MODELLING APPROACHES IN FREQUENCY DOMAIN ELECTROMAGNETICS AND APPLIED IN SHALLOW GROUNDWATER INVESTIGATIONS

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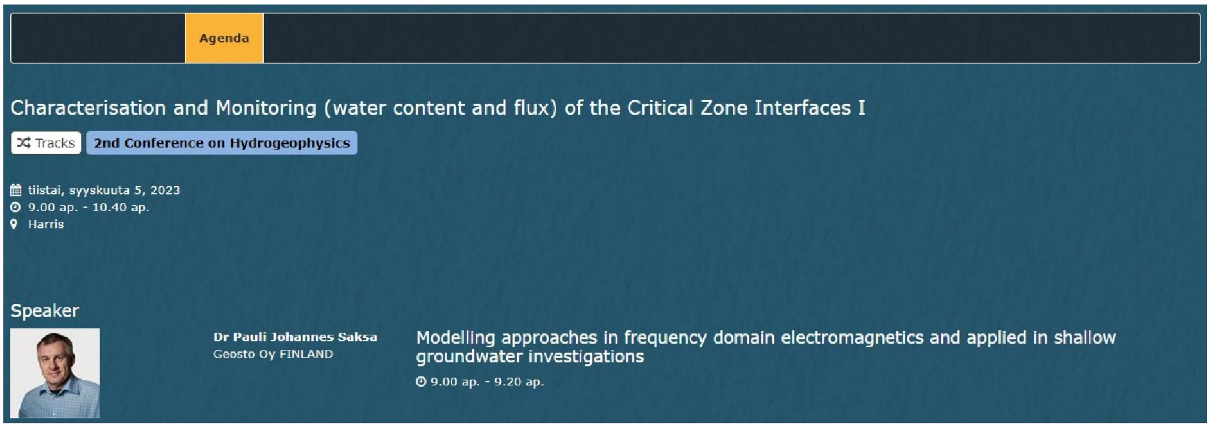


Introduction

Between 2013–2017, Geosto Oy developed a new groundwater monitoring system based on shallow electromagnetic (EM) surveying. The system is called by name NOVEL-EM and the concept is straightforward; in the first phase, permanent lines are marked and baseline EM measurements are taken. In addition, a ground-penetrating radar (GPR) survey is run, and geological and borehole data along with supplementary hydrogeological and infrastructure data are collected in a database. During the subsequent monitoring phase, these same lines are re-measured and the EM results are compared. Changes in groundwater chemistry are reflected in changes occurring in the calculated differences in electrical conductivity (EC).

The main focus of the system is on accurate, high-quality and comparable measurements and on data processing which compensates for changes in soil moisture, temperature and groundwater levels, and also levels the EM data sets well. All this has been implemented in customised MS Excel spreadsheets to which input EM data is imported. Processing produces from data levelling to resistivity cross-sections, quality checks and EC change logs. Finally, the length and magnitude of EC change are calculated for each EC change zone and then listed and transferred to the client's reporting and GIS system. The EM-based monitoring system has been used now at several large Finnish mining sites with more than ten years of results gained (Saksa, 2023).

All this is and can be done without any numerical EM modelling software, but this presentation discusses how numerical modelling can further supplement the investigations, solve water-related parameters, and provide additional insight. The EM main instrument used was the GSSI EMP-400 Profiler, which provides data from three frequencies within a range of 1 – 16 kHz at a time and records secondary field real (Re) and imaginary (Im) values (in ppm).

Modelling tools

Rather early on, it was noted that no flexible and customised numerical processing software was available. Therefore, the main 1D modelling package EMDC1D was programmed to be able to calculate forward and inversion results for EM short-coil spacing systems in HCP and VCP modes, Slingram HCP, VLF-R, AMT and RMT, and for several direct current (DC) resistivity measurement configurations (Wenner etc.). We also implemented a text-based general input data format, called .dat-files. The plotting module presents model and calculated data graphics.

In addition, two auxiliary software modules were developed for monitoring application. The following assistive functions were programmed into a converter module: resistivity pseudosection calculation, 2-layer magnetic susceptibility calculation, formation analysis and calibration with water EC, water chemistry calculation with soil-rock data, and model transfer as an XYZG point cloud for 3-D visualisation and volume modelling (Rockworks 2022). The fourth component is the GROUNDMODEL module, wherein the ground model can be defined in text input file format and visualised. The ground model can be linked to an input EM&DC data file and used to constrain the inversion process. The graphics use the DISLIN library (Michels, 2017).

In a subproject, 2D and 3D modelling tools were also developed in 2017 based on the ArjunAir and SamAir codes developed and published earlier in AMIRA project. Development, re-coding and the GUI were carried out by PhD Markku Pirttijärvi, Radai Oy.

Modelling usage

There are several situations in which 1D modelling is helpful and can improve processing quality. Model calculation can identify static offset errors, show outliers well, and indicate in the form of a

frequency effect if the line data covers a ground section that has several electrically varying layers, and therefore changes with depth. This helps to decide what kind of layer structure is to be used.
Forward modelling is one use and is mostly applied to study in the shallow EM context if the depth or layer of interest can be mapped, and if a certain resistivity change in the groundwater layer is detectable. This leads to the selection of instrumentation and frequencies applied. However, the site noise level is usually not known but average noise levels recorded in comparable conditions can be used.

The easiest use is direct layer model inversion without constraints (automatic model) or applying a user-constrained model. This can function well for data lines where soil structure does not change much. It can also be used for solving variation in EC when there is a single dominating layer of groundwater. A more detailed model can be calculated by using constraining ground model geometry. Each layer can also have resistivity limits and changes in inversion which are regulated by setting fix-free parameters. Resistivities for main groundwater layers can be solved using this method.

Modelling can also sometimes cover bedrock and its groundwater variations. Water in bedrock is demanding to solve because porosity is very low in crystalline metamorphosed rock conditions. At mining sites, mineralised bedrock may also occur, which makes determining water chemistry even more demanding. Electrically conductive bedrock also sometimes manifests in Re-components, and magnetic susceptibility modelling can help to identify the influencing lithology.

Water chemistry calculation requires well-solved resistivities for hydraulically conductive groundwater layers. Typically, the EC, TDS or eNaCl of the water is calculated with the help of soil and temperature parameters. The main soil model applied in our approach is Waxman-Smits, along with Archie's law for the electrolytic part. On many occasions, soil parameters are not known, so the converter module can use groundwater sample data linked to model layer data sections and calculate the formation factor, which is used as calibration in further water chemistry calculations.

The use of 2D and 3D modelling has been very limited. The reason for this is that there are very seldom several parallel lines forming a dataset which enables 3D modelling and inversion. However, 2D modelling can solve narrow zones crossing EM data lines well, such as a shallow bedrock fracture zone, or a defect observed in an embankment dam structure.

Examples

Model calculation types are exemplified in one 565 m line data example. Only Im-component values were used in inversion (Re-comp weight = 0.0). Three different model types are used: automatic, user-constrained and ground model-constrained. The automatic and user-constrained models consistently have three layers. The ground model was created with the help of GPR and soil drilling data. The Im-component profiles and the ground model applied are shown in Figure 1.

Automatic inversion uses internally determined layer thicknesses and resistivities as starting values. The user-constrained model had layers for peat, moraine and bedrock. Peat and moraine in 2-metre-thick layers had fix-free values of 0.9. The layers had initial resistivities of 200, 200 and 500 Ωm (fix-free 0.5, 0.0 and 0.3), respectively. The fix-free stiffness parameter is 0.0 when it can change freely, and 1.0 when fixed completely. The ground model has stratigraphy of four layers and layer geometry is fixed in inversion. Resistivity limits and stiffness per layer were set so that major changes can occur in moraine and broken rock layers. The inversion run results are shown in Figure 2. The automatic model varies the most widely. In the user-constrained model, resistivity variations concentrate on the middle moraine layer as pre-conditioned in the inversion by fix-free parameters set. In the ground model-constrained inversion, variations in resistivity results occur mostly in moraine and broken rock layers, and topographical variation is also depicted.

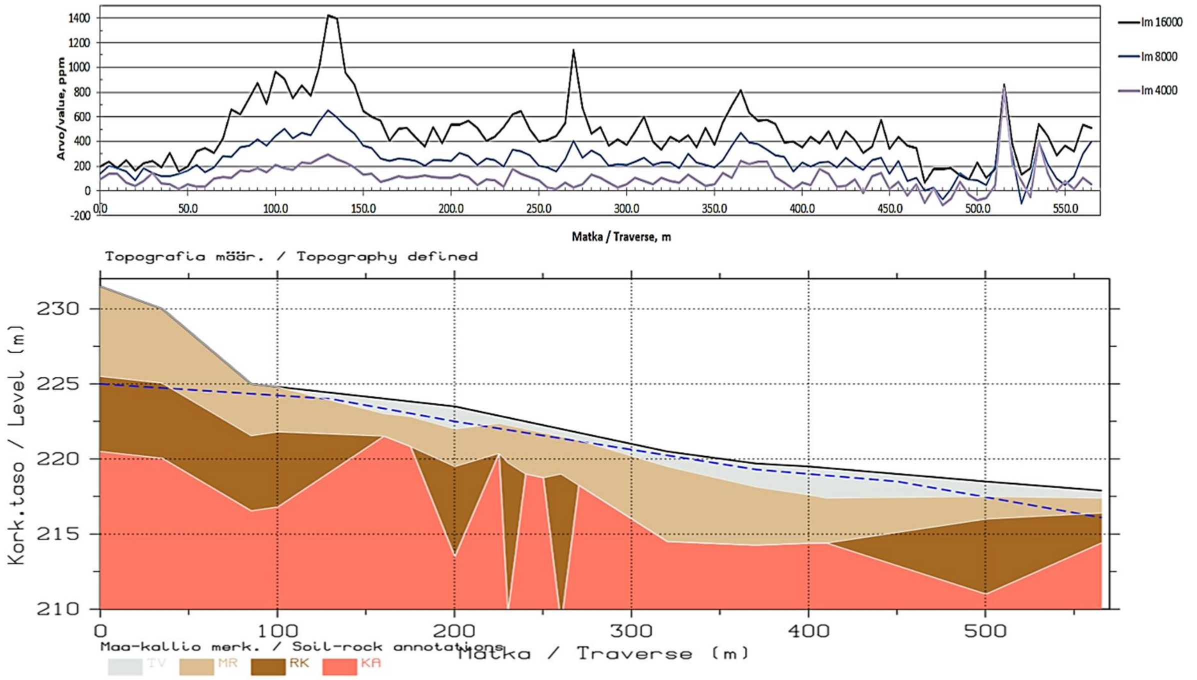
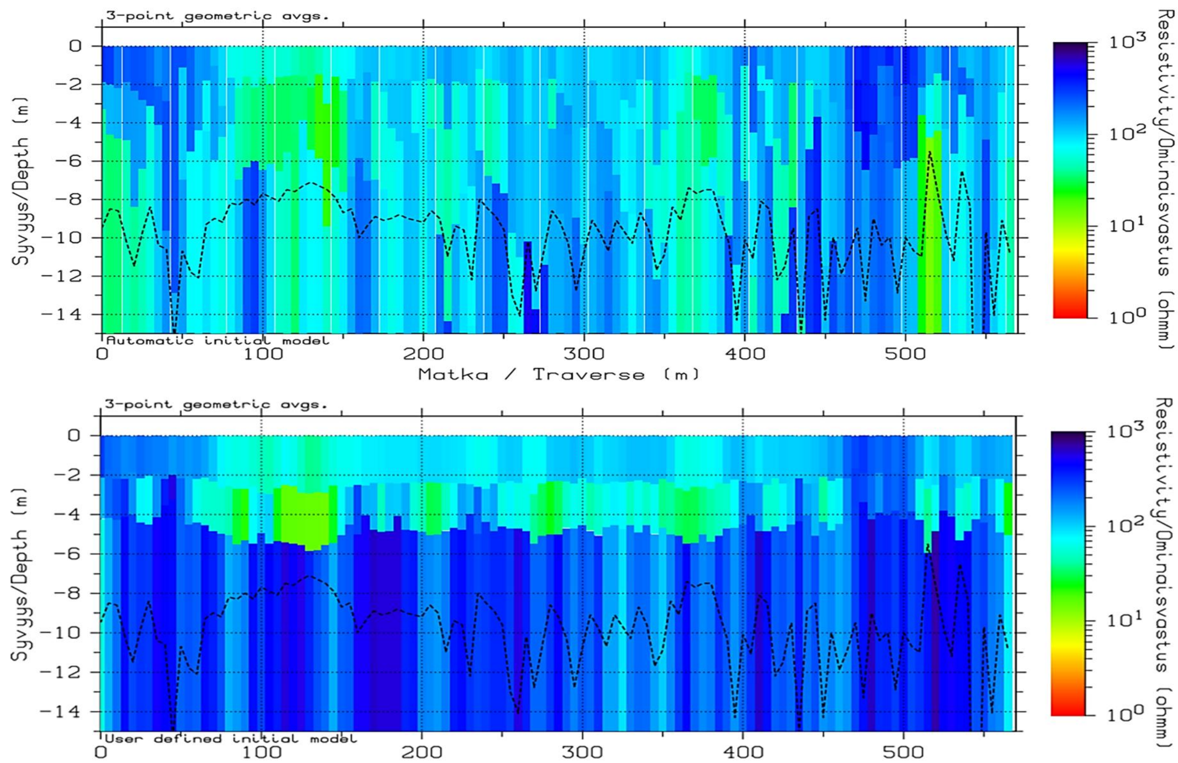


Figure 1. *Example line data Im-component profiles are shown above and a ground model constructed for the line is shown below. Soils TV = peat (grey), MR = moraine (light brown), RK = broken rock (brown), KA = intact bedrock (red).*

Further derivation and an example of water EC calculation are shown in Figure 3, with focus and parameters set on the moraine layer. Three major water chemistry flow zones intersect the line between 80 – 150 m, 190 – 255 m and 270 – 275 m. A groundwater standpipe at 200 m had water EC of around 150 mS/m in 2020 and derivative modelling yielded 260 – 360 mS/m for the location. A section of broken rock was also found there exhibiting higher values.



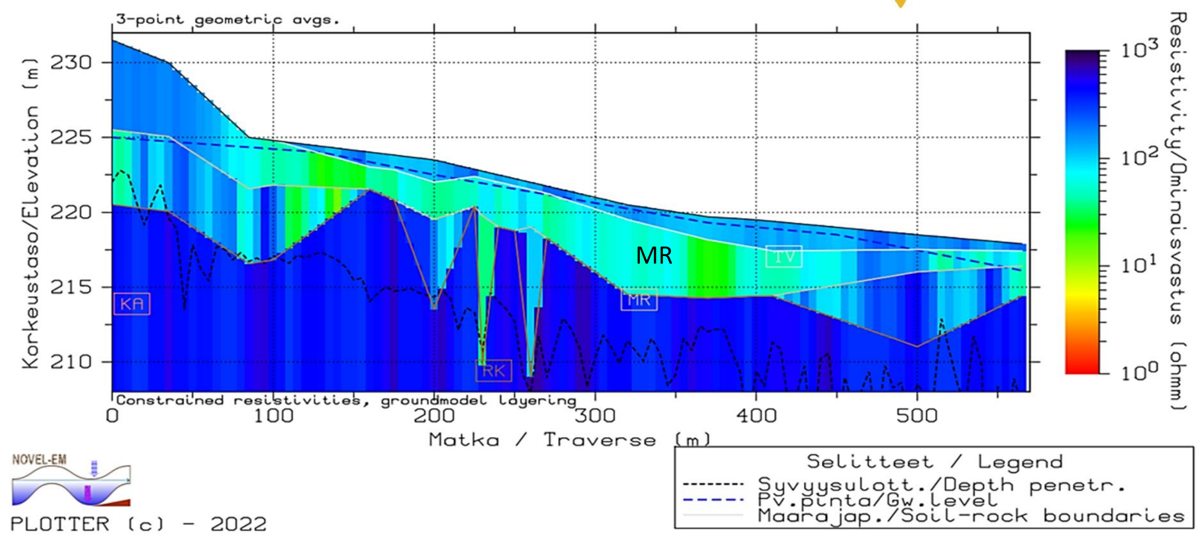


Figure 2. *Example line modelling results with three alternative inversion settings: above is the automatic 3-layer model, in the middle is the user-constrained 3-layer model, and at the bottom is the ground model-constrained geometry and resistivities constrained per layer in inversion settings.*

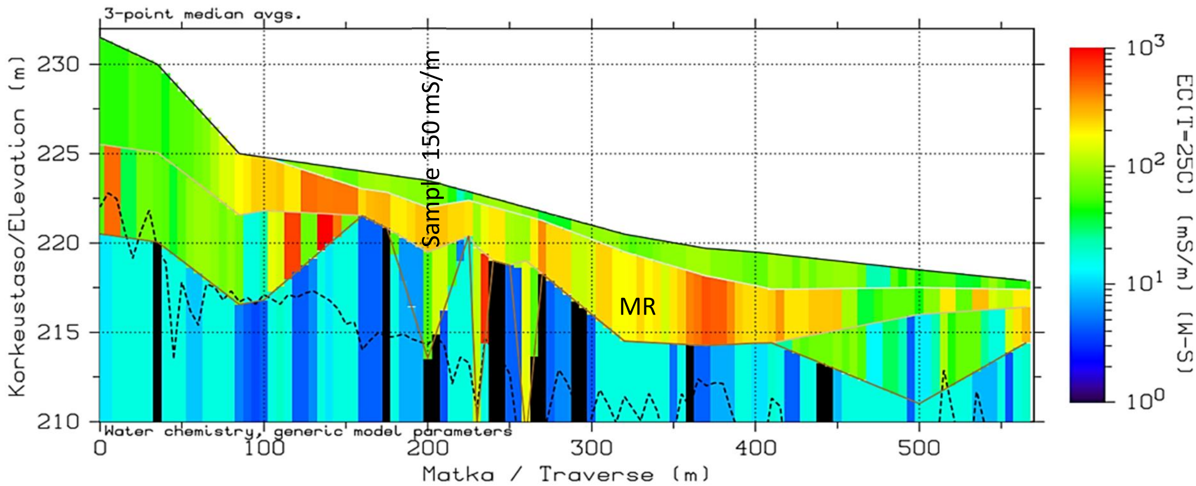


Figure 3. *Figure 2 ground model inversion-based water EC calculation values, focus on moraine (MR) layer (porosity 30%, temperature +5°C, clay content 5% and CEC = 5 meq/100g).*

Conclusions

It is concluded that layer modelling can provide insight and allow more detailed parameter calculations in the context of monitoring effluent water from mining. Dam integrity and similar outflow zones can also be inspected in the same way. The ground model-based modelling approach enables more detailed control of the inversion process behaviour and focuses on key layers and parameters of interest. Solving hydrological soil parameters adds new challenges for input data.

Acknowledgements

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References

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