Tailings pond outfiltration monitoring with electrical conductivity surveying

Pauli J. Saksa[1]* depicts the baseline setting from one mine site, one monitoring line time-lapse result, and an example of how the water electrolyte content have evolved along the exemplified monitoring line and assesses the modelling potential.

Abstract

A new, shallow penetration electromagnetic (EM) surveying method for the detection and monitoring of contaminated mining water, called NOVEL-EM, was developed between 2013 and 2015. It has been used at several mine sites in Finland and abroad. The method is comprised of instrumentation, systematised on-site measurements, processing, and modelling procedures which aim to achieve high accuracy and repeatable data and the results of water chemistry changes in the surface or groundwater layer within a depth range of 0-10 m. This article depicts the baseline setting one mine site, one monitoring line time-lapse result, and an example of how the water electrolyte content have evolved along the exemplified monitoring line.

The second part of the article discusses modelling potential, although monitoring itself does not require numerical modelling. Layer-based modelling provides several supplementary uses. Constrained modelling can more accurately focus resistivity changes on layers of primary interest. Water chemistry calculations are possible with ground models. Finally, modelling can help to develop data processing as scoping calculations show the influence and significance of various physical conditions that are encountered – such as the variability of ground temperature.

It has been verified that detected anomalies are related to changes in water chemistry, and the monitoring line network has been expanded over the course of the years.

Introduction

Geosto Oy developed an electromagnetic surveying method for the detection and monitoring of contaminated mining water at shallow depths between 2013 and 2015 in the Finnish Green Mining programme. The system consists of hand-held electromagnetic (EM) frequency domain measurements for establishing a baseline, and subsequent monitoring surveys. The EM method and hand-held instrumentation were selected for this purpose due to the applicable depth range, cost-efficiency in field work, and high accuracy in measured responses and time-lapse differentiation.

The system included a measurement technique, processing, and software development. 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. 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) after processing.

In addition, a ground-penetrating radar (GPR) survey is run, other electrical conductivity measurements are taken (DC soundings, borehole logging) and geological and borehole data along with supplementary hydrogeological and infrastructure data are collected in a database. A special processing methodology was developed. The EM main instrument used was the GSSI EMP-400 Profiler, which provides data from three frequencies at a time within a range of 1-16 kHz at a time and records secondary field real (Re) and imaginary (Im) values (in ppm).

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 results from data levelling to resistivity cross-sections and profile plots, 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, 2023a). The first part of the article includes the findings and experience gained during the ten-year period from 2013 to 2022 and from surveys conducted at several operating mining sites. Monitoring can be done without any numerical EM modelling software, but the second part of this article discusses how numerical modelling can further supplement the investigations, solve water-related parameters, and provide additional insight (Saksa, 2023b).

Monitoring method and theory

The hand-held short coil spacing instrument typically has coil spacing between 1 and 4 metres. It operates either in geometric

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or frequency sounding modes and within a frequency range of 1-50 kHz. The depth range covered depends on the electrical conductivity of the ground, but usually stays between 1 and 10 m. The situation is very suitable for shallow groundwater layer observations (when the water level is situated within reach of the system and less than 5 m from the ground surface). The main idea is to first measure the baseline response at several frequencies and within a depth range of 0-10 m, and after each time-lapse survey, solve the differences at the same points. For surveying, we used the GSSI EMP-400 Profiler instrument, which can simultaneously record three frequencies in the 1-16 kHz range, either in HCP (Horizontal Coil Profiling) or VCP (Vertical …) modes. The surveyed lines were at staked points close to the edges of the waste area, and placed in natural, non-disturbed ground. The surveyed point locations are within ±1m of subsequent line point recordings.

Figure 1 depicts the apparent depth ranges D_a surveyed in the frequency domain, calculated as the square-root of skin-depth values from EM theory (Saksa 2014) and for the EMP-400 system. Various soil types and resistive rock are also marked on corresponding curves. However, depth penetration in itself does not guarantee resistivity mapping from an embedded groundwater layer. The layer or volume must be situated well within the maximum depth penetration, the resistivity difference must create a measurable signal, and the EM instrument and site conditions must enable low noise levels in data. We evaluated the stability and accuracy of the EMP-400 unit at a system level and found that in the 1 – 16 kHz band, an accuracy of ±10 ppm can be achieved for the secondary field imaginary (Im) component (Saksa and Sorsa, 2017). The real component is used as a relative value, an indicator of noise field, and for magnetic responses.

Baseline data holds crucial importance as all later data are compared against it. Preferably, the baseline should be recorded before or in the very early stage of waste disposal activities. Regarding mining that has taken place over a period of years or decades, or for closure stage conditions, Figure 1 also shows the EM response variability with geology, which is then present and makes the detection of small resistivity changes resulting from water chemistry that is particularly difficult and uncertain to infer.

During data processing, there are several factors which influence the recorded EM baseline-monitoring data and which has to be compensated before the differences can be evaluated. They can be divided into instrument and survey site, hydrological, and meteorological categories. In the first category, EM system calibration and stability have to be controlled (pre-survey site calibration, on-site point measurements, frequency cross-correlations), measurement points have to be the same and changes in surface conditions have to be recorded and treated. In-house EMDC1D, PLOT, CONVERTER and GROUNDMODEL software modules were developed for various modelling modes, water chemistry calculations and presentations.

Hydrological changes also influence the measured EM signals. Groundwater level, water infiltration conditions, and the degree of saturation in unsaturated soils can change. In the meteorological category, precipitation over time changes continuously, as does soil temperature (depth profile). Developed processing routines remove and compensate for all these as much as possible. In anomaly pick-up, it is noted if any conditions along the profile section have changed. It is also important to collect associated background data from the site, such as geology-hydrogeology, groundwater standpipe and drilling data, water levels, water drainage arrangements, and changes in infrastructure and land conditions.

Processing of EM Im-components included component static levelling per frequency, corrective-predictive filtering using the developed OXZM-method (outlier, x-z directional and median filtering), final level adjustments, and electrical conductivity (EC) change zone calculations. Change zone detection applies threshold values regarding zone length, change magnitude, and presence at the used frequencies to avoid false or uncertain zone identifications. Each zone is labelled, and a mass index (average conductivity increase in groundwater multiplied by zone length, in mS units) is calculated. Typically, an increase of 50-100 ppm is required per frequency in the Im-component for change zone

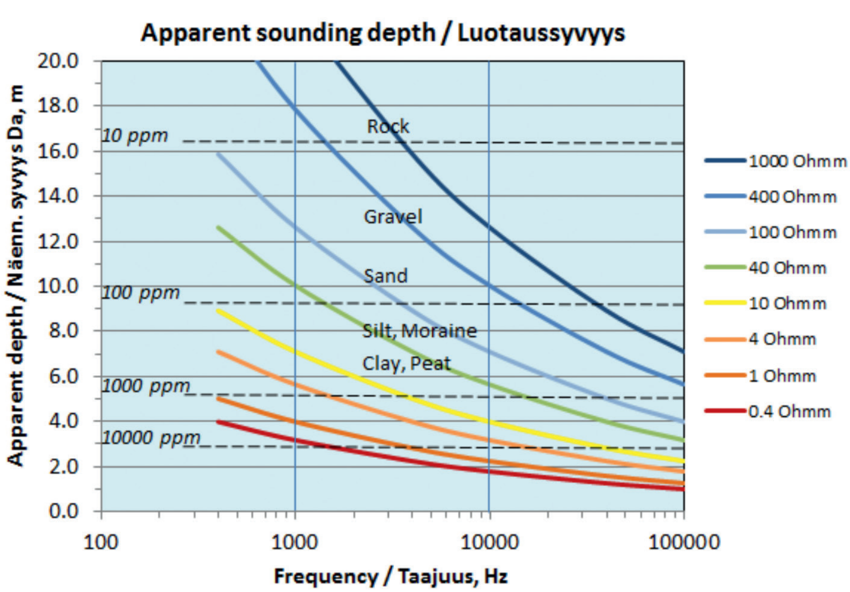

Figure 1 Apparent depth ranges Da in small coil-spacing EM frequency domain surveying (Saksa 2014).

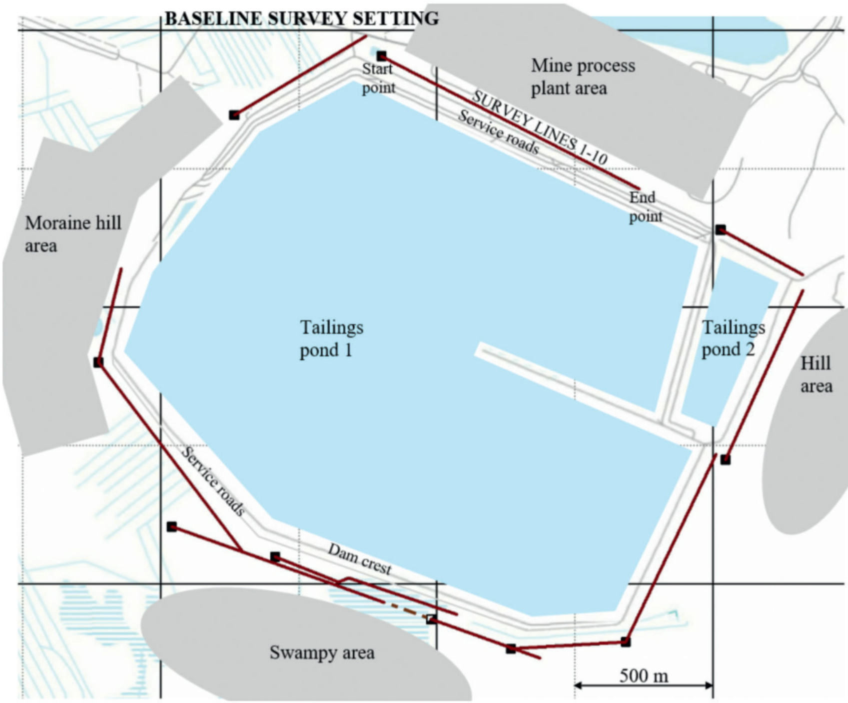

Figure 2 Baseline line network around a mine site and its major tailings ponds.

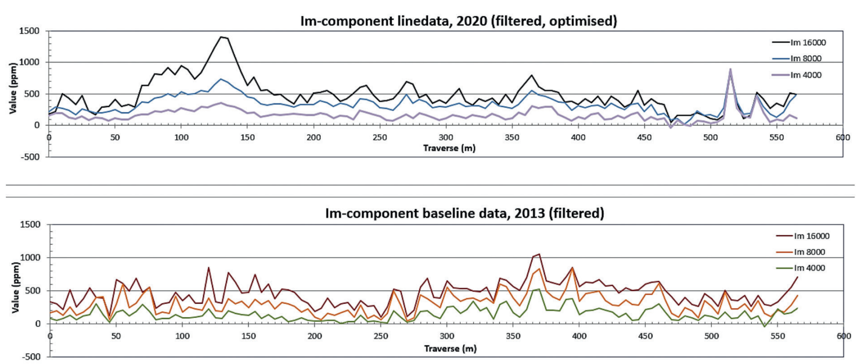

Figure 3 Monitoring line data from 2020 and baseline data from 2013, showing Im-components.

detection, but this depends on the overall apparent resistivity level, noise signal, and the variability of hydrogeological conditions.

Finally, all line data is presented as electrical conductivity change maps, as binary change zone maps, in profile presentations, and as a list of zones. Every monitoring data point has a coordinate, and data tables calculated in this way are transferred and documented in the client's GIS-system, for example, to assess the location for a new groundwater sampling point.

Monitoring examples

At one large Finnish metal mining site, the baseline survey was done in 2013. During the first stage, 10 lines were staked around two tailings ponds at a total length of 7.2 km. The baseline survey formed the basis for all future evaluations. The baseline was also interpreted against geology-hydrology main setting and normally provides some new geological-hydrological information, too. Figure 2 shows the location of the lines around the tailings pond areas.

Monitoring first took place in 2015 and has since been carried out roughly once per year. Many new lines have been added since 2015 based on water management interests and observations of changes in water chemistry. One particular addition was the establishment of lines along certain service roads along the dam perimeter. These can show outfiltration points closest to the wastewater reservoir and therefore enable rapid operational actions like drilling, wells, and water sampling. Figure 3 displays Im-component data from one line, originating from the baseline and from monitoring in 2020.

Together, time-lapse measurements show how distinct zones related to changes in water chemistry have developed over the years, Figure 4. The main ones are zones A) and B), and their magnitudes reduced in 2022 due to the establishment of nearby pumping wells. Mass index values for the change zones are shown. The line network has been expanded at the mining site to cover the dam perimeter lines (along the service roads) and to cover monitoring of the rock disposal area at one side. The total line network currently in operation at the mining site is about 23 km. At certain locations, more detailed EM studies and monitoring have been conducted, for example, to characterise dam structures.

Modelling tools and approaches

Rather early on, it was noted that no flexible and customised numerical processing software was available**.** Therefore, the

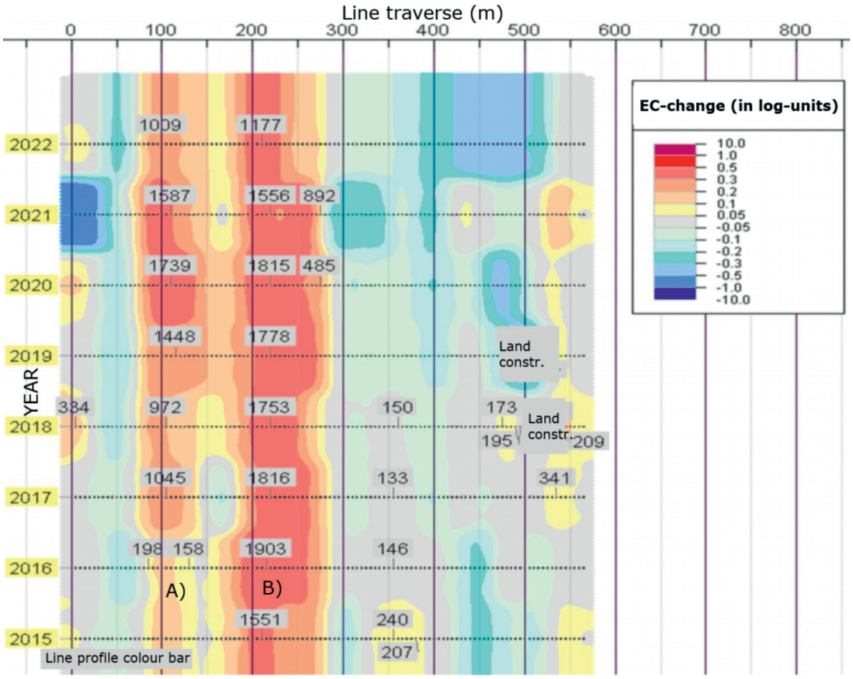

Figure 4 Figure 3 monitoring of line change zone development through the years, EC changes shown as log-values.

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, audio- and radiomagnetotellurics (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 the 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 us 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 (Schön, 2004), 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 5.

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

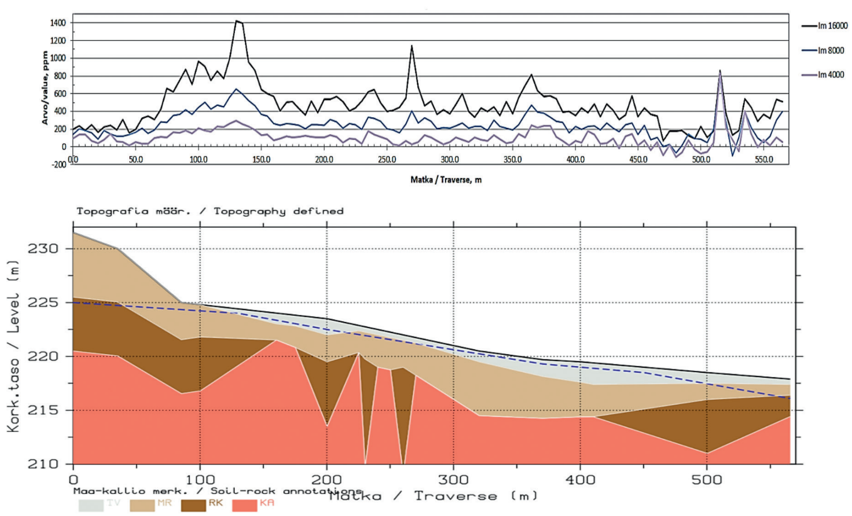

Figure 5 Example line data Im-component profiles are shown above and a ground model constructed for the line is shown below. Soils TV = peat (grey), MR = moraine (light brown), RK = broken rock (brown), KA = intact bedrock (red). Groundwater level is shown as a dashed blue line.

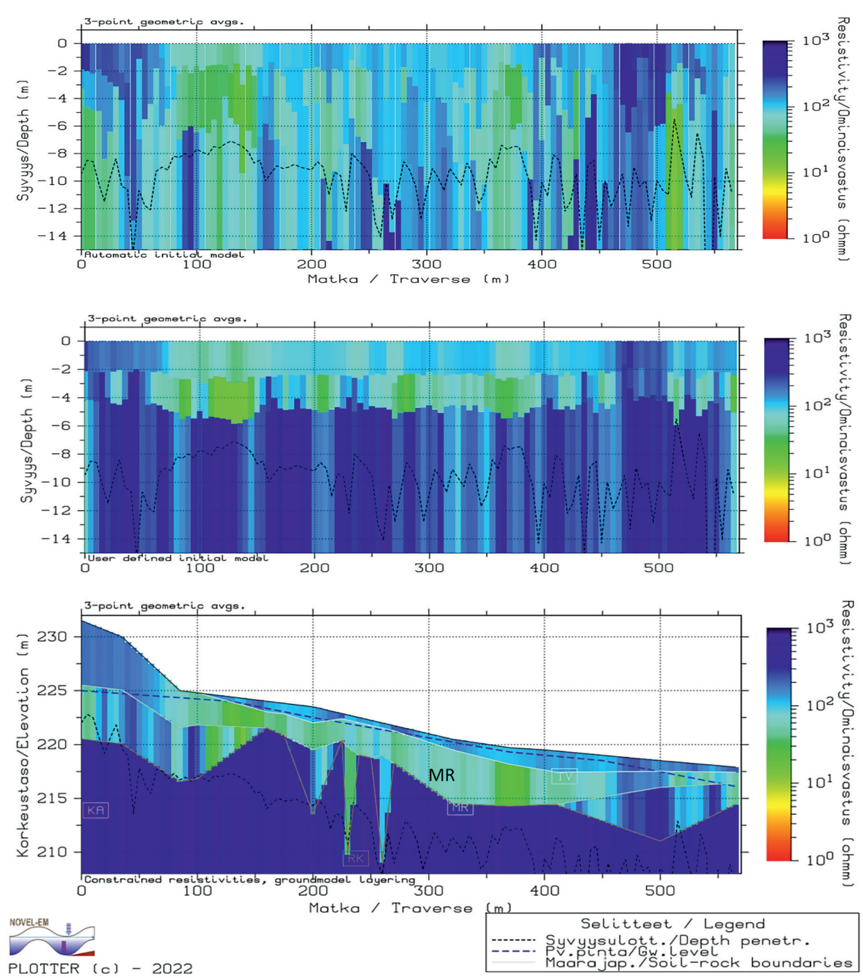

Figure 6 Example line modelling results with three alternative inversion settings: above is the automatic 3-layer model, in the middle is the user-constrained 3-layer model, and at the bottom is the ground model-constrained geometry and resistivities constrained per layer in inversion settings.

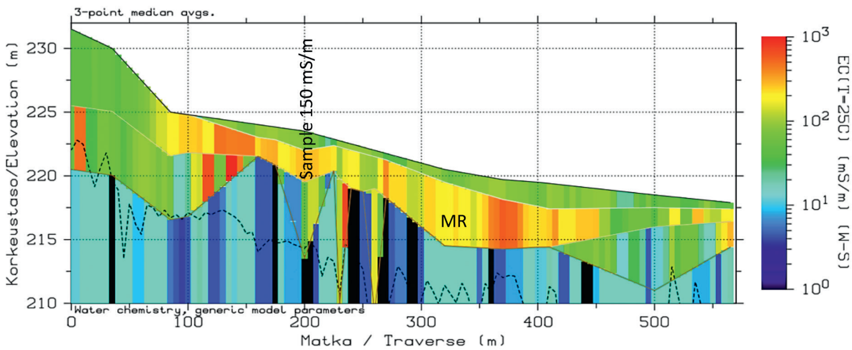

Figure 7 Figure 2 ground model inversion-based water EC calculation values, focus on moraine (MR) layer (porosity 30%, temperature +5°C, clay content 5% and CEC = 5 meq/100g).

COLOR SCALE: - 7.0 | -4.6 | -2.3 | 0.1 | 2.5 | 4.8 | 7.2 | 9.5 | 11.9 | 14.3 | 16.6 | + 19.0

	Day	January		February		March		April		May		June		July		August		September		October		November		December	
Depth, m	1	15	30	45	60	75	90	105	120	135	150	165	180	195	210	225	240	255	270	285	300	315	330	345	360
0.0	-6.0	-7.7	-8.8	-8.9	-8.2	-6.5	-4.1	-1.1	2.3	5.9	9.4	12.7	15.4	17.5	18.7	19.0	18.4	16.9	14.6	11.6	8.3	4.7	1.1	-2.2	-5.0
0.25	-3.9	-5.7	-7.0	-7.5	-7.2	-6.0	-4.2	-1.7	1.2	4.4	7.6	10.7	13.3	15.4	16.9	17.5	17.3	16.3	14.5	12.1	9.3	6.1	2.9	-0.2	-2.9
0.5	-2.0	-3.9	-5.3	-6.1	-6.1	-5.4	-4.0	-2.0	0.5	3.2	6.1	8.9	11.5	13.6	15.1	16.0	16.2	15.6	14.3	12.4	10.0	7.2	4.4	1.5	-1.1
0.75	-0.4	-2.2	-3.8	-4.7	-5.0	-4.7	-3.7	-2.1	-0.1	2.3	4.9	7.4	9.8	11.9	13.5	14.6	15.0	14.8	13.9	12.4	10.4	8.1	5.6	3.0	0.5
1.0	1.1	-0.7	-2.3	-3.4	-3.9	-3.9	-3.2	-2.0	-0.4	1.7	3.9	6.2	8.4	10.4	12.1	13.2	13.9	13.9	13.3	12.2	10.7	8.7	6.5	4.2	1.9
1.5	3.4	1.7	0.2	-1.0	-1.8	-2.2	-2.0	-1.5	-0.4	0.9	2.6	4.4	6.2	8.0	9.5	10.8	11.7	12.1	12.1	11.6	10.6	9.3	7.7	5.9	4.1
2.0	5.0	3.6	2.2	1.0	0.1	-0.5	-0.7	-0.6	-0.1	0.8	1.9	3.2	4.7	6.2	7.6	8.8	9.8	10.4	10.7	10.6	10.2	9.4	8.3	7.0	5.6
2.5	6.0	4.9	3.7	2.6	1.7	1.0	0.6	0.4	0.6	1.0	1.7	2.7	3.7	4.9	6.1	7.2	8.1	8.9	9.4	9.6	9.5	9.1	8.4	7.5	6.4
3.0	6.6	5.7	4.8	3.9	3.0	2.3	1.7	1.4	1.3	1.5	1.9	2.5	3.2	4.1	5.1	6.0	6.9	7.6	8.2	8.5	8.7	8.6	8.2	7.6	6.9
3.5	6.8	6.2	5.5	4.7	4.0	3.3	2.8	2.3	2.1	2.1	2.2	2.6	3.1	3.7	4.4	5.2	5.9	6.6	7.2	7.6	7.9	7.9	7.8	7.5	7.0
4.0	6.8	6.4	5.9	5.3	4.7	4.1	3.6	3.2	2.8	2.7	2.7	2.8	3.1	3.5	4.0	4.6	5.2	5.8	6.3	6.8	7.1	7.3	7.3	7.2	7.0
4.5	6.7	6.4	6.1	5.6	5.2	4.7	4.2	3.8	3.5	3.3	3.1	3.1	3.3	3.5	3.9	4.3	4.7	5.2	5.7	6.1	6.5	6.7	6.9	6.9	6.8
5.0	6.5	6.3	6.1	5.8	5.5	5.1	4.7	4.3	4.0	3.8	3.6	3.5	3.5	3.6	3.8	4.1	4.5	4.8	5.2	5.6	5.9	6.2	6.4	6.5	6.5
5.5	6.2	6.2	6.0	5.9	5.6	5.3	5.0	4.7	4.4	4.2	4.0	3.9	3.8	3.8	3.9	4.1	4.3	4.6	4.9	5.2	5.5	5.8	6.0	6.1	6.2
6.0	5.9	6.0	5.9	5.8	5.7	5.5	5.2	5.0	4.7	4.5	4.3	4.2	4.1	4.0	4.1	4.2	4.3	4.5	4.7	5.0	5.2	5.4	5.7	5.8	5.9
6.5	5.7	5.8	5.8	5.7	5.6	5.5	5.3	5.2	5.0	4.8	4.6	4.4	4.3	4.3	4.2	4.3	4.3	4.5	4.6	4.8	5.0	5.2	5.4	5.5	5.7
7.0	5.5	5.6	5.6	5.6	5.6	5.5	5.4	5.3	5.1	4.9	4.8	4.7	4.5	4.4	4.4	4.4	4.4	4.5	4.6	4.7	4.9	5.0	5.2	5.3	5.4
7.5	5.3	5.4	5.5	5.5	5.5	5.5	5.4	5.3	5.2	5.1	4.9	4.8	4.7	4.6	4.6	4.5	4.5	4.5	4.6	4.7	4.8	4.9	5.0	5.2	5.3
8.0	5.2	5.3	5.3	5.4	5.4	5.4	5.4	5.3	5.2	5.1	5.0	4.9	4.8	4.8	4.7	4.6	4.6	4.6	4.6	4.7	4.8	4.8	4.9	5.0	5.1
8.5	5.1	5.1	5.2	5.3	5.3	5.3	5.3	5.3	5.2	5.2	5.1	5.0	4.9	4.9	4.8	4.7	4.7	4.7	4.7	4.7	4.8	4.8	4.9	5.0	5.0
9.0	5.0	5.1	5.1	5.2	5.2	5.2	5.3	5.2	5.2	5.2	5.1	5.1	5.0	4.9	4.9	4.8	4.8	4.8	4.7	4.8	4.8	4.8	4.9	4.9	5.0
9.5	5.0	5.0	5.1	5.1	5.1	5.2	5.2	5.2	5.2	5.2	5.1	5.1	5.1	5.0	4.9	4.9	4.9	4.8	4.8	4.8	4.8	4.8	4.9	4.9	4.9
10.0	4.9	5.0	5.0	5.1	5.1	5.1	5.1	5.2	5.2	5.2	5.1	5.1	5.1	5.0	5.0	5.0	4.9	4.9	4.9	4.8	4.8	4.8	4.9	4.9	4.9
11.0	4.9	4.9	5.0	5.0	5.0	5.0	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.0	5.0	5.0	5.0	4.9	4.9	4.9	4.9	4.9	4.9	4.9
12.0	4.9	4.9	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.1	5.1	5.1	5.1	5.1	5.1	5.0	5.0	5.0	5.0	5.0	5.0	4.9	4.9	4.9	4.9
13.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
14.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
15.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0

Figure 8 Average half-space ground temperatures at 60 latitude. July temperature values are used to set resistivity sections to 100 Ωm level.

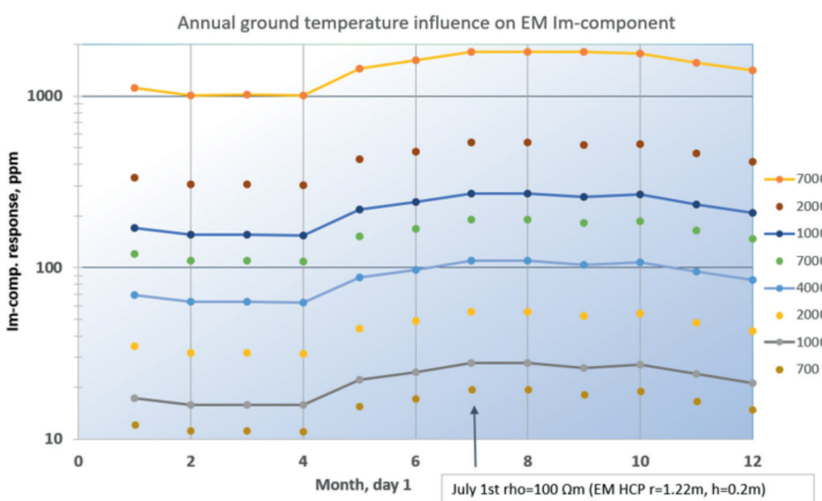

Figure 9 Calculated Im-component values for 100 Ωm ground (set for July) at other times during a year.

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 6. 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.

Further derivation and an example of water EC calculation are shown in Figure 7, with focus and parameters set on the moraine layer. Three major water chemistry flow zones intersect the line between 80 and 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.

An example of scoping calculation modelling

Ground temperature influences ground resistivity, increasing the electrical conductivity by approximately 2.2% per centigrade. In addition, there can be a frozen layer at the surface. Monitoring surveys at the site can be done at various times due to access restrictions and whenever needs arise, for example. Annual heat waves penetrate down to 5-10 me and change the measured resistivity response. Figure 8 shows typical half-space ground temperature changes at the Helsinki level (60° latitude). To calculate variations in resistivity, the ground response in July is normalised to 100 Ωm at varying depths. This means in practice that the structural parameters of the earth change with depth as the temperature changes. For other months, resistivities are calculated with 2 8-layer models using temperature-based differences compared against the resistivity normalisation for July.. In addition, a maximum ground frost depth of 0.5 m is considered, but the influence of snow cover is not accounted for in this case.

It is obvious that surveying at other times than in July would yield different results even in this simple case. Using calculated layer resistivities, the Im-component responses are calculated for the EM system used and presented in Figure 9. Annual resistivity changes are significant and need to be accounted for in data levelling for monitoring purposes. There are also periods like February, April and July, October when site temperature conditions are quite stable and only minor levelling is required.

Conclusions

During 2018, independent evaluation indicated that geophysics-based EC change zones and samples correlate well with direct groundwater sampling electrolyte results. Monitoring has also helped in positioning new groundwater standpipes and other environmental management actions that have been taken. A small number of lines have turned non-measurable due to earthworks at the site and the construction of new power lines. It has been noted that water chemistry change zones can also disappear or change form. The reasons for this include construction activities on the land, tailings pond operations, or other temporal sources of electrolytes. Pumping-related changes in the electrolyte content were also observed.

It can be also 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. Modelling is also needed in scoping calculations for variations occurring in site physical conditions, such as the example shown for temperature.

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