Three-dimensional Imaging With tTEM to Support Managed Artificial Recharge

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Introduction

Managed artificial recharge (MAR) provides a means to store water underground to meet the water supply demand for when a water shortage is encountered (Asano, 2016). Water extracted as a part of MAR projects typically is used for landscape or agricultural irrigation or, less commonly, for potable resource. Mapping the distribution of coarse- and fine-grained deposits is critical for determining a site's recharge potential and for planning the MAR facilities. Locating an optimal site for artificial infiltration is crucial for a successful project. This in turn requires a detailed characterization of the aquifer systems, which can most efficiently be achieved by investigations using non-invasive geophysics.

Geophysical methods can determine the distribution of sand and clay within an aquifer. For optimal location of artificial infiltration sites, there is a need to rapidly image, in full three-dimension (3D), the uppermost 100 m of the subsurface. At a large scale, this can be a labor-intensive task with traditional geophysical methods or boreholes. Traditionally, boreholes, electrical resistivity tomography (ERT) or airborne electromagnetics (AEM) have been the methods of choice. ERT is a proven method and covers the depth range of interest with the necessary resolution, but it typically produces 2D profiles, therefore mapping more than a few hectares in 3D is heavily time- and labor-intensive (Maurya et al., 2017). Ground conductivity meters (GCM or EMI) are efficient for mapping large areas but the depth of investigation (DOI) is limited to 5– 8 m (Christiansen et al., 2016) and even the best and most modern system can have pronounced problems with data calibration. Airborne electromagnetic systems such as SkyTEM (Sørensen and Auken, 2004) have the capability to map large areas, but they do not have sufficient resolution of the very shallow layers both vertically or horizontally (Auken et al., 2017). Hence, there is an un-met need for geophysical methods capable of characterizing the shallow subsurface (down to 60-70 m) in full 3D. Auken et al. (2018) presented a new towed transient electromagnetic system (tTEM) with a depth of investigation (DOI) of about 70 m, with the DOI depending on the resistivity structure of the subsurface. The previous tTEM system was recently upgraded to achieve a target depth of up to 100 m. The tTEM system can map the subsurface with high resolution both vertically (shallow resolution is about 2-3 m) and horizontally (down to 10 x 10 m). The tTEM system has been used for various purposes in Denmark, the United States and Sweden. In Denmark, the tTEM system is being used extensively for mapping geology, raw materials, aquifer vulnerability, shallow soil with respect to construction, nitrate-retention potential, and pathways contributing to flow and transport of contaminants (tTEM white paper). In Sweden, tTEM was used to investigate artificial infiltration sites and to map the geological materials within the watersheds.

In the U.S.A, tTEM surveys were used to investigate the location of artificial recharge sites within the Tulare Irrigation District. Tulare is in an arid region of the California Central Valley (Behroozmand et al., 2019). In the Lower Mississippi River Valley, the system was successfully tested in a number of different settings where one of them was to characterize the aquifer adjacent to the Tallahatchie River near Shellmound, MS for an MAR pilot project under development by USDA. Here, we present the technical details of the tTEM system and the artificial infiltration case study from the Shellmound area.

The tTEM System

The tTEM system is a compact, mobile, transient electromagnetic (TEM) system (Figure 1).). The overall design goal has been to develop a system capable of imaging from the surface to a depth of 30 m (which in practice turned out to be as much as 100 m) at a high vertical and horizontal -resolution. The transmitter coil (Tx) is a one turn 4 x 2 m^2, single-turn coil, sitting on a platform made of fiberglass and composite materials. The receiver coil (Rx) has an effective area of 20 m^2 and is 7 m behind the Tx coil in an offset configuration. Many smaller parts for the tTEM system were 3D printed using carbon reinforced material, whereas the larger pieces are modified off-the-shelf material parts. Transmitter and Rx sleds can be equipped with real-time kinematic (RTK) GPS's. The accuracy of these GPSs is not necessary for geo-locating data but the relative position of the Tx and Rx coils with respect to each other can be determined with an accuracy down to a few centimeters. This accuracy makes it possible to precisely determine the relative distance between Rx-Tx coils which is used in the inversion of the data. In addition, an automatic data-culling process was implemented to filter out the data from when one or both of the coils get too close to the all-terrain vehicle (ATV) typically used for towing (for example, during turning), which causes coupling in the data. In addition, a GPS navigation system has been developed, enabling the ATV driver to load tracks into a GIS platform and follow the planned survey. The onboard navigation system also provides real-time monitoring of system components providing continuous operational status of the system in an easy-to-understand format.

The system transmits low and high moments (LM, HM) in the single-turn Tx coil providing information from both shallow and deep intervals. The LM transmits 3 Amps (A) with a turn-off time of 2.6 microseconds (µs) and a first usable gate at 4 µs (hence, the first gate opens 0.58 µs from end of ramp and is 1.65 µs wide) while the HM transmits at 30 A. The repetition frequencies for the two moments are approximately 2000 and 800 Hertz (Hz), with small variations depending on a 50- or 60-Hz power-line frequency. A full dataset is obtained every 0.8 seconds corresponding to a 3-4 m spacing between soundings with a mapping speed of 15-20 km/h. At that speed, the tTEM can map an area of about 100-250 hectares per day with a line spacing of 20 m, which is a typical distance between driving tracks on farm fields.

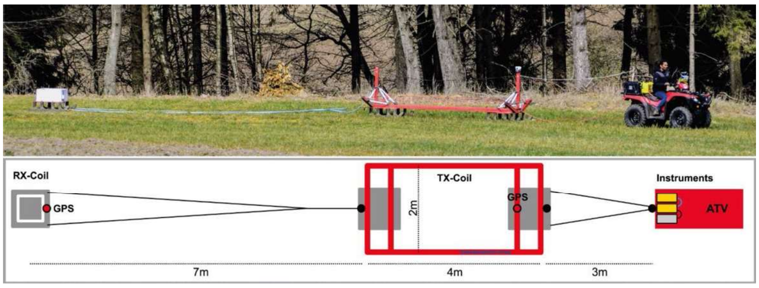

Figure 1. Top: Photograph of the tTEM system during data collection. Bottom: Simplified sketch of the system.

To have a completely stable turn-off ramp the transmitter is regulated so the temperature of the transmitting electronics is kept within 4% of nominal 45°C and the current within 2% of the nominal 30 A. The system has less than 1% bias on the very first gate in a 100-ohm-meter (Ωm) geology. The system was calibrated at the Aarhus test site for TEM instruments (Foged et al., 2013). Repeated weekly measurements over a period of more than a year, showed no variation in calibration, which indicates that the electronics package is stable and does not change characteristics over time.

The DOI of the tTEM system is up to 100 m without loss of resolution in the very near-surface. This was achieved by designing a new Rx coil with a noise-floor four times lower compared to the previously used Rx coil (Auken et al., 2018). A new filtering technique has been implemented to efficiently suppress any motion induced noise from the rotation of the RX coil in Earth's magnetic field.

Comparison of Sensitivity of tTEM, SkyTEM and GCM

The resolution of any EM system is characterized by what is called the sensitivity distribution (Christensen, 2014). The distribution of sensitivity express how much a given part of the subsurface contributes to the final measurement. A spatially narrow distribution means that the method is sensitive to changes from small volumes in subsurface resistivity while a more diffuse and spread-out distribution means that the method only sees changes over larger volumes. For a time-domain system each time gate has its own distribution where early gates have most resolution to the shallow geology, while later gates also contain information on the deeper geology. For frequency domain systems there is a distribution per frequency and coil separation.

To characterize the resolution capabilities of tTEM compared to other methods Figure 2 shows vertical slices in the 3D sensitivity distributions of SkyTEM, tTEM and GCM (ground conductivity meter such as the DualEM-421s) systems. All systems are with

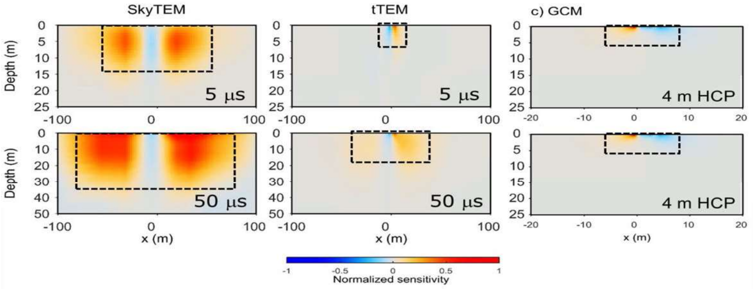

Figure 2 Comparison of sensitivity of SkyTEM, tTEM at 5µs and 50 µs. For GCM a Tx-Rx separation of 4 meter is assumed at an operating frequency of 9 kHz. The dashed line indicates the volume capturing the majority of the sensitivity, the narrower the better. Note that the horizontal axis of the GCM plot is magnified to reveal the details.

“standard RX” receiver-TX configurations. For the SkyTEM and the tTEM systems, the sensitivities are plotted for times equal to 5 µs and 50 µs. Since the GCM operates at a constant frequency, the sensitivity is constant in time, and here we only show the deepest sensitivity from the longest coil-separation (4 m). All sensitivities are computed on a homogenous half-space with a resistivity of 30 Ωm. It is clear from the figure that the airborne SkyTEM has the largest footprint both vertically and laterally and has a significantly larger lateral footprint than tTEM. The GCM has the highest sensitivity to near surface structures, but also has a very limited footprint depth.

A Case Study From the Mississippi Alluvial Plain

The following presents a case study from the Mississippi alluvial plain (MAP) regional water-availability assessment (USGS, 2019). The MAP Plain is one of the most important agricultural regions in the United States, and it depends heavily on groundwater resources. The groundwater system in MAP is poorly understood and shows signs of substantial hydrologic changes. Historic declines in groundwater levels have occurred due to heavy use of the available groundwater resources within the MAP region. In Mississippi, direct injection has received increasing attention as a potential means of artificial recharge, aiming to enhance the groundwater availability. A pilot project under development along the Tallahatchie River will investigate the potential to use riverbank filtered water as a source for injection wells to increase recharge to the aquifer in heavily stressed areas. Figure 3 shows an extraction site for the pilot project is located along the Tallahatchie River near Shellmound. The injection site is approximately 3 km west of the extraction site. At these two sites, closely spaced tTEM surveys was carried out to characterize the aquifer system and enhance knowledge of hydraulic connectivity of the river to the aquifer. Understanding the spatial and vertical distribution of coarse (sand)- and fine-grained (clay) materials is important to access the recharge and subsequent water re-extraction potential.

The tTEM survey was conducted with approximately 12 m line spacing at the extraction site and approximately 30-m line spacing at the injection site. The mapping speed of the survey was 10-12 km/hr. Data were processed in Aarhus Workbench (www.aarhusgeosoftware.dk) following a well-established processing scheme original developed for airborne TEM data (Auken et al., 2009). During the processing, data affected by power lines and other infrastructure were removed. Following the removal of data affected by coupling, data were averaged, and a sounding was created every 2.5 seconds, resulting in 8-10 m sounding distance. Finally, data were inverted using the smooth 1D spatially constrained inversion algorithm (SCI) by Viezzoli et al. (2009).

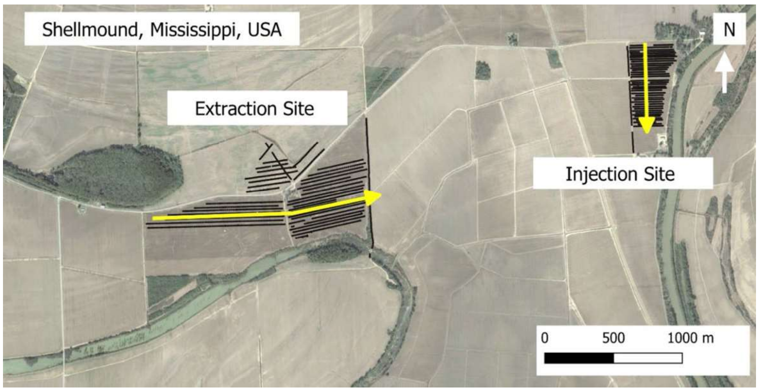

Figure 3 Location of tTEM survey in Shellmound, Mississippi U.S.A. The black lines represent the tTEM survey lines, the yellow linesline (with arrow showing direction) at injection and extraction sites indicates the profile sections sections shown in figure 4 and 5. (Modified from White et al. (2019)).

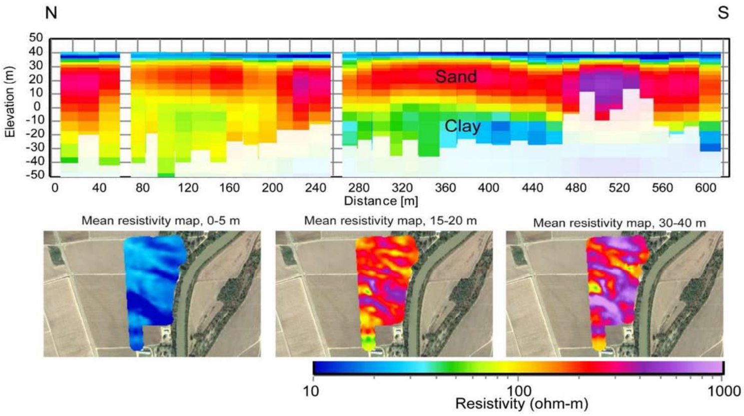

Figure 4 tTEM inversion results from extraction site (Shellmound, Mississippi). Top: N-S resistivity profile section (See figure 3 for location), bottom: mean resistivity maps (in ohm-meters) at selected depths.

Figure 4 shows the inversion results from the Shellmound extraction site. The north-south resistivity profile shows a shallow (8-10 m) low-resistivity layer interpreted as a clay layer above the thick (20-25 m) highly resistive sand aquifer. The thickness of the sand layer varies significantly along the profile. On the northern end of the profile the thickness of the aquifer is approximately 50 m thick; whereas in the middle of the profile (near 360 m along the profile) the aquifer is only 30 m thick. Below the sand layer, a clay layer is observed within the DOI in most of the profile. The mean resistivity maps show overall sharp horizontal changes, which are likely related to the erosional and depositional history of the river. In other words, they show images of the results of a rapidly changing depositional environment leaving a complicated pattern of alternating clay, sand and gravel. The same pattern of alternating low and high resistivities is observed from north to south. By using these high-resolution images, optimal locations of screens in the wells can be selected with respect to aquifer thickness and connectivity.

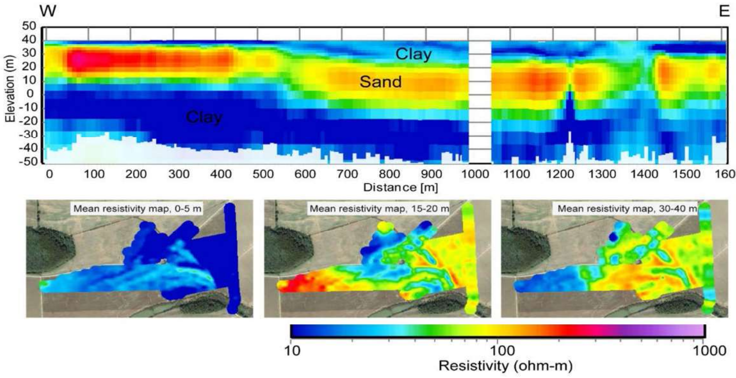

Figure 5 tTEM inversion results from injection site (Shellmound, Mississippi). Top: W-E resistivity profile section (See figure 3 for location), bottom: mean resistivity maps (in ohm-meters) at selected depths.

Figure 5 shows the inversion results from the injection site. The resistivity profiles also show a three-layer model similar to the extraction site. The thickness of the top clay layer varies from approximately 5 to 20 m along the profile. On the western end of the profile (from 0-500 m), the resistive sand layer is at a depth of about 5 m and has a uniform thickness of about 20 m. On the eastern end of the profile (from 500 to 1600 m),) the resistive sand layer is deeper than to the west. This change again is likely related to the river's erosional and depositional history. The mean resistivity maps at depth intervals 15-20 and 30-40 m show the detailed small-scale structures that can be resolved with the tTEM method. Determining these spatial and vertical distributions of coarse (sand)- and fine-grained (clay) materials is important to improve local groundwater models and better inform estimates of recharge potential under natural and engineered conditions within the MAP aquifer system.

The injection and extraction sites compose an area of 117 hectares in total. The 117 hectares were mapped in only 5 hours, providing a detailed 3D imaging of the ShellmoundShellmound sites. In general, 100-200 Hectares can be mapped in one day, and preliminary processing can be completed overnight or within a day of collection, making the tTEM method an efficient method for site characterization. When considering the cost of equipment calibration, mobilization, demobilization, mapping and geophysical data processing and interpretation, the total expense of tTEM profiling is cost effective compared to borehole drilling, logging or traditional geophysical methods that can be spatially limited, labor intensive and expensive.

Discussion and Conclusions

A relatively small towable transient electromagnetic system has been developed and field tested. Based on intensive research and engineering, the system has been greatly improved over the last year. The system has bias-free data starting at 4 µs from the beginning of the current ramp. The sensitivity distribution of tTEM system shows that it has a smaller footprint both horizontally and vertically, compare to SkyTEM systems. The GCM has the highest sensitivity to near-surface structures, but also has a very limited footprint depth compare to tTEM.

Data processing and inversion are performed using processing techniques that are well established for airborne electromagnetic surveys. The system can be used for rapid data collection and preliminary inversion results can be delivered within 24 hours of the survey, so that further survey planning can be tuned and optimized. Apart from coupling due to infrastructures, one main limitation of the tTEM method is accessibility. Like any ground-based method, tTEM is restricted to map were land access is granted and possible. In forested areas only the forest roads would typically be accessible and in the open land some areas might be too wet to be accessed by an ATV.

The resulting resistivity images are very high resolution, down to 10 x 10 m. Recently, it was used in Mississippi to map shallow coarse- and fine-grained layers that affect aquifer recharge. Determining the spatial and vertical distribution of sand and clay deposits is important to improve groundwater-flow models and better inform estimates of recharge potential under natural and engineered conditions. Based on these promising results, it appears that the tTEM system has the potential to be a game changer for high-resolution 3D geologic mapping for artificial recharge applications.

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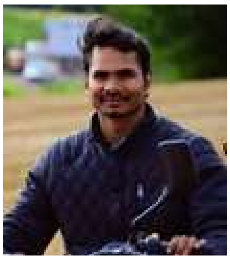

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