Using Mise-a-la Masse to delineate conductive aquifers

ABSTRACT

Mise-a-la-masse is one of the oldest geophysical methods. It is an electrical resistivity technique that has historically been used in the mining industry to map the orientation and approximate limits of electrically conductive ore bodies at depth. More recently, this method has successfully been used to delineate the limits of contaminated aquifers and coastal saline-water intrusion. In this study, we use the MALM method in combination with surface resistivity measurements to map the limits of a conductive aquifer at depths that would make it difficult to map using only surface resistivity measurements.

Mapping the limits of an aquifer with high total dissolved solids (TDS) is often conducted using a combination of drilling and pumping tests. In certain areas however, drilling additional holes may not be possible or practical, and in these situations geophysical methods are often used to help fill in the data gaps. Surface geophysical methods, however, are subject to decreasing sensitivity with depth, and may have difficulty detecting a high-TDS aquifer when it is thin and deep. Under certain circumstances this problem can be addressed using Mise-a-la-masse (MALM). This combined geophysical survey provided a valuable contribution to this investigation because it took place at a site that is ecologically and archaeologically sensitive, limiting the number of boreholes that could be drilled.

INTRODUCTION

The site for this study was located in northern Alberta. At the site, a single borehole encountered a thin aquifer with high total dissolved solids (TDS) that was of concern for the local industrial operator. The proximity of a river meant that additional drilling to map the limits of the aquifer needed to be limited to a few holes; however, understanding its limits was important to the operator.

The region is the setting for large-scale resource extraction, which can result in the production of high-TDS fluids that need to be properly disposed of. The region also hosts the large-scale dissolution of a deep salt layer that can result in the formation of naturally occurring high-TDS aquifers. Differentiating between these sources is important to ensuring that high-TDS fluids resulting from industrial operations are not being released into the environment.

Geophysical methods are a good option for acquiring information about the subsurface away from drill-holes and where drilling is not an option. Geophysics can also make drill investigations more efficient by targeting drilling based on an estimate of subsurface properties. The objective for this study; however, was not an ideal target for commonly used geophysical methods. This study focuses on the use of Mise-a-la-masse, which is an older geophysical method that is not commonly used, to address some of these limitations to allow mapping of the limits of the anomalous high-TDS aquifer.

METHODS

Subsurface mapping using geophysical methods is based on certain physical properties of the soil, and identification of an anomaly requires that there be a measurable contrast in those physical properties.

High-TDS in pore fluids typically result in high electrical conductivity (or low electrical resistivity) which for the setting of this study would be a contrast with the host formation sands as shown in Figure 1. This is similar to many environmental remediation sites and is the reason that electrical methods such as electromagnetics (EM) or electrical resistivity tomography (ERT) are typically used to map the extent of high-TDS fluids at these sites. The depth and thickness of the aquifer detected at this site was such that the expected electrical conductivity contrast would not be measurable from the surface using these commonly used methods.

To address the objectives of this study, we chose to use a combination of ERT and Mise-a-la-masse, which is an older geophysical technique originally designed to map the extent of ore bodies at great depths. Although we did not expect the ERT method to be able to map the limits of the conductive aquifer where it was very thin, it uses the same survey equipment and layout as the MALM method so we took the opportunity to collect both datasets to compare and contrast the methods for this difficult target.

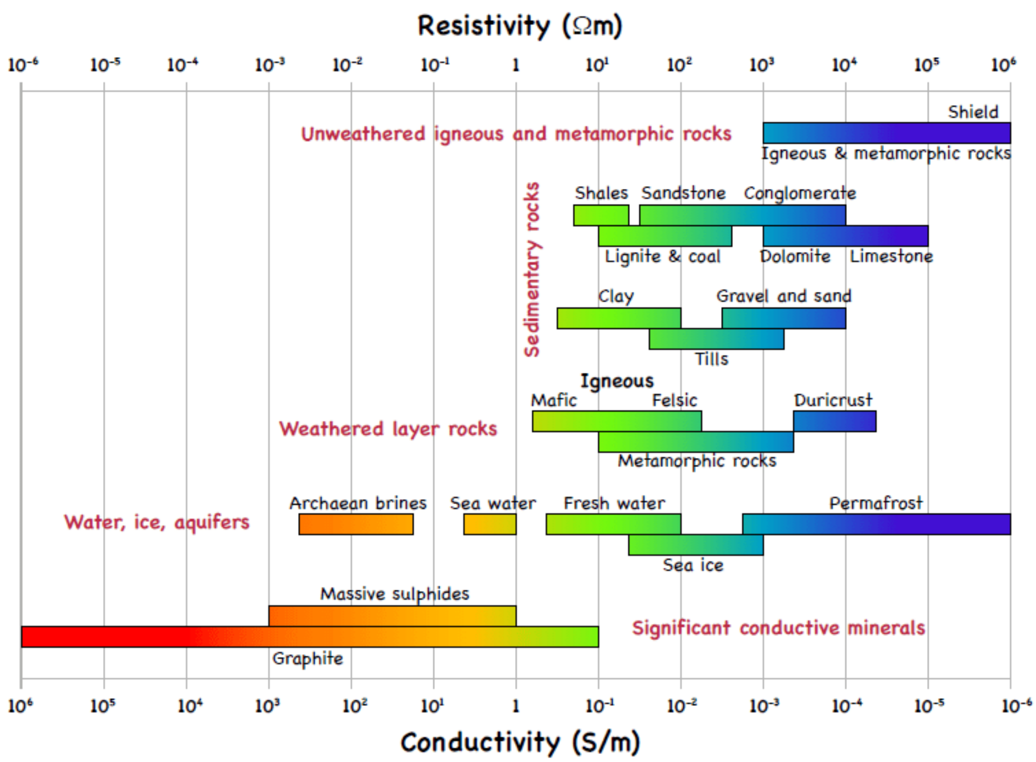

Figure 1: Typical ranges of electrical resistivities for common subsurface materials (from Yeomans, 2011). For this study, it is important to note that salt water is orders of magnitude less resistive than the host formation sands.

Electrical Resistivity Tomography (ERT) method

The ERT method is commonly used to map the distribution of subsurface materials with varying electrical conductivities such as clays, gravels, and high-TDS water. The method involves injecting current between two electrodes on the surface and then measuring the electrical potential differences between electrodes at other locations on the surface as shown in Figure 2.

The results from an ERT survey are inverted to produce sections of electrical resistivity (or conductivity) that are used to interpret the locations of units of contrasting electrical properties.

One of the limitations of the method is resolution, which decreases with depth. This limitation means that electrically conductive units such as the target for this study may be detectable if they are thin and near the surface, but they may not be detectable if they are thin and deep.

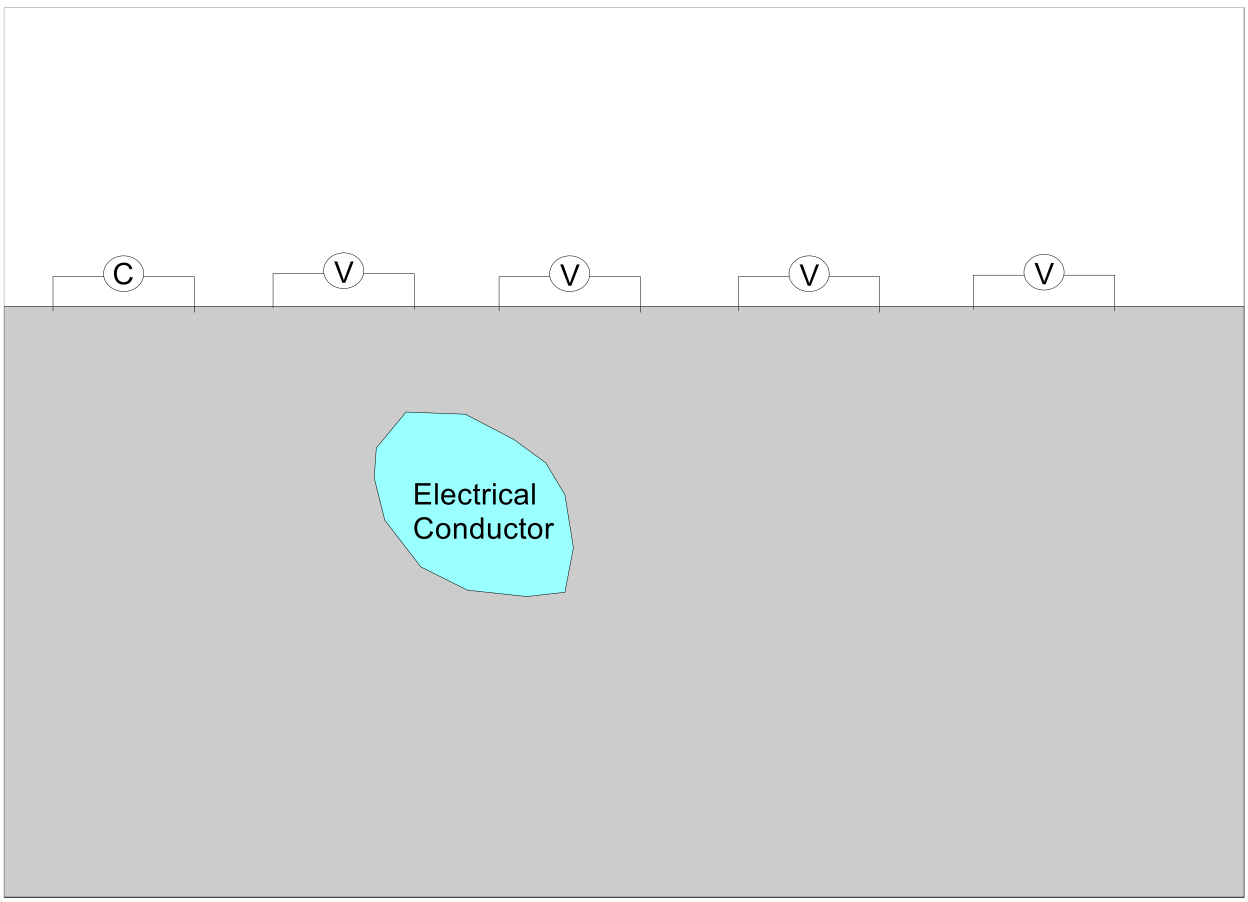

Figure 2: Typical set-up for an ERT survey. In this image "C" represents the current electrodes and "V" represents the potential difference measurement electrodes.

Mise-a-la-masse (MALM) method

The MALM method was originally a mining technique that was used to define the orientation of electrically conductive ore bodies (Schlumberger, 1920; Parasnis, 1967). The method involves placing a current electrode into an ore body and a distant current electrode outside of the survey area as shown in Figure 3. Current is injected across the current electrodes and electrical potential voltages are measured on the surface from the ore body outward.

Above the conductive body, the electrical potential gradient radiating out from the current injection borehole is low, and outside of the conductive body the gradient increases, as shown in Figure 4, indicating the approximate edges of the ore body. Recently, the MALM method has been used to delineate the approximate shape of electrically conductive groundwater plumes (Osiensky & Donaldson, 1994; Osiensky, 1997; Nimmer & Osiensky, 2002; Perri, et al., 2018).

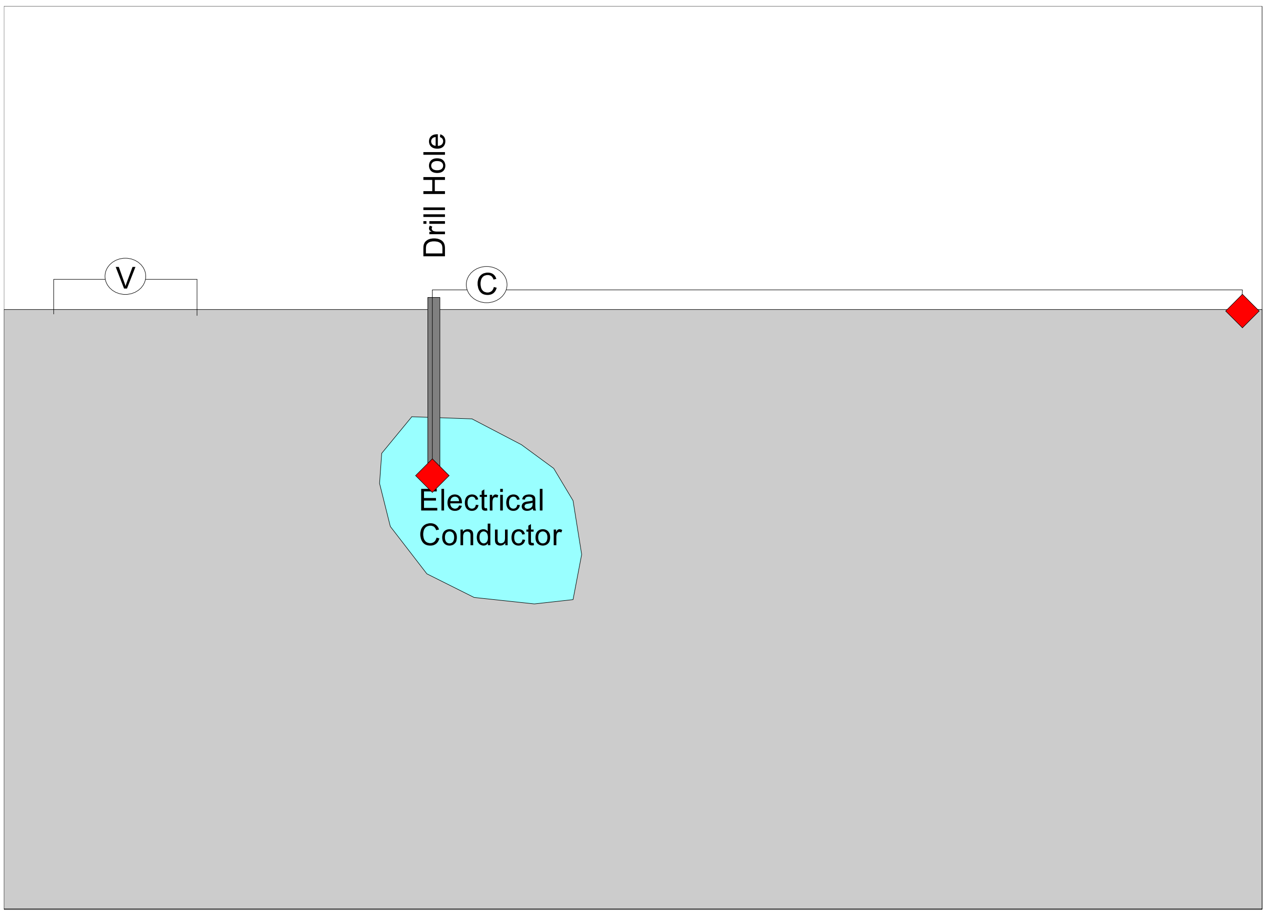

Figure 3: Typical set-up for a MALM survey. In this image "C" represents the current electrodes and "V" represents the potential difference measurement electrodes.

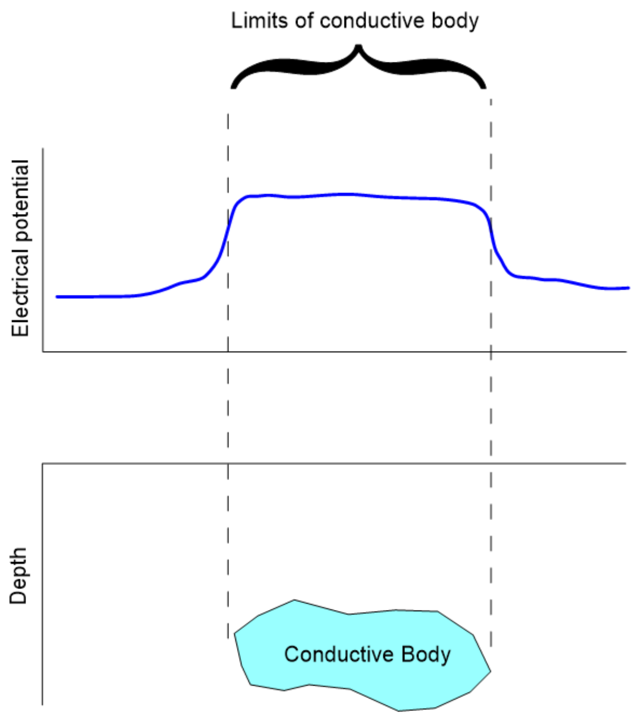

Figure 4: Illustration of the electrical potential over a conductive body for a typical MALM survey. The limits of the conductive body are determined based on the potential drop-off at its edges.

Forward Modelling

While geophysical surveys can bring great value to a project by being able to provide information where it is impractical to drill, it also comes with risks. One of the risks of using any geophysical survey is that there is not a measurable contrast in the physical properties being measured or that the survey is not designed appropriately to map that contrast. This can lead to an unsuccessful project, which may damage the user's confidence in geophysical techniques for future projects. To reduce this risk, forward modelling of the geophysical survey over expected geology can be used to guide survey design and to build confidence that the survey will be successful.

For this project the expected geology presented several challenges for the design of a geophysical survey including: the conductive aquifer was anticipated to be both thin and deep; there was a potential for near-surface electrically conductive clays which may limit the success of the survey; and the survey lines that were available to us were not typical for MALM surveys as shown in Figure 5.

We tested the feasibility of the survey design for this project using forward modelling to examine the effect of a thinning conductive aquifer and near surface conductive clays. Based on the forward modelling, we determined that the MALM method would be effective when the conductor is thin and that the effect of near-surface clays would be negligible. We also determined that we could effectively estimate what the potential surface would look like based on the modified acquisition geometry.

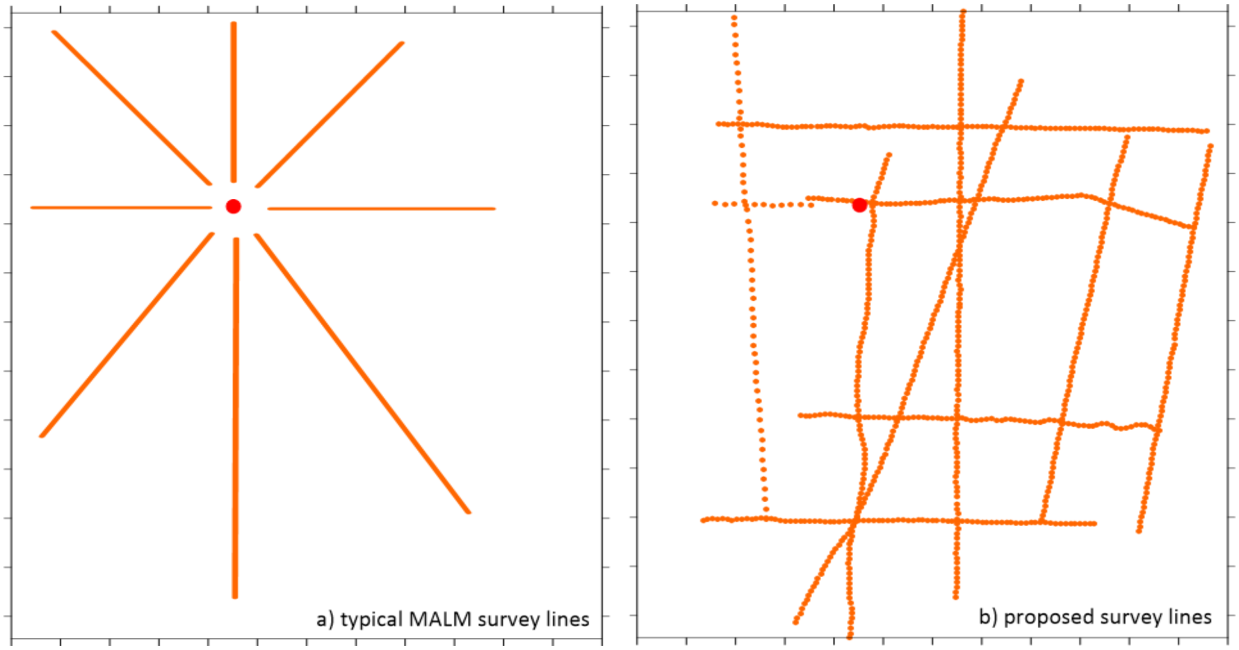

Figure 5: Illustration of a) typical MALM acquisition setup and b) the survey lines that were available for this survey. The well that encountered the high-TDS aquifer is marked in red.

RESULTS AND DISCUSSION

The ERT portion of the study showed that there is a ~ 4 m thick aquifer as shown in Figure 6. The western edge of the conductive aquifer noted in the ERT data appeared to be at the borehole where the high-TDS fluids were encountered.

The present study differs from many of the typical MALM surveys in the orientation of the potential difference measurements: in typical MALM surveys, potential differences are measured radially from the current electrode that is located in the electrical conductor; and in the present study, potential difference measurements were acquired along survey lines that were predominantly EW and NS. The result of this modified geometry was that the raw data (shown in Figure 7) were not straight forward to interpret because only one component of the potential gradient was measured. The potential field surface was estimated using Tikhonov regularization.

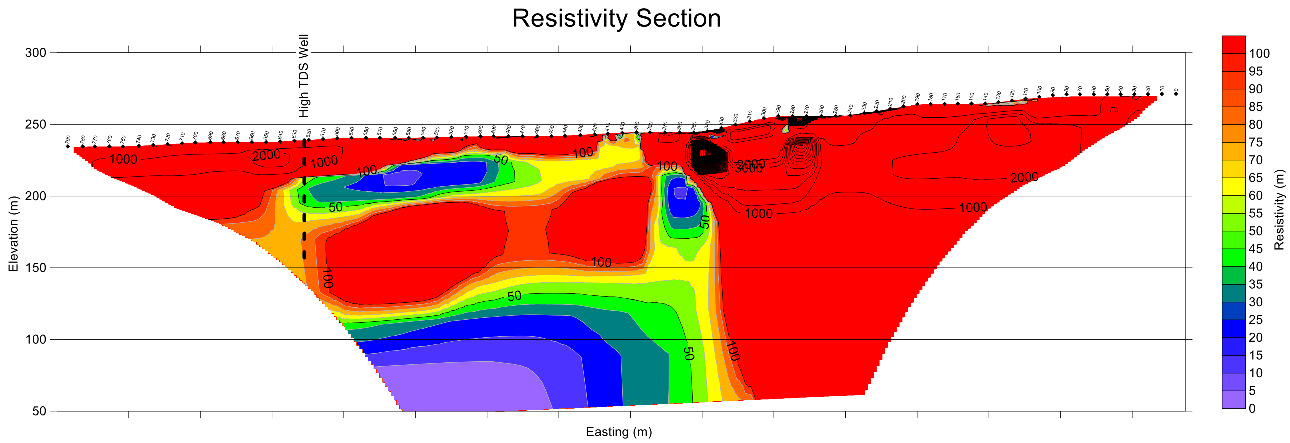

Figure 6: Results from the ERT survey. These results show that there is a conductive unit to the east of the well that noted the high-TDS water sample.

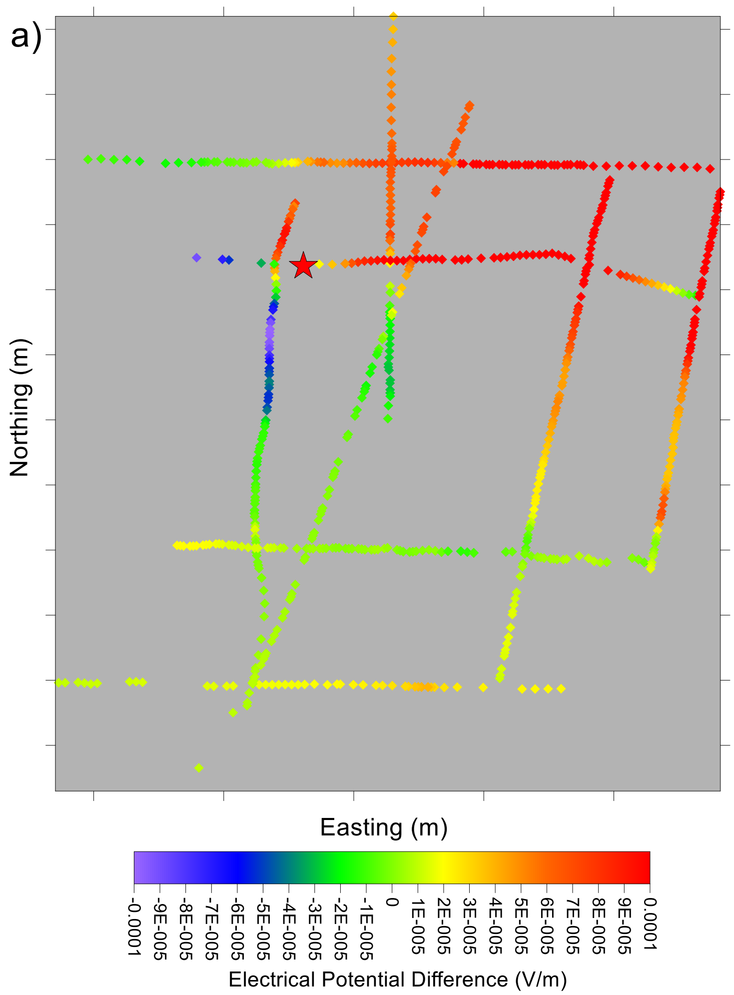

Figure 7: Raw potential differences. For typical MALM surveys this data would be used directly to interpret the limits of the subsurface conductive body. The atypical survey geometry made the usual interpretation for this dataset difficult without further processing

The potential field surface is shown in Figure 8, and the limits of the conductive aquifer from the MALM was estimated to be where the potential field gradient was the highest. In Figure 8 the location of the limit of the conductive aquifer based on the ERT is also presented. The difference between the limits from the two methods is likely due to the aquifer thinning to the west beyond the resolution limits of the ERT system.

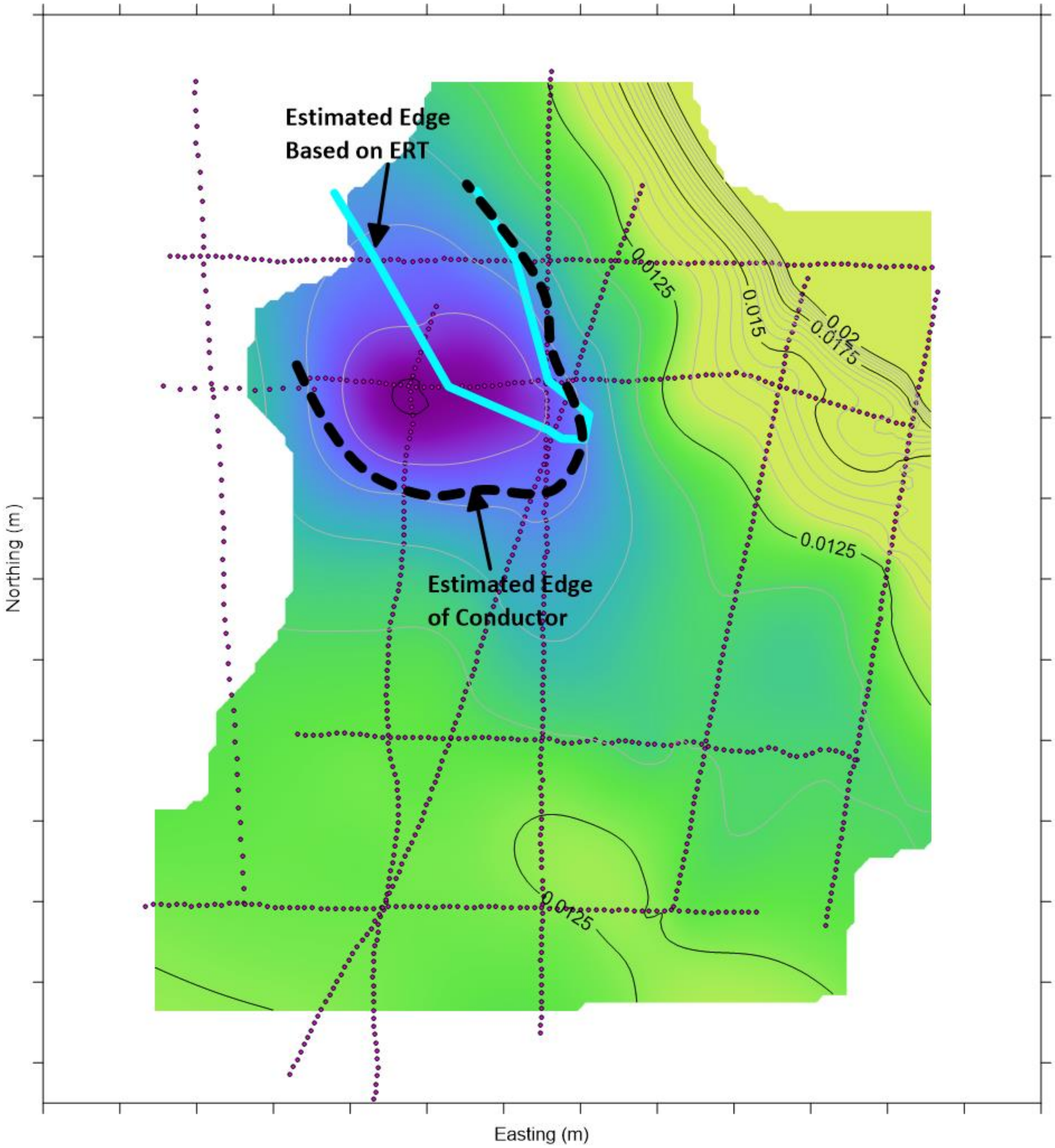

Figure 8: Processed potential difference surface. The limit of the conductive aquifer based on the MALM is indicated by the dashed black line. The limit of the conductive aquifer based on the ERT is indicated by the cyan line. The difference between the two limits is likely due to the limitations of the ERT when the aquifer becomes very thin.

These results were used to design a limited follow-up drilling program that confirmed the limits of the conductive aquifer based on the MALM method. Based on these results the number of drill holes required to delineate the aquifer was significantly reduced, limiting both the environmental impact and the cost of the program.

CONCLUSION

The current study described the use of two geophysical methods that were aimed at mapping the limits of a conductive aquifer that was not ideally suited for mapping with conventional geophysical methods. By modifying an older geophysical method to suit the survey site constraints we showed that the limits of the aquifer could be detected using atypical methods and that forward modelling helped to reduce the uncertainty associated with using a non-standard survey design. These results were confirmed by a limited drilling program which increases the confidence in this method for similar future problems.

This work was presented at SAGEEP2019

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