GCM for Groundwater Recharge Investigations

Peter Thomsen
Rambøll A/S
Olof Palmes Alle 20
Denmark
prt@ramboll.com
Bio ▶

Max Halkjaer
Olof Palmes Alle 20
Denmark
maxh@ramboll.com
Bio ▶

Figure 1 System setup for optimal operation. The DUALEM421-S sensor is mounted in the PVC pipe, Ramboll.

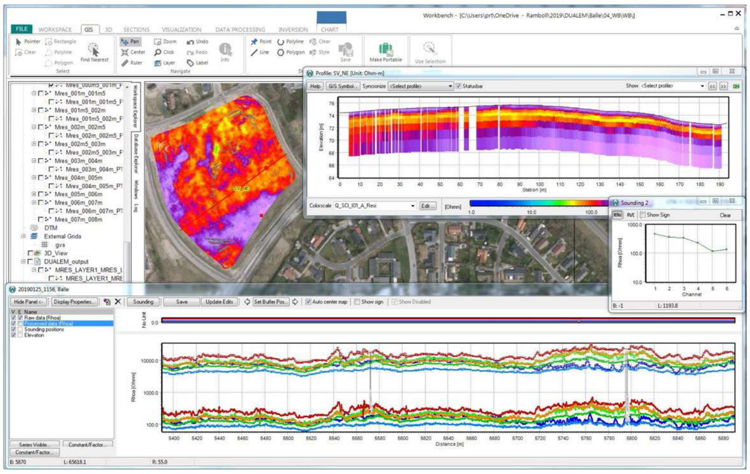

Figure 2 The Aarhus Workbench software packages for processing and inversion.

Abstract

Focus on climate change resilience has led to an increased need for detailed hydrogeological investigations of the near surface sediments and the ability to infiltrate water from the terrain to the underlaying aquifers. GCM (Ground Conductivity Meter) (McNeill, 1980) investigations together with hydrogeological data has proven to provide valuable background data for evaluating Managing Aquafer Recharges (MAR) solutions. When designing infiltration or detention basins, infiltration rates can be predicted by correlating geophysical results with ground truths from boreholes and hydrological tests. The GCM instrumentation, DUALEM421-S is optimal for detailed mapping of the electrical conductivity down to approximately 20 feet and has shown to provide cost effective spatial distributed investigations.

DUALEM421-S

The DUALEM421-S (Dualem Inc., Milton, ON, Canada) system is a single frequency multi configurated GCM sensor. The system uses a 9kHz frequency and a total of six different coil configurations. The receiver coils have dual orientation, respectively: horizontal co-planar geometry (HCP) coils at 1, 2 and 4 m separation, and perpendicular geometry (PRP) coils placed 1.1, 2.1 and 4.1 m apart. The sensor has shown a high repetition accuracy, a relatively high signal to noise ratio and can be calibrated using a roll test (DUALEM INC., 2019). The setup provides a total of six different apparent resistivities, justifying a geophysical inversion of the collected data. For optimized data acquisition, a system setup has been designed, where the sensor is installed in a PVC pipe mounted on a non-metallic sled pulled by a vehicle, Figure 1. This setup ensures smooth operations, a low stable operating height, with minimum pitch and roll. By keeping the sensor close to the ground, (approx. 25cm) the highest possible vertical as well as horizontal resolution is obtained. The collected data is merged with GPS coordinates. Maintaining a safe distance (min. 10 feet) to the ATV, as well as using a non-metallic sled ensures that no metal elements interfere with the measured data. Under optimal conditions, a daily production of 60 miles can be obtained.

The high efficiency enables robust dense covering of larger areas. Linear distances between survey lines can vary from 3 to 75 feet depending on project's needs, and the dense covering results in a reliable and detailed description of the sub surface's resistivity, with high consistency between data acquisition lines.

Processing and inversion

The collected data is processed and inverted in the software packages Aarhus Workbench (Auken et al., 2009) using a dedicated component for GCM data. Aarhus Workbench is specially designed for handling larger geophysical data sets. After filtering and removing noisy and coupled data, the dataset is inverted using a smooth Spatially Constrained Inversion (SCI) scheme, optimized for spatial inversion of larger data sets (Viezzoli et al., 2008). By applying the inversion scheme, the data is converted from measured apparent resistivity to depth-related true resistivity images of the subsurface. Results are inspected and then visualized as resistivity sections, sliced resistivity maps and 3D presentations.

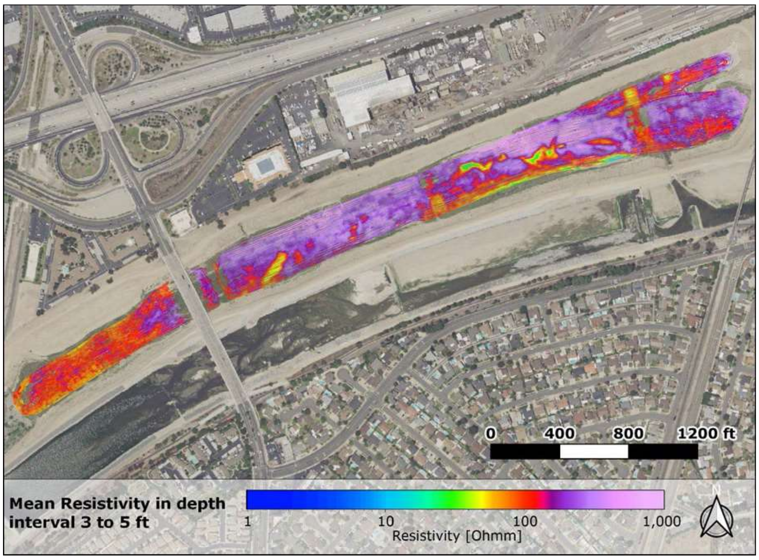

Figure 3 Mean- resistivity in the 3-5 feet depth interval for the off-channel infiltration basin at Santa Ana River, California.

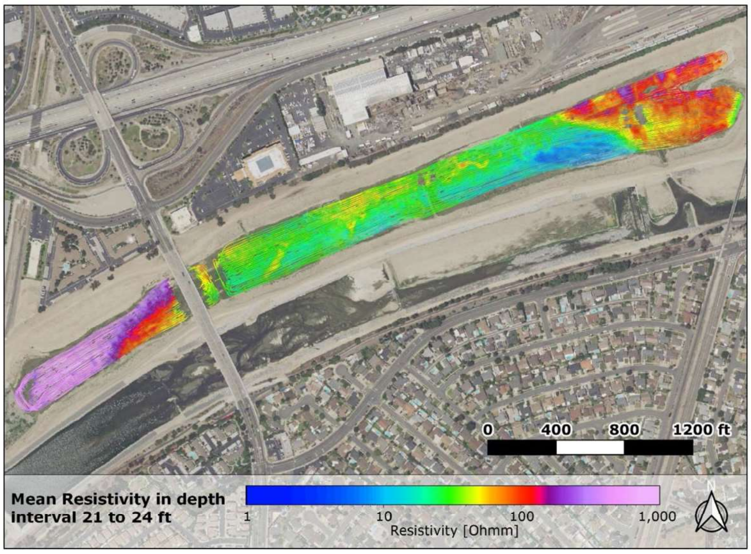

Figure 4 Mean- resistivity in the 21-24 feet depth interval for the off-channel infiltration basin at Santa Ana River, CA.

Applications

Throughout the last 6 years, the system has been used intensively for different applications on more than 120 projects and has satisfied the increasing demand for detailed investigations of the shallow sediments.

Most projects have been for climate adaptation studies. Other projects involve delineation of landfills and other contaminated sites, as well as geotechnical investigation for road or pipeline routing. Geological sediment characterization from additional shallow boreholes, allows the geophysical results to be interpolated and extrapolated to obtain the most accurate assessment of the near surface conditions.

Case: Geophysical investigation, lower off-river channel, Anaheim

Orange County Water District (OCWD) has used managed aquifer recharge of multiple water sources, including water from the Santa Ana River to sustainably manage the Orange County groundwater basin since the early 1930s. Surface water from the Santa Ana river is diverted to multiple recharge facilities, including an off-river channel for infiltration. The off-river channel is continuously maintained to optimize infiltration by removing the accumulated clogging layer within the upper inch.

To optimize infiltration, a geophysical survey was conducted to identify areas with finer-grained sediments within the upper 5 feet and for mapping the deeper sediment to 20 feet. To accomplish this, a very detailed DUALEM421-S survey was been initiated by OCWD, in the lower part of the off-river channel. A total of 32 acres was been covered in two days by a total of 55 miles by the DUALEM421-S within the channel while the channel was dry.

The results show that within the upper 5 feet, areas with relatively low resistivity can be correlated with areas of finer grained sediments, (Figure 3). To optimize the infiltration in the channel, these identified finer-grained sediment could potentially be excavated and replaced with more coarse sediments. However, the area with low resistivity is limited in size and in general the top sediments are characterised by higher resistivity, implying coarse sediments.

In the 21 to 24 feet depth interval the resistivities varies, with highest resistivity, hence most coarse sediments, in the upper and lower part of the channel, and lower resistivity in the central part, correlating with less permeable sediment (Figure 4).

Combined with existing knowledge, OCWD is now able to develop a maintenance and potential remediation program to optimize off-river channel performance.

Case: Investigation for handling stormwater, Tarphede

The municipality of Viborg in Denmark has classified a 500-acres area for urban development, Tarphede. When planning urban development, chosen solutions for handling of rainwater has a large impact on the architectural landscape design in the area, where blue and green infrastructure is often a high priority. Different solutions for handling rainwater can be applied and combined. Rainwater can be led to rainwater pipes, either directly or delayed through detention basins. If possible, rainwater can be infiltrated applying low impact development solutions through infiltration basins or through combined infiltration and detention basins.

Infiltration, either locally or through basins, requires that an unsaturated zone is available and that the sediments in the unsaturated zone are permeable and therefore suitable for infiltration. Detailed geophysical investigation combined with shallow boreholes and hydraulic tests are effective tools to obtain information of the unsaturated zone.

The investigation at Tarphede included initially a detailed geophysical investigation using the DUALEM421-S system. For obtaining the desired level of detail, a total of 150 miles were collected with a distance between lines of approximately

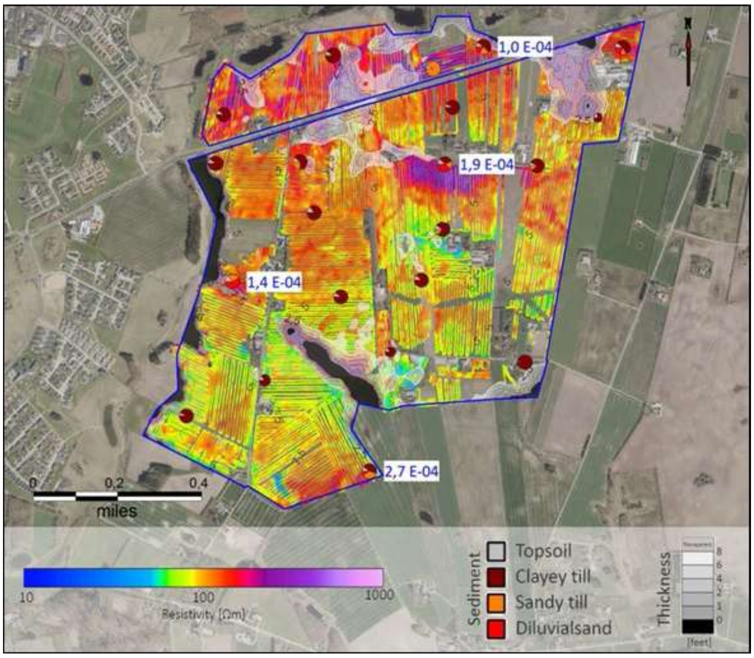

Figure 5 Resistivity, soil characterization, thickness of the unsaturated zone and hydraulic conductivity [meters/sec], Tarphede.

30 feet. The area was covered in three days, and the collected data was processed and inverted using the Aarhus Workbench software package. Based on mean-resistivity maps derived from the DUALEM survey and the digital elevation model a total of 21 boreholes were planned and drilled. The mapped resistivity combined with the lithological description of the soil samples resulted in a detailed evaluation of the unsaturated zone. For sandy sediment samples a hydraulic conductivity was estimated based on the grain size analysis. Thickness of the unsaturated zone was calculated from the digital terrain model and the hydraulic head measured at the boreholes.

In Figure 5, data describing the unsaturated zone are presented. The coloring show the resistivity of the unsaturated zone, where black graded areas indicates areas were the thickness of the unsaturated zone is less than 8 feet. At every borehole, sediment characterization of the unsaturated zone is shown and estimated hydraulic conductivity k-values are plotted for four boreholes.

Evaluation of potential solutions for handling rainwater is based on the detailed investigations. In limited areas in the northern part of the investigated area direct infiltration of rainwater can be applied. In the remaining area solutions will include detention basins with delayed discharges to nearby recipients. Dimensioning of the basins must meet the requirements for unchanged median flow in the recipients, including one basin at every catchment. This general strategy for handling of rainwater is now ready to be used in the detailed design of applicable solutions, were blue-green environment will be a natural part of the solutions.

Case: Pre-geotechnical investigation of Hedensted Ring Road.

As part of pre-investigations for the geotechnical assessment at Hedensted Ring Road, and for evaluation of how to handle stormwater, a detailed DUALEM421-S survey has been carried out. The purpose of the investigation is to obtain valuable information of the sediment distribution along the planed route and to assess potential locations of detention or infiltration basins. To obtain the optimal background data, a 120 feet wide corridor has been mapped by collection data along 10 parallel lines. The mapped road section is 1.5 miles and a total of 15 miles of DUALEM421-S data was collected.

In Figure 6, mean resistivity in the 5 to 7 feet depth interval is shown within the corridor. It is obvious that certain areas are dominated by sediments with high resistivity, correlating with sandy sediments, while other areas show a lower resistivity, which can be correlated to more clayey sediments. Likewise, variations are seen within the width of the corridor. At the model section, Figure 6, a highly resistive top layer of varying thickness is seen within the upper meters. Below these top generally sandy sediments, the resistivity varies, correlating to sediments of varying lithologies.

Based on the results from the DUALEM421-S survey, detailed geotechnical investigation can be planned for optimal description of the soil conditions along the route. Furthermore, optimal locations for infiltration or detention of rainwater can be pinpointed.

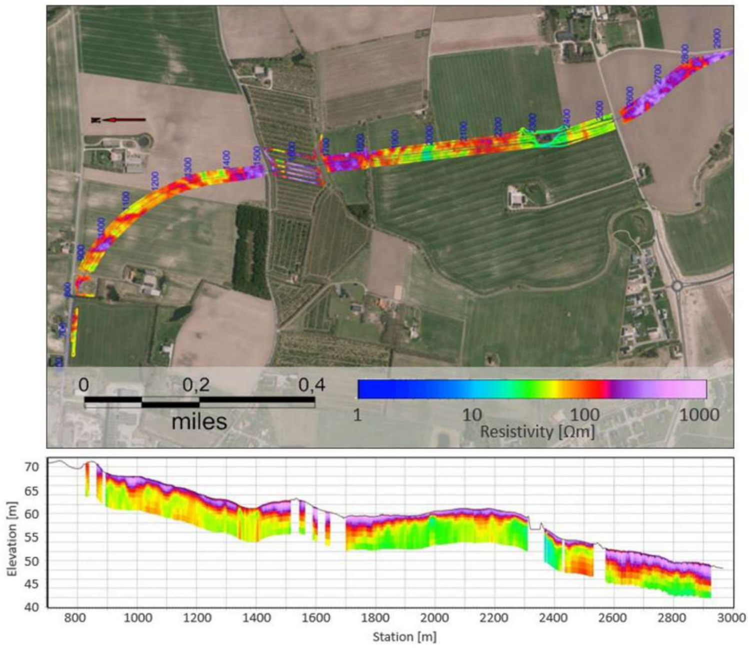

Figure 6 Mean resistivity in depth interval 5 to 7 feet. Cross section along the route.

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Author Bios

Peter Thomsen

Peter Thomsen Rambøll A/S,

Olof Palmes Alle 20

Denmark

prt@ramboll.com

Peter Thomsen holds a M.Sc. in hydro-geophysics from University of Aarhus. In his 18 years at Ramboll he has had a focus on developing and adapting innovative geophysical techniques for groundwater investigations. In the recent years Peter has focused on electromagnetic techniques used to characterize the near surface sediments as part of Managed Aquifer Recharge projects.

Max Halkjaer

Rambøll A/S,

Olof Palmes Alle 20

Denmark

maxh@ramboll.com

Max Halkjaer has a Master's degree in geology and geophysics from the University of Aarhus. He has 24 years of experience in groundwater management and especially application of geophysical methods. Since 2016 he has been a Senior Hydrogeologist and Market Manager for Ramboll Water with a focus on California.