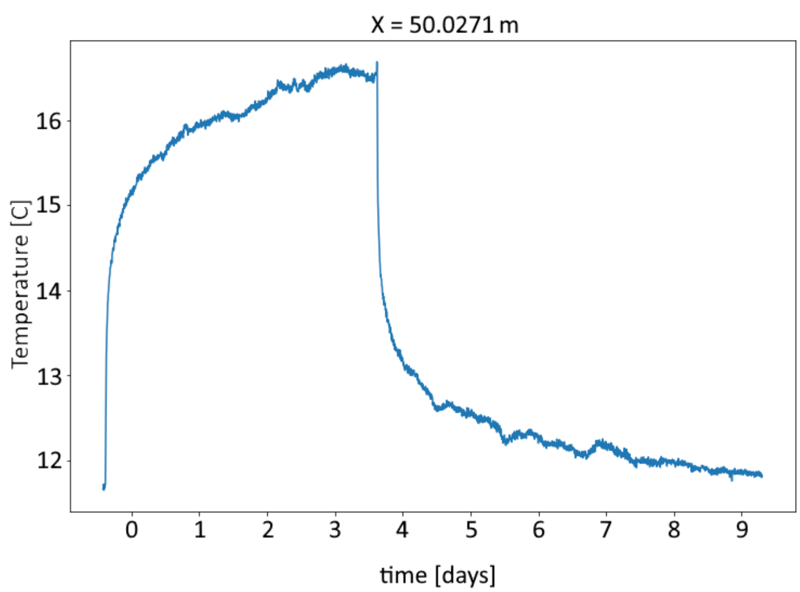


Figure 7: Initial temperature response, where x is the cable length (does not correspond to depth)

Figure 8: Overview of the location (Horstermeerpolder)

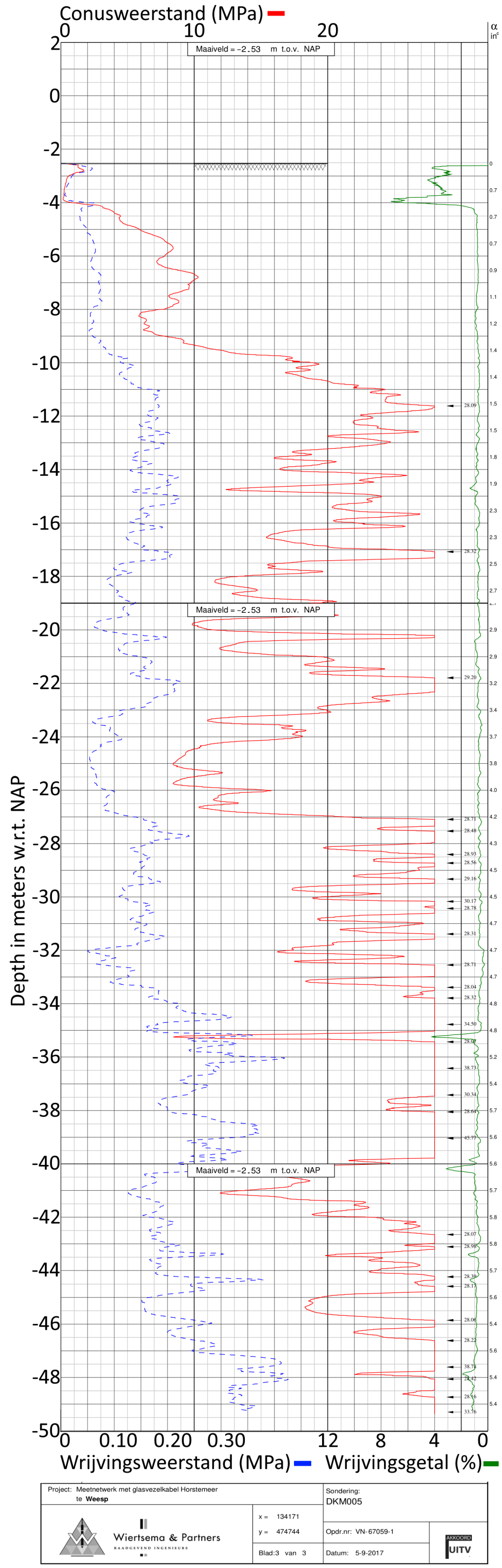


Figure 9: Probing results

5.2 Calibration

Calibration sets the temperature right by comparing the temperature of a known part of the cable to the measured values. This calibration leads to the parameters mentioned in section 2.1 which results in a more accurate representation of the temperature, this report will not go deeper into these calibration steps. It is important to realise that a wrong calibration can have disastrous results. For example a poorly positioned thermometer in the calibration bath, or a non-homogeneous temperature inside the calibration bath induces errors into the calibration. Figure 10 shows the measured temperatures from both thermometers. It is clear that there is a temperature difference between them. This could be due inhomogeneities in the temperature in the calibration bath. Figure 11 shows the result of a bad calibration. This calibration made use of both temperature measurements. Especially the cooling part is represented badly. This can be seen by comparing to figure 12b which shows the cooling temperature in blue according to formula 7. Therefore, this calibration cannot be used. Making use of the internal reference temperature is usually a bad idea (see section 3.2.2) but in this case has to be used due to the inhomogeneneous temperature in the calibration bath. This will also be treated in chapter 7.

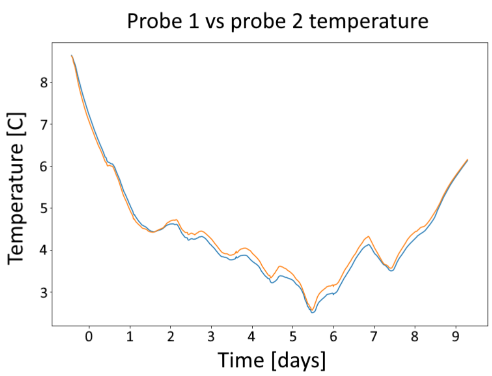


Figure 10: Calibration bath temperature according to two thermometers

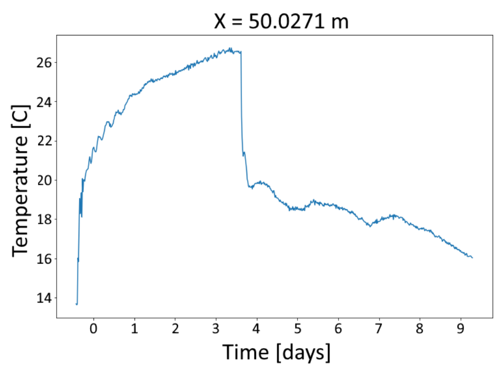
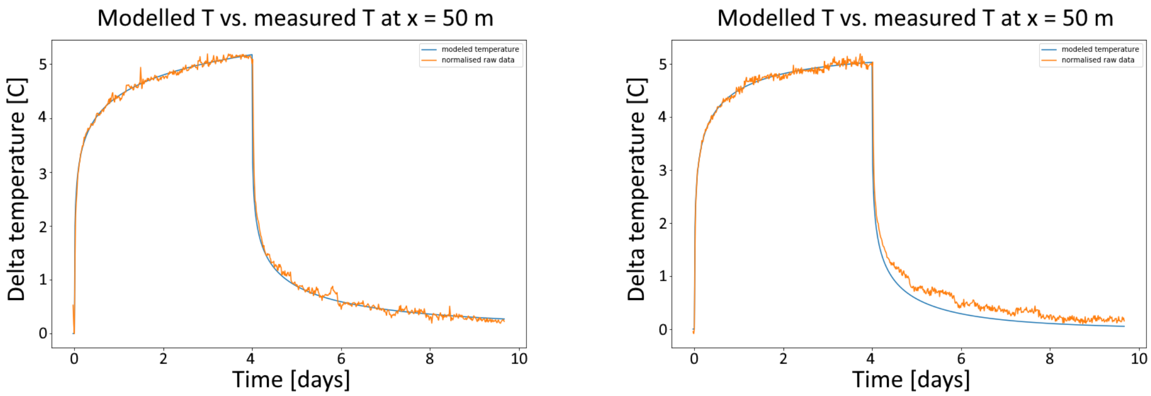


Figure 11: Day and night pattern induced by using both probes

5.3 Model fitting

As described in chapter 2 the model is fitted by fitting the normalised calibrated temperature to formula 7. This report has fitted the data solely to the heating phase of the measurements. The results in the cooling phase can therefore be off.

Figures 12a and 12b show respectively the modeled temperature and normalised raw data fitted on the calibration on the internal reference temperature and on the calibration in the calibration bath between 5.3m and 8.9m. The modeled temperature shows a better fit for the values retrieved from calibrating on the internal reference temperature. This could be caused by the inhomogeneities in the calibration bath seen in figure 10, resulting in a worse fit for figure 12b.



(a) Calibrated on internal reference temperature

(b) Calibrated on calibration bath between 5.3 and 8.9m

Figure 12: Comparison of model fitting

The result of fitting the physical model to the normalised temperature are the parameters A, $\frac{r}{B}$ and $T(t_\infty)$. The fitting method used by des Tombe et al., 2019, has been adjusted for more realistic results. These changes left out the parameter α ands will be treated in chapter 6. The parameters are then used to plot the modelled temperature response and for estimating the specific discharge.

For each measurement along the optic fibre cable, every horizontal layer of the soil, these parameters are fitted. Giving each layer their own properties. The fitted parameters are attached with this report.

5.4 Specific discharge

The specific discharge can now be determined by using equation 6. It can be seen that the specific discharge only depends on the fitted parameters A and $\frac{r}{B}$. The rest of the parameters have been estimated. This report makes use of the estimation of the parameters used in the research of des Tombe et al., 2019, who have done the experiment and provided the data from the Horstermeerpolder.

5.4.1 Cable positioning

To present the discharge in the vertical depth profile of the soil the length of the fibre optic cable underground has to be determined. This is done based on the variance. Above ground the temperature has large fluctuations, resulting in a higher variance. In the soil the temperature fluctuates less, therefore having a lower variance. This results in the fibre optic cable going into the soil at $x = 27m$ until $x = 119m$ with the centre in the middle at $x = 73m$, which can be seen in figure 13. The cable therefore is going 46 meters deep. The measurements are not accurate in the first two meters due to influences from the surface and neither in the last two meters at the bottom due to the cone left behind after installing the cables.

5.4.2 Resulting discharge

The results of the estimated discharge can be seen in figure 14a.

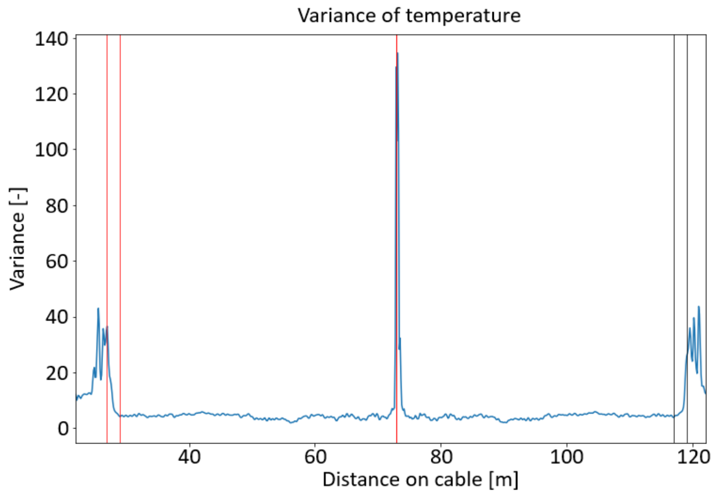
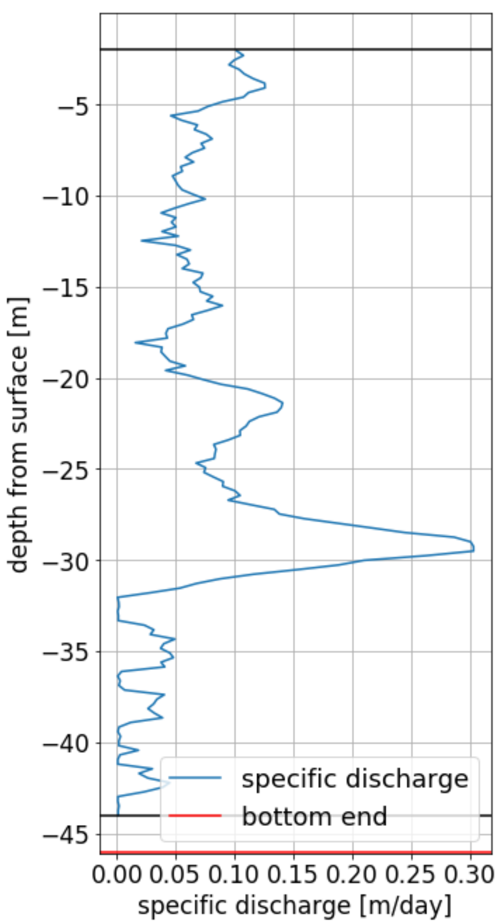
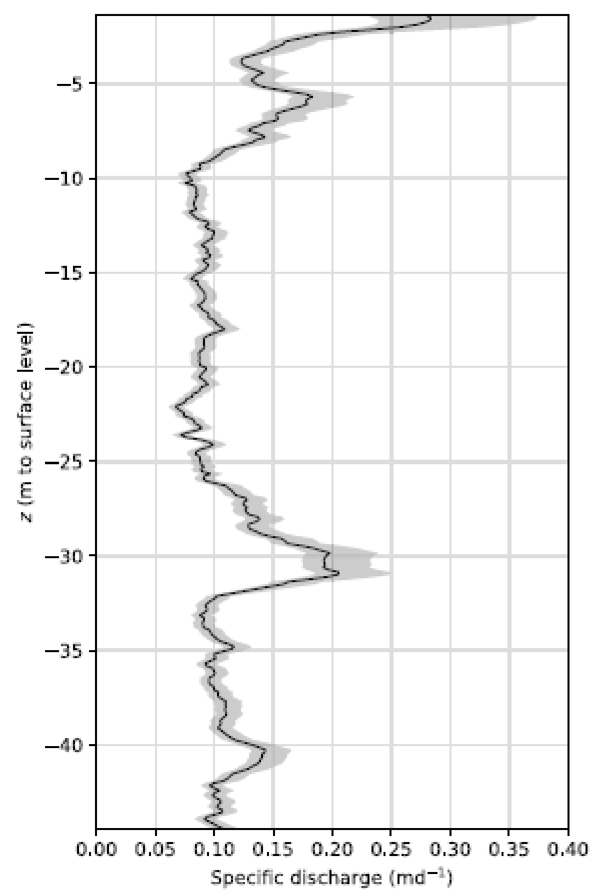


Figure 13: Variance of temperature





[0.4]

(a) Results of this study1

(b) Results of [des Tombe et al., 2019]

Figure 14: Comparison of results Horstermeerpolder

6 Conclusion

When comparing the results (figure 14a) of the paper this report is based on [des Tombe et al., 2019] and this experiment, significant differences can be observed. The main features such as the peak around -30 m are present, but the specific discharge varies a lot whereas the paper presents a more constant flow over depth, see figure 14b. Extremes are enlarged, where dips become practically zero and peaks overestimate the flow. Secondly somewhat of a vertical shift can be perceived, the peak around -30 meters is slightly shifted upwards. Due to this vertical shift the large peak in figure 14b around -2 meters falls of the image. The vertical shift can be explained due to the method used of determining the cable position, described in section 5.4.1. Due to the variance gradually becoming more constant there is a grey area in which the cable is entering the soil.

It can be concluded that the process is extremely sensitive. Differences in boundary conditions of the fitting procedure can create large differences in specific discharge. Due to this the fitting procedure can result in multiple parameters sets, which results in different specific discharges. The fitted parameters are attached at the end of this document. When comparing with the boundary conditions in table 1 it can be seen the parameters are not bounded properly by these restrictions. The fit report shows a high correlation between $\frac{r}{B}$ and $T(t_\infty)$ this can be seen in the resulting parameters as well.

Parameter	Lower boundary	Upper boundary
A	2E-5	2E-3
$\frac{r}{B}$	7E-4	7E-2
$T(t_\infty)$	0	inf

Table 1: Boundary conditions parameter fitting

As mentioned in section 5.3 the fitting procedure deviates slightly from the method des Tombe et al., 2019, describe in their paper. This results in a slightly worse fit since the fitting procedure in this experiment only minimises the root mean squared error (RMSE) instead of the root mean squared error of the noise (RMSN), excluding α. However, minimising the RMSN increases the sensitivity of the boundary conditions even more, which resulted in unrealistic groundwater velocities.

To improve the results in following studies a few recommendations are discussed in chapter 7.

7 Recommendations

This chapter treats recommendations for improving the previously presented results.

7.1 Calibration

Calibration of the measurements should be more accurate inside a calibration bath. Either due to inhomogeneities or due to time constraints the right calibration settings have not been found and instead the internal reference temperature has been used. However, using the calibration bath should result into better, more accurate results. Making sure that the calibration bath has a homogeneous temperature distribution is important. If the calibration bath can adopt a constant temperature, e.g. by cooling, will improve the results.

7.2 Fitting with α and optimising boundary conditions for A, $\frac{r}{B}$ and T

Des Tombe et al., 2019 showed that with minimising the RMSN of the measurements and the physical model the parameters A, $\frac{r}{B}$, T and α can be retrieved. This report excluded this step due to the sensitivity of the boundary conditions and minimised the RMSE instead. With the autoregressive parameter α included the parameters make the model fit extremely good but the specific discharge becomes unrealistic.

Optimising the boundary conditions of all parameters and including α should improve the results further.

7.3 Adding 95% confidence interval

A clear addition that would improve the results is the 95% confidence interval. Knowing within what kind of range the specific discharge lies adds value to the results.

7.4 Model fitting over full dataset

As has been mentioned in section 5.3 the model fitting has only been executed on the heating part of the data. This gives good results but leads to slight mistakes in parameter estimations. Including the cooling phase for fitting improves the parameter estimations.

7.5 Code optimisation

As has been mentioned in chapter 6 this report did not succeed in reproducing the results of des Tombe et al., 201,) properly. It should be noted the location of the experiment differs, albeit a couple of hundred meters. However, both experiments have been done in the Horstermeerpolder and the expected pattern has not been achieved. The lack of proper understanding of processes within python could lead to inefficient or wrong coding for this thesis. Checking parts of the code is an important improvement that should be made. Different DTS systems have different output and the code to read these can be refined. The fitting procedure which in this study came up with parameter values outside of the defined boundaries should be looked at, as well as the coding for adding the 95% confidence interval.

7.6 Plotting specific discharge

Figure 14a shows the part of the fibre optic cable going down into the soil. Due to the splice at the bottom of the probe the signal distorts and the measurements do not overlap, therefore only the part going down is plotted. Optimising by implementing the recommendations above might solve this, but this is an issue that should be looked into.

8 Acknowledgement

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