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Vertical hydraulic gradient estimation in clay till, using MiHPT advanced direct-push technology

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Abstract

The vertical transport of contaminants from source areas is employed in many risk assessment models and screening tools in order to estimate the contaminant mass discharge (CMD) into underlying aquifers. The key parameters for estimating CMD are the contaminant source area and concentration, and the vertical water flux, the latter of which depends on the vertical hydraulic conductivity and the vertical hydraulic gradient in the subsurface. This study focuses on advancing the use of the combined membrane interface probe hydraulic profiling tool (MiHPT) to investigate the vertical hydraulic gradient across a clay till overlying a sandy aquifer at a contaminated site in Denmark. Only the HPT is necessary for the estimate of vertical hydraulic gradient. The hydraulic head, clay till thickness, and resulting vertical hydraulic gradients found using the MiHPT compared well with observations from nearby nested wells. The parameter with the largest discrepancy was the thickness of the clay till. The advantage of the MiHPT is its relatively quick depth discrete access to information regarding subsurface permeability, vertical hydraulic gradients and
contaminant distribution across a site. In this case study, performance of additional dissipation tests during the HPT log to acquire determination of the vertical hydraulic gradient increased the cost by 3% compared to standard HPT logs.

**Introduction**

Worldwide, groundwater resources are at great risk of being contaminated, due to subsurface pollution from anthropogenic sources such as chlorinated solvents from e.g. dry cleaning and metal degreasing. Subsurface geology plays an important role in determining the risk of groundwater resource contamination. Aquitards have often been thought of as protective layers for underlying aquifers, but this is highly dependent on the hydrogeology and lithology of the aquitard (Cherry et al. 2006; Butler 2010; Filippini et al. 2020).

Heterogeneous geology, such as clay till, can affect contaminant transport in different ways: As a highway with contaminant transport traveling through vertical fractures, and as a channel network due to connected or embedded sand lenses (e.g. Damgaard et al. 2013; Kessler et al. 2012; Chambon et al. 2010). Furthermore, the porous matrix can act as a long-term, secondary source that leaches through back diffusion from the clay till matrix to the fractures—and thereby underlying aquifers (Chambon et al. 2011). This makes risk assessments in these settings difficult. Efficient and cost-effective approaches and methods to investigate contaminated sites in clay till settings are needed, particularly in early-stage screening investigations. A key challenge in this regard is assessing vertical transport from the clay till to the aquifer.

A useful metric to characterize the risk from a contaminated site is contaminant mass discharge (CMD), used mainly for sand and gravel aquifers and estimated at a vertical control plane in the plume down-gradient the source (e.g. Verreydt et al. 2012; Troldborg et al. 2010; Newell et al. 2011). The method can also be applied quantifying the vertical CMD from the source, with a focus
on the contaminated area, concentration, and vertical water flux from a secondary source in risk assessment models (Kamath et al. 2006; Chambon et al. 2011; RISC5 2011; Locatelli et al. 2019). Commonly, either net infiltration, often determined through large scale hydraulic models, or the product of the vertical hydraulic gradient and vertical hydraulic conductivity (Darcy’s law) (Overheu et al. 2014; Locatelli et al. 2019) is used as the vertical water flux in early-stage risk assessment. At later stage of the site investigation, estimates of the vertical water flux should be made specifically for the site. Using the vertical hydraulic gradient and vertical hydraulic conductivity is particularly relevant for contamination in areas that are paved or built up, where net infiltration is difficult to define or does not exist.

Measuring the hydraulic head variation over depth to determine vertical hydraulic gradients is a challenge using traditional nested wells as this requires several short screens. Recent studies have used depth discrete measurements of the hydraulic head within an aquitard, along with geological and hydraulic properties, to estimate the thickness and vertical hydraulic gradient of a low permeable zone, as well as to locate high permeable zones, e.g. fractured areas, within the aquitard (Meyer et al. 2008; Meyer 2014; Filippini et al. 2020). Furthermore, the high resolution profiles of hydraulic head has contributed to better understanding of the solute transport of contaminants through clayey aquitards (e.g. Keller et al. 1989; Parker et al. 2004). In clay till, several sand lenses are often embedded in the matrix, and the vertical hydraulic gradient between the sand lenses and the underlying aquifer can vary over a contaminated area. This variation is caused by the differences in the thickness of the clay till between the sand lenses and the aquifer. Determining the vertical hydraulic gradient in such a geological setting requires nested wells, well clusters or multilevel systems in order to measure the hydraulic head in both the sand lenses and the aquifer. The same notion applies, for example, when investigating the vertical hydraulic gradient within an aquifer. Furthermore, the measurements of hydraulic head within the aquitard is valuable to assess
preferential flow paths within the aquitard. Consequently, in order to determine variations in the vertical hydraulic gradient at a site, several nested wells or other monitoring systems are required.

The membrane interface probe hydraulic profiling tool (MiHPT) that has been applied in this study is a direct push tool, and over the past years it has gained acceptance as a means of field characterization in the risk assessment of contaminated sites (McCall et al. 2014; McCall and Christy 2020). The MiHPT is a combination of a membrane interface probe (MIP) and a hydraulic profiling tool (HPT). The MIP has four detectors for different contaminant groups, such as aliphatic hydrocarbon, and they indicate the contaminant level at depth on a relative scale. The HPT describes the relative permeability of the subsurface as the probe descends, by detecting the necessary pressure needed to inject a certain flow of water. Furthermore, the MiHPT detects electrical conductivity at depth. The electrical conductivity provides a measure of the soil electrical conductivity which can be used as support to distinguish between sandy and clayey materials. In order to investigate the vertical hydraulic gradient only the HPT is necessary. However, as previously stated, the MiHPT was used for this study and it will be referred to as MiHPT throughout the paper.

The objectives of this paper are (a) to evaluate the use of the MiHPT direct push method as a tool to determine the vertical hydraulic gradient between sand lenses embedded in clay till and the underlying aquifer; (b) to estimate additional cost in reference to extra time required for data gathering. This was carried out through fieldwork and a comparison of the following: Measured and estimated hydraulic heads through MiHPT estimates and hydraulic head measurements of traditional nested wells (individual well casings within a single borehole); the thickness of the clay till estimated from MiHPT logs and borehole logs; and the resulting vertical hydraulic gradients obtained via the two previously mentioned methods. Furthermore, the application of the new method for determining vertical hydraulic gradients in other geological settings, as well as its use
for estimates of hydraulic conductivity, CMD, and risk assessment, is discussed.

**Equipment and Method**

**Contaminated field site**

Field investigations were conducted at an industrial site located in Vassingerød, Denmark. A map of the site, showing well installations and infrastructure, is presented in Figure 1. Industrial activity at the site (cutting and laminating Styrofoam) started in 1962.

Site investigations have shown groundwater contamination with trichloroethylene (TCE) (NIRAS 2019). An extensive geological investigation of the site showed a sandy aquifer overlain by a clay till with embedded sand lenses (Figure 2). These sand lenses are fully or partly water-saturated.

Several monitoring wells were installed, some with screens in the sand lenses and the aquifer, respectively. Geological and hydrogeological characterization along with quantification of contaminant mass distribution were completed in both the source zone and plume areas from ground surface into the underlying sandy aquifer. Apart from knowledge from the nested wells, this was done through the use more than 20 MiHPT logs. However, not all of the MiHPT logs were operated with this study in mind. Therefore, seven MiHPT logs and seven nested wells were examined for this study.
Figure 1: Illustration of the MiHPT logs and wells at the field site located in Vassingerød, North Zealand, Denmark. The sand lens units are described in detail in the section “Comparative analysis”. The colored points are the ones referred to in this study. The MiHPT logs performed prior to this study, did not include dissipation tests in the sand lenses. Therefore, no information on the hydraulic head in the sand lenses can be obtained from these MiHPT logs, however, they support the geological model for the site. The placement of the source zone is approximate.
Figure 2: Geological profile from A-A’ (see Figure 1) along the flow direction. It illustrates the clay till with embedded sand lenses underlain by a sandy aquifer. The geological profile was created through information taken from the bore logs from nested wells, corrected HPT pressure (described in the section “Determination of the vertical head and hydraulic gradient”), and soil samples. Only the nested wells (W) and the corrected HPT pressure (H) are depicted in the figure. The field investigation focused on the hydraulic head in the sand lenses and the underlying aquifer.

Determination of the vertical head and hydraulic gradient

The vertical hydraulic gradient is defined in equation (1):

\[ i_v = \frac{\Delta h}{\Delta d} \]  (1)

where \( i_v \) (m H\(_2\)O/m distance) is the vertical hydraulic gradient, \( \Delta h \) (m H\(_2\)O) is the change in the hydraulic head, and \( \Delta d \) (m distance) is the vertical distance between the examined hydraulic heads.

In clay till with embedded sand lenses, distance (\( \Delta d \)) is assumed equal to the thickness of the low
permeable clay till, as this controls any changes in the hydraulic head ($\Delta h$) between the sand units (Cherry et al. 2006; Meyer 2014; Filippini et al. 2020). In this study, the change in the hydraulic head ($\Delta h$) is the head in the sand lens subtracted from the head of the aquifer. Hence, a negative vertical hydraulic gradient value indicates a downward hydraulic gradient.

The hydraulic heads were estimated from dissipation tests carried out as a part of the MiHPT logs (e.g. the black and blue triangles in Figure 3). A dissipation test is used to measure the naturally occurring water pressure in a saturated zone which is used to correct the HPT pressure and provide an estimate of the hydraulic conductivity. When the probe reaches a high permeability zone situated below the water table, the probe and water flow are stopped and the pressure is recorded over time until stable pressure is obtained. This stabilized pressure is the hydrostatic pressure in the formation. Subtracting the atmospheric pressure found prior to the probe advancement through a pre- and post-log HPT reference test (see McCall and Christy 2020 for more information) from the stabilized pressure indicates the hydraulic head at the specific depth of the dissipation test. It is possible to perform several dissipation tests during a MiHPT probe advancement (McCall 2011) and thereby determine depth-specific pressure potentials/hydraulic heads in high-permeability zones (McCall and Christy 2020). The data processing software for the HPT is called DI-viewer (free download from https://geoprobe.com/direct-image-viewer). This software uses the atmospheric and hydrostatic pressure to correct the HPT pressure for the pressure exceeded by the water column in the formation (corrected HPT pressure). For comparison, the hydraulic heads were measured in traditional nested wells (vertical lines, Figure 3). In both cases, a vertical hydraulic gradient can be calculated with Equation 1, when the thickness of the intermediate low-permeability layer is known. The thickness of the clay till used for the monitoring wells was found through the descriptive bore logs, where the lithology was noted every half meter and when changes were observed. For the MiHPT, the thickness of the clay till was estimated based on the corrected HPT pressure alongside
the soil’s electrical conductivity (EC). An increase in corrected HPT pressure indicates a decrease in permeability, whilst an increase in EC can indicate both an increase in the amount of clay particles and/or an increase in ionic strength of pore water (McCall 2010; Maurya et al. 2018; McCall and Christy 2020). The thickness of the clay till was estimated by a combination of an observed increase in the corrected HPT pressure along with an increase in the EC. No specific threshold of the corrected HPT pressure were used. The estimated thickness from the MiHPT is indicated with the red box overlying the logs in Figure 3.
Figure 3: Illustration of the parameters used to estimate the vertical hydraulic gradient for the MiHPT log and well. The two graphs to the left are EC and corrected HPT pressure. The third graph is the hydraulic head for the MiHPT log (H19) and well W02, where the vertical line indicates screen placement and length. The blue triangles are the dissipation test used to estimate the vertical hydraulic gradient. The bore log of well W02 is shown to the right. The illustration shows the results for sand lens unit number 5 (see Figure 2).
Comparative analysis

For each of the seven MiHPT logs, relevant nested wells were chosen based on their placement at the site with respect to which sand lens they intercepted. The sand lens units were identified from the geological interpretations at the site and regular water level measurements in the nested wells monitored over a period of nearly two and a half years. The MiHPT logs were performed during two field campaigns (two different years). At each of the field campaigns, the hydraulic heads were measured in the nested wells close by the MiHPT logs within the same week as the MiHPT logs were carried out. The lateral distance between the MiHPT logs and nested wells within a sand lens unit varied between 1.8 and 35 meter. An example of a comparison between a nested well and an adjacent MiHPT log is shown in Figure 3. The two graphs on the left of the figure illustrate results from the MiHPT log, the third shows the hydraulic head from the MiHPT and nested well, while the illustration on the right explains the geology described in the bore log.

The two measurements are different in the sense that the MiHPT is a point measurement and the nested well is an integrated measurement over the length of the screen. However, previous investigation at the site has showed no variation of hydraulic head over the depth of the sandy aquifer. Furthermore, one of the MiHPT logs had three dissipation tests carried out in the sand lens (Figure S4). This log showed no variation in the hydraulic head over the depth of the sand lens. Therefore, the comparison between the two methods at this field site is acceptable.

In total, five different sand lens units were compared (Figure 1), representing seven MiHPT logs and seven nested wells. Please note that the relevant well in sand lens unit 3 (W11) was dry at the time the H20 was performed, so the “measured” hydraulic head in W11 was set equal to the bottom of the screen. The water levels in the nested wells were, as mentioned previously, monitored regularly and W11 showed similar trends in decrease and increase of the hydraulic head as the nested wells nearby. Therefore, it was assumed that the hydraulic head in W11 followed observed changes in
other sand lenses at the site, from August 2018 to November 2018. Subtracting the decrease in the observed hydraulic head in the nearby nested wells from the observed hydraulic head in W11 in August 2018, resulted in a hydraulic head equaling the bottom of the screen for W11. Therefore, the assumption seemed justified.

The comparison was done for both the estimated hydraulic heads in the sand lenses and the aquifer, the thickness of the clay till, and for the estimated vertical hydraulic gradient between the sand lenses and the aquifer. For each of these comparisons, the difference in head between the MiHPT and wells was calculated as (2):

$$Diff\ % = \frac{\text{MiHPT}_{-}\text{well}}{(\text{MiHPT}_{+}\text{well})/2} \cdot 100\%$$  \hspace{1cm} (2)

where $\text{MiHPT}$ and $\text{well}$ are the head, thickness of clay till, or vertical gradient estimated from the MiHPT and well, respectively. A negative number indicates that the results from the MiHPT measurements were lower than from the well measurements and vice versa.

**Estimation of additional time and cost for the dissipation tests**

Additional time in the field, required for the extra dissipation tests, was calculated as the difference between the time spent on the dissipation tests, viewing the results as a standard MiHPT log, and as an investigation into the vertical hydraulic gradient. The additional cost was calculated using an estimate of the cost of the dissipation tests for each of the MiHPT logs. As the investigations were carried out in Denmark, the cost was converted from Danish crowns (DKK) to US$. The absolute cost will differ for other geologies and countries, as it is dependent on the permeability of the soil and the hourly price charged by technicians carrying out the work.
Results

Estimated hydraulic head

A comparison of the estimated hydraulic heads in the sand lenses from the MiHPTs and wells showed very good accordance (Figure 4a, Table S1 and Figures S1-S7). Differences between hydraulic head estimates from the MiHPTs compared to the wells were between -0.66% and 1.3%.

The estimated hydraulic head from the two methods in the aquifer also compared very well. The differences between the estimates were small and varied between -1.3% and 0.78%. Overall, both the results from the sand lenses and the results from the aquifer showed that the MiHPT made a good estimate of the hydraulic head. Furthermore, there was no trend in whether the hydraulic head from the MiHPT was higher or lower than what was measured by the traditional hydraulic head measurement in wells. This indicates that it is rather a local variation in the head than any uncertainty in the method causing differences in measurements.
Figure 4: a) The estimated hydraulic head found from the MiHPT logs and the wells. b) The vertical hydraulic gradients estimated from the MiHPT logs and well. The negative values for the vertical hydraulic gradient indicate an overall downward vertical hydraulic gradient.

The biggest difference in hydraulic head estimates in the sand lens was observed in sand lens unit 1 (Figure 4a and Figure S1-S3). Here, the measured hydraulic head in the wells showed a slightly lower hydraulic head than the three MiHPT logs. This is a unit with a relatively large spatial volume (see Figure 1) where the geology is less well-known than for the other units. Therefore, differences in the hydraulic heads could imply that the investigated sand layer does not constitute a single sand lens but rather some smaller disconnected sand lenses. The biggest difference in hydraulic head estimates in the aquifer was observed in sand lens unit 4 (Figure 4 and Figure S6). The screen was
placed in the transition zone between the clay till and the aquifer, where permeability is not as high as in the aquifer. The dissipation test was performed at the same depth as the screen was placed, but unfortunately stable values were not obtained, most likely causing the difference in the hydraulic head.

**Thickness of the clay layer**

In sand lens unit 4, the difference between the thickness of the clay till layer estimated from the MiHPT and the well log (Figure S6) was very small (-2.6%). However, the thickness of the clay till was overall the parameter that differed the most in the comparison between MiHPT estimates and the well logs. The differences between the two methods were between -79% and 64%, and hence there was no trend in whether the MiHPT yielded a thicker or a thinner layer of clay till than the bore log of the well, which once again indicated no systematic difference between the methods. The thickness of the clay till is determined in different ways in the two methods: From the nested wells, geologic interfaces are estimated while drilling and the soil samples subsequently geologically evaluated. Whereas, for the MiHPT, it is determined from depth discrete logs of subsurface permeability and hydraulic properties. The interpreted thickness of the clay till therefore differed somewhat due to differences in the methods. This results in some discrepancies in the calculated vertical hydraulic gradient, as shown in the section “Comparison of vertical hydraulic gradient estimates using the two methods”.

The largest differences were seen in sand lens units 3 and 5 (Figure S5 and S7, respectively). In both cases, the thickness estimated from the MiHPT was smaller than from the well logs. The detailing of the bore log in sand lens unit 3 was sparse. The thickness of the clay layer from one of the bore logs located in sand lens unit 5 was found to be very heterogeneous and consisting of clay and silt, which resulted in a larger thickness than found with MiHPT. Observations of the lithology in bore logs can vary according to the person describing the sediment as well as the recovery of the
soil on the auger. Furthermore, drilling makes the sample interval more uncertain than for the MiHPT. The thickness of the clay till from the MiHPT is dependent on how the logs are interpreted. For instance, the chosen corrected HPT pressure at which you would expect clay materials, or whether the EC has been used to back up the estimated thickness of the clay till. However, the data from the MiHPT is more discretized than the samples from the bore logs.

The observed differences did not indicate a systematic divergence between the methods, as they showed both higher and lower estimates from the MiHPT than from the well; therefore, these differences were mainly due to local geological spatial variations and as mentioned before, the interpretation of the MiHPT logs and the bore logs.

**Comparison of vertical hydraulic gradient estimates using the two methods**

The resulting vertical hydraulic gradients (Figure 4b) showed good agreement between the two methods. The difference between the estimates was between -49% and 58%. There was no pattern in whether the use of the MiHPT resulted in a higher or a lower vertical hydraulic gradient than the wells. The highest difference was seen in sand lens unit 3, which also had the highest difference in the thickness of clay till estimated from the two methods. Another difference was found in sand lens unit 1, which covers a large area. The large variation in both the hydraulic head and the vertical hydraulic gradient could imply that there is more than one sand lens in unit 1. It was determined that the highest gradient observed at the site is related to the thinnest separating clay unit.

**Estimated cost of the additional dissipation tests and materials**

The time spent to perform the additional dissipation tests required to evaluate the vertical hydraulic gradient at the field site was 76 min in total for four of the MiHPT logs (H18-H21), i.e. an average of 19 min per MiHPT log (Table 1). This resulted in an added cost of 39 USD (Danish price level), or an increase of 48%, when only considering the time spent on the dissipation tests. Taking into
account the cost of the logs (the drilling and dissipation tests), the cost increase was only 3% for the total field work required for the four MiHPT logs, which took place over three days. This corresponds to an increase of the daily workload of 25 min for the drilling team. It should be noted that this added cost is without desktop time for interpretation however, this part is difficult to calculate as the new data also allows for estimation of the vertical contaminant mass discharge, which could not be determined properly without this information (see discussion section). The time required for the dissipation test will be dependent on the soil permeability.

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>Time and cost of performing one MiHPT log, with and without the focus on estimating the vertical hydraulic gradient.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dissipation tests needed</th>
<th>Time spent on dissipation tests</th>
<th>Dissipation tests</th>
<th>Total, drilling + dissipation test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular MiHPT</td>
<td>4 tests</td>
<td>27 min</td>
<td>82 USD</td>
</tr>
<tr>
<td>Vertical hydraulic gradient MiHPT</td>
<td>6 tests</td>
<td>46 min</td>
<td>121 USD</td>
</tr>
<tr>
<td>Additional test, time and cost</td>
<td>2 tests</td>
<td>19 min</td>
<td>48%</td>
</tr>
</tbody>
</table>

The estimate is based on an average of four of the MiHPT logs from the field site (H18-H21), taken over three days.
Discussion

Vertical hydraulic gradient measurements

The results showed that the vertical hydraulic gradient can be determined with reasonable confidence in a clay till setting, using MiHPT and nested wells, respectively. Vertical hydraulic gradient estimation is relevant not only for clay till sites, but also in general for low-permeability aquitards. Baiocchi et al. (2013) simulated a hydrogeological system from Cimino-Vico (Italy), consisting of two aquifers separated by an aquitard (vulcanite and flysch). They found that the vertical hydraulic conductivity and thickness of the aquitard, and hence the vertical hydraulic gradient, were the main drivers of the interaction between the two aquifers. Cherry et al. (2006) & Meyer et al. (2008) discussed the use of detailed head profiles to locate contrasting hydraulic conductivity units and where aquitards are fractured or disconnected. The combination of the HPT pressure log and the dissipation test (i.e. hydraulic head measure) from the MiHPT offers the opportunity to generate continuous vertical profiles of permeability and hydraulic head both within and across an aquitard. Therefore, it is possible to use the MiHPT to evaluate the plausible path for water flow and contaminant transport within an aquitard. Hart et al. (2008) suggest that the best location for measuring the vertical hydraulic gradient is in the layer boundary, which can be difficult to determine beforehand when installing nested wells. Due to the uncertainty regarding the recovery of the soil on the auger, the exact location of the boundary layer between two units can be difficult to determine as precisely during drilling as is possible with the MiHPT. Furthermore, the screens in the nested wells give an average of the hydraulic head across the screen length, and therefore not the actual hydraulic head in the boundary layer. The permeability reading from the MiHPT can be helpful in investigating the optimal placement of the dissipation tests, but moreover, utilizing the MiHPT as described in this paper is also applicable when investigating the vertical hydraulic gradient within an aquifer.
Application of the vertical hydraulic gradient for CMD estimates

At a contaminated site, both vertical and horizontal contaminant mass discharges are widely used measures to perform a risk assessment. Vertical contaminant mass discharge is used to describe how much contamination is leaching from the source zone into the underlying aquifer (contaminant mass/time), and most often, it is described as (3) (e.g. Locatelli et al. 2019):

\[ CMD_v = C \cdot A \cdot I \]  \hspace{1cm} (3)

where \( CMD_v \) is vertical contaminant mass discharge, \( C \) is concentration (contaminant mass/volume), \( A \) is area (distance squared), and \( I \) is infiltration (distance/time), the latter of which is often determined at a regional scale, whereas both area and concentration are given for a specific site. In some instances, infiltration can be difficult to justify, due to paved areas and buildings on the surface and preferential pathways in the subsurface. In order for all three parameters to be site-specific, infiltration can be substituted by the vertical hydraulic gradient and vertical hydraulic conductivity, which will result in (4):

\[ CMD_v = C \cdot A \cdot K_v \cdot i_v \]  \hspace{1cm} (4)

where \( K_v \) is vertical hydraulic conductivity (length/time). The vertical hydraulic gradient can be determined for the site by using the MiHPT tool as described in this paper.

For the field site used in this study, elaborate field investigations and modelling of the site show a site specific vertical hydraulic conductivity of the clay till between \( 6.1 \cdot 10^{-9} \) m/s and \( 8.2 \cdot 10^{-9} \) m/s.

Other field and modeling studies of Danish clay tills have shown vertical hydraulic conductivities ranging between \( 1.2 \cdot 10^{-7} \) and \( 1.5 \cdot 10^{-9} \) m/s (Nilsson et al. 2001; Jørgensen et al. 2002, 2004; Mosthaf et al. 2020), which places the vertical hydraulic conductivity for this specific site in the low range.

Applying site specific information of the source area, as well as concentrations therein and averaged estimated vertical hydraulic gradient found in this paper (440 m², 3000 µg/L and 0.44, respectively),
the resulting vertical CMD of TCE from the clay till into the aquifer is between 112-149 g/year. This compares well with the initial site investigation estimating a vertical CMD of 27-202 g/year (NIRAS 2019).

**MiHPT and nested wells as tools for site investigations**

Using the MiHPT as a tool with a focus on obtaining information about the vertical hydraulic gradient will provide the risk assessment of a contaminated site with crucial data. In addition, a variety of depth discrete information can be collected, including: Subsurface permeability, an estimate of hydraulic conductivity, and the distribution of contaminants at depth. Furthermore, the correlation of geological units can be done with a higher degree of certainty compared to the subjective geologically interpreted bore logs. However, some knowledge of the local geology is needed, as the MiHPT probe does not provide aquitard/aquifer material for geological description. With the MiHPT, it is possible to obtain information on variations in the vertical hydraulic gradient across a site with multiple different embedded sand lenses in clay till, as well as depth discrete information on the relative contaminant level and permeability of the subsurface. The pressure measurements for the MiHPT log is performed with the use of a pressure transducer. A calibrated transducer typically has an accuracy of +/- 7 kPa or +/- 0.07 meter of water under static conditions. Applying this accuracy to the sand lens unit with the highest difference between the MiHPT and well measurements (sand lens unit 1), results in an increased difference between the methods from 1.3 % to 1.5 %. This is acceptable taking the uncertainty of the estimate of the clay layer thickness into account. The disadvantage of the MiHPT is that it is not a permanent installation, and therefore it is not possible to investigate changes in the relative contaminant levels and vertical hydraulic gradients over time at the same point. The use of other direct push probes can also provide information on the vertical hydraulic gradient, as long as the probe shows subsurface permeability (e.g. corrected HPT pressure), the EC signal,
and is able to perform a dissipation test or in other ways determining the hydraulic head. Such a probe could be: the combined HPT-GWS or Waterloo APS, which both allows for groundwater sampling in the high permeable layers of the aquifer, or simply the HPT or CPT.

An advantage of the nested well is the ability to monitor changes in both contamination and the hydraulic head over time. In addition, information from soil samples is obtained when drilling is carried out. The disadvantage of the nested well is that information is only available for the specific depths and lengths of the screens installed (low discretization and integrated measurements over the screen length).

Overall, the two methods are useful at different times during a site investigation. The MiHPT can be used as a screening tool to do an initial investigation at a contaminated site in respect to which further site investigations are needed as well as the placement of these. The logs from the MiHPT can be used to assist in the placement of the nested wells or other permanent monitoring systems such as multilevel systems. Furthermore, the MiHPT logs can be used to determine whether or not these monitoring systems are even needed for further investigation of the site in question.

**Conclusion**

This field study investigated the possibility of estimating the vertical hydraulic gradient between two aquifers separated by a low-permeability layer such as clay till, using the MiHPT tool. A comparison between the MiHPT and nested wells paired in five different sand lens units showed very good accordance between the two approaches. Hence, it is possible to investigate the relative contaminant level, the hydrogeology of the subsurface, and the vertical hydraulic gradient, using the MiHPT. The daily added workload in the field for investigating the vertical hydraulic gradient in our case was 25 minutes, but this would of course vary depending on the permeability of the soil and aquifer material in question.
It is expected that the results shown in this paper will also apply to complex unconsolidated geologies other than clay tills, as well as open up the possibility of obtaining vertical hydraulic gradients within aquifers. The cost is expected to be less for a less complex geology, as this would most likely require fewer dissipation tests.

This study advocates for the use of the vertical hydraulic gradient combined with vertical hydraulic conductivity, in order to estimate the vertical contaminant mass discharge from the source zone into an underlying aquifer. Both the MiHPT and the nested well offer the ability to obtain vertical hydraulic gradients. Using the MiHPT, with a focus on the vertical hydraulic gradient, as a screening tool, supplemented with nested wells and/or other field methods to quantify the specific contaminant concentrations at a site, allows for a better risk assessment.
References


Meyer, J.R., B.L. Parker, and J.A. Cherry. 2008. Detailed Hydraulic Head Profiles as Essential Data


Supporting Information:

Table S1

The difference in estimate of hydraulic head, thickness of clay layer and vertical hydraulic gradient.

<table>
<thead>
<tr>
<th>Sand lens unit #</th>
<th>Hydrualic head</th>
<th>Thickness of clay layer</th>
<th>Vertical hydraulic gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sand lens</td>
<td>Aquifer</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.3 %</td>
<td>0.48 %</td>
<td>64 %</td>
</tr>
<tr>
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<td>-0.10 %</td>
<td>-0.35 %</td>
<td>50 %</td>
</tr>
<tr>
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<td>0.03 %</td>
<td>-79 %</td>
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<tr>
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<td>-1.25 %</td>
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<td>5</td>
<td>0.50 %</td>
<td>0.78 %</td>
<td>-14 %</td>
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* the screen located in the sand lens in the two relevant wells were dry at the time of the fieldwork.

The hydraulic head in the sand lens has therefore been set to be equal the bottom of the lower of the two screens. The calculations show the difference from the MiHPT compared to that of the wells for each of the five sand lens units. As some units have more than one of each measurement per method, the stated value is the largest difference within the sand lens unit. A negative value is showing that the estimate from the MiHPT is smaller than that of the well.
Figure S1: Illustration of the parameters used to estimate the vertical hydraulic gradient for the MiHPT log and two wells. The two graphs to the left are EC and corrected HPT pressure. The third graph is the hydraulic head for the MiHPT log (H23), well W06 (black) and well W20 (blue), where the vertical line indicates screen placement and length. The blue triangles are the dissipation test used to estimate the vertical hydraulic gradient. The bore logs of the wells are shown to the right. The illustration shows the results for sand lens unit number 1 (see Figure 2).
Figure S2: Illustration of the parameters used to estimate the vertical hydraulic gradient for the MiHPT log and two wells. The two graphs to the left are EC and corrected HPT pressure. The third graph is the hydraulic head for the MiHPT log (H22), well W06 (black) and well W20 (blue), where the vertical line indicates screen placement and length. The blue triangles are the dissipation test used to estimate the vertical hydraulic gradient. The bore logs of the wells are shown to the right. The illustration shows the results for sand lens unit number 1 (see Figure 2).
Figure S3: Illustration of the parameters used to estimate the vertical hydraulic gradient for the MiHPT log and two wells. The two graphs to the left are EC and corrected HPT pressure. The third graph is the hydraulic head for the MiHPT log (H25), well W06 (black) and well W20 (blue), where the vertical line indicates screen placement and length. The blue triangles are the dissipation test used to estimate the vertical hydraulic gradient. The bore logs of the wells are shown to the right. The illustration shows the results for sand lens unit number 1 (see Figure 2).
Figure S4: Illustration of the parameters used to estimate the vertical hydraulic gradient for the MiHPT log and well. The two graphs to the left are EC and corrected HPT pressure. The third graph is the hydraulic head for the MiHPT log (H21) and well W08, where the vertical line indicates screen placement and length. The blue triangles are the dissipation test used to estimate the vertical hydraulic gradient. The bore log of the well is shown to the right. The illustration shows the results for sand lens unit number 2 (see Figure 2).
Sand lens unit 3

Figure S5: Illustration of the parameters used to estimate the vertical hydraulic gradient for the MiHPT log and well. The two graphs to the left are EC and corrected HPT pressure. The third graph is the hydraulic head for the MiHPT log (H20) and well W11, where the vertical line indicates screen placement and length. The blue triangles are the dissipation test used to estimate the vertical hydraulic gradient. The bore log of the well is shown to the right. The illustration shows the results for sand lens unit number 3 (see Figure 2).
Figure S6: Illustration of the parameters used to estimate the vertical hydraulic gradient for the MiHPT log and well. The two graphs to the left are EC and corrected HPT pressure. The third graph is the hydraulic head for the MiHPT log (H18) and well W13, where the vertical line indicates screen placement and length. The blue triangles are the dissipation test used to estimate the vertical hydraulic gradient. The bore log of the well is shown to the right. The illustration shows the results for sand lens unit number 4 (see Figure 2).
Figure S7: Illustration of the parameters used to estimate the vertical hydraulic gradient for the MiHPT log and two wells. The two graphs to the left are EC and corrected HPT pressure. The third graph is the hydraulic head for the MiHPT log (H19), well W02 (black) and well W18 (blue), where the vertical line indicates screen placement and length. The blue triangles are the dissipation test used to estimate the vertical hydraulic gradient. The bore logs of the wells are shown to the right. The illustration shows the results for sand lens unit number 5 (see Figure 2).