GELMON 2025

Seventh International Workshop in Geoelectrical Monitoring

17-20 February 2025 | TU Wien | Austria

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GELMON
GEOELECTRICAL MONITORING WORKSHOP

GeoSphere Austria

TU WIEN

TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

GELMON 2025

7th International Workshop on Geoelectrical Monitoring

Book of Abstracts

February 17th – February 20th, 2025

Editor: Birgit Jochum, David Ottowitz, Nathalie Roser, Clemens Moser, Ingrid Schlögel and Adrián Flores Orozco

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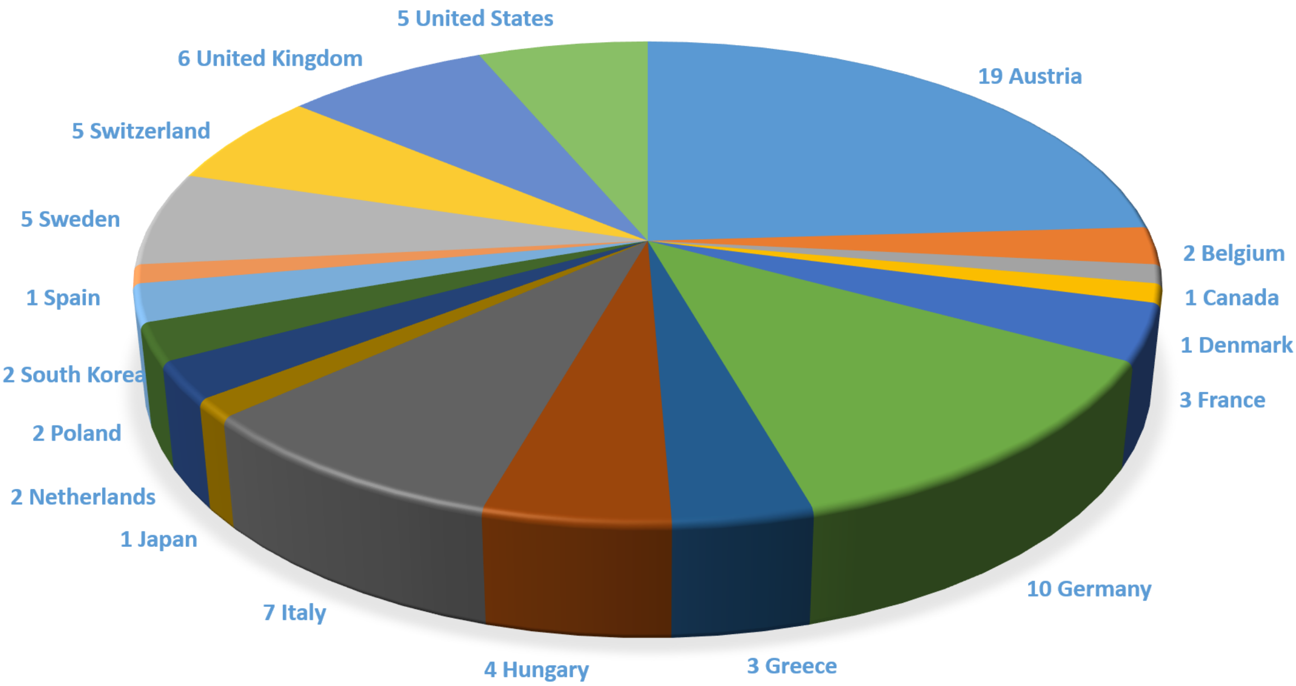
PREFACE

Dear participants and readers of this abstract book of the GELMON 2025 workshop,

We are happy to present you 50 abstracts (24 talks and 26 posters) submitted to the the international workshop on geoelectrical monitoring (GELMON). The book of abstracts include contributions from international experts on the use of geophysical electrical methods for the monitoring of subsurface processes. The submissions for the 2025 workshop revealed a significant interest on the topics of temperature correction and inversion of monitoring data. Further topics discussed in the workshop included case studies conducted in dams and embankments, landslides, frozen ground and permafrost sites as well as technological developments regarding monitoring systems.

GELMON 2025 was for the first time co-organized by the Geophysical Research Units of the GeoSphere Austria and TU Wien. Besides the participation in person, online attendance was also possible for all presentations. Before to the GELMON workshop, there was “a short course on versatile processing and inversion of geoelectrical monitoring data” given by Prof. Thomas Günther and Prof. Florian Wagner.

Our 79 participants, with affiliations to institutes from 18 countries around the world, were registered for the GELMON workshop:



We are looking forward for your participation in the GELMON workshop in 2027

The GELMON organizing team at the GeoSphere Austria: Birgit Jochum, David Ottowitz & Ingrid Schlögel

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Time Schedule

Date: Monday, 17/Feb/2025	
9:00 - 16:00	**pyGIMLi short course -** available for those registered to the short course
16:00 - 22:00	**Ice breaker party**
Date: Tuesday, 18/Feb/2025	
9:00 - 9:20	**Workshop Opening**
9:20 - 10:20	**Temperature I**
10:20 - 10:40	**Coffee break**
10:40 - 11:40	**Temperature II**
11:40 - 13:00	**Lunch**
13:00 - 14:00	**Permafrost**
14:00 - 14:20	**Coffee break**
14:20 - 17:00	**Poster session temperature, permafrost and contaminants**
19:00 - 23:55	**Conference dinner**
Date: Wednesday, 19/Feb/2025	
9:00 - 10:40	**Inversion**
10:40 – 11:00	**Coffee break**
11:00 – 12:00	**Landslides**
12:00 - 13:00	**Lunch**
13:00 - 13:40	**Soil moisture**
13:40 - 15:10	**Poster session inversion and landfill/dam**
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15:30 - 17:00	**Poster session infiltration/recharge**
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11:00 - 13:00	**Workshop Closing**

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ABSTRACTS

Temperature I

Study of the effect of surface temperature changes on the subsurface soil's/regolith's electrical resistivities as monitored by the ERT method.

Konstantinos Polydoropoulos, Panagiotis Tsourlos, George Vargemezis, Marios Karaoulis, Prodromos Louvaris

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Shallow Electrical Resistivity Tomography (ERT) monitoring experiments are highly affected by the diurnal and seasonal surface temperature oscillations, which need to be carefully monitored and considered for resistivity correction. The study is focused on the propagation of the surface temperature oscillation into the shallow subsurface, the estimation of the thermal diffusivity of the soil and the extrapolation of the propagation into deeper horizons where no in situ temperature measurements were available. In addition, approaches to compensate for the temperature effect specifically on time-lapse ERT data were tested. In particular, the standard correction method (i.e. temperature correction after time-lapse inversion) was tested against methods, which perform the time-lapse inversion after applying the temperature compensation. The results of this study are verified using synthetic examples and were also tested on real data collected over a 40-month period as part of a larger hydrogeological monitoring project, related to an infiltration study. Overall, at local scales, both diurnal and seasonal temperature variations can be predicted successfully based on relatively shallow single temperature sensors (e.g. at -15cm), provided that a realistic average thermal diffusivity value is known for the monitoring area. Further, the results indicate that there are correction techniques, which are more efficient in handling temporal electrical resistivity variations.

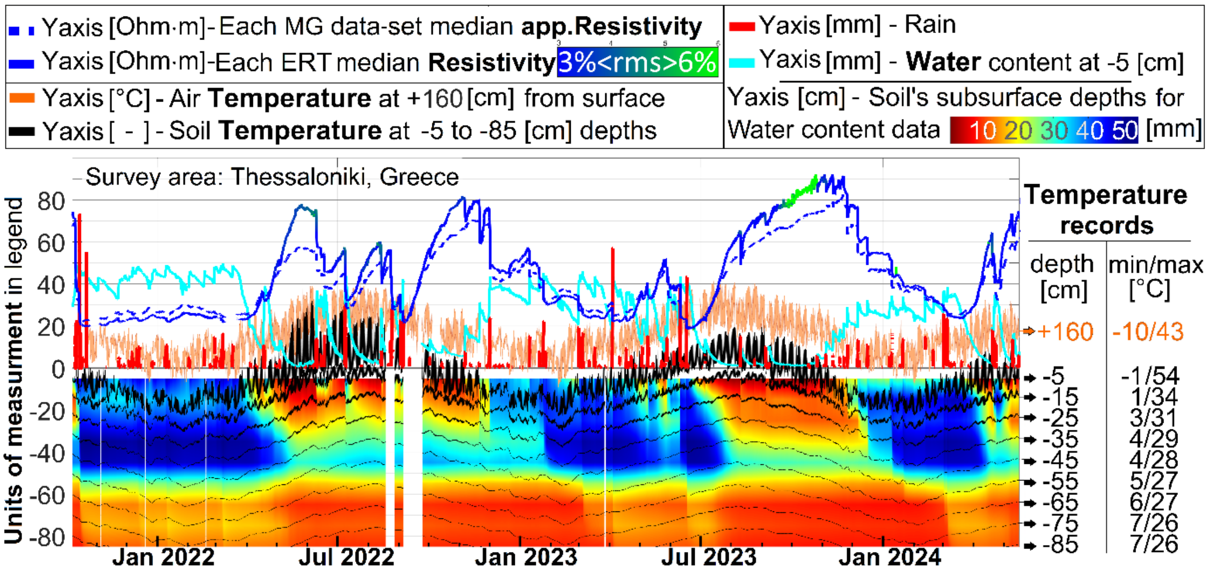

Figure: Electrical resistivity, temperature and water content surveyed data overview.

Modelling temperature effect in Time-Lapse DC monitoring experiments through inversion of thermal diffusivity

Alessandro Signora, Gianluca Fiandaca
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The seasonal temperature effect on electrical resistivity data is too often overlooked in ERT monitoring surveys and modelling efforts. When oversight, this can lead to anomalies in the models that are orders of magnitude greater than the target anomalies being monitored, potentially resulting in unusable or misleading results. When not overlooked, temperature correction involves costly and logistically complex measurements of ground temperature alongside resistivity data collection.

In this study, we propose a novel Time-Lapse inversion scheme, named ARES, to address the seasonal temperature effect without the need of subsoil measurements. The ARES correction directly incorporates temperature into the modelling, estimating subsoil temperature by solving the heat diffusion equation for each time-step and introducing the thermal diffusivity of the medium as an inversion parameter. We present synthetic modelling to test the effectiveness of the ARES correction and develop guidelines for implementing ERT monitoring with the ARES correction. Subsequently, the application of ARES scheme to a 20-month ERT monitoring project over a Municipal Solid Waste landfill is presented, where a 3D acquisition layout is employed to observe waste evolution and identify area of high biogas productivity. The monitoring study was not featured by any thermal monitoring despite the atmospheric temperature effect on data is extremely strong. Our results demonstrate that without the ARES correction, temperature effects overshadowed target anomalies, hindering interpretations. However, with the ARES correction, we successfully compensated for temperature effects in the inversion models. The new Time-Lapse inversion scheme finally enabled the detection of anomalies associated with the biogas formation and allowing for their volumetric analysis.

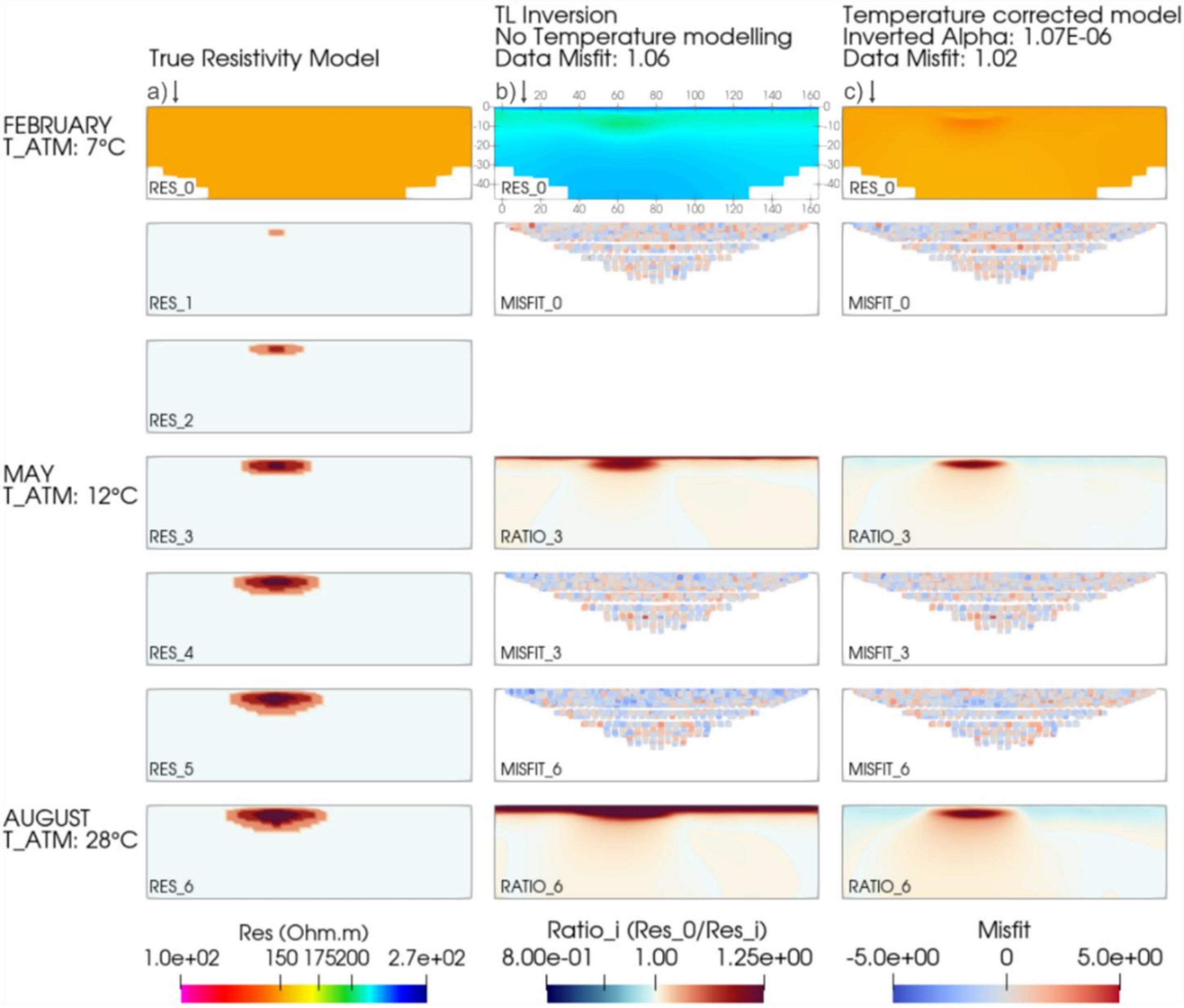

Figure: Inversion results

Electrical Resistivity Tomography monitoring of thermal plume development during a heat abstraction experiment at the UK Geoenergy Observatory in Glasgow

Paul Wilkinson, Oliver Kuras, Jimmy Boyd, Andrés González Quirós, David Boon, Mylene Receveur, Kyle Walker-Verkuil, Vanessa Starcher, Alison Monaghan

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The UK Geoenergy Observatory in Glasgow is a research facility designed and constructed by the British Geological Survey (BGS) on behalf of the Natural Environment Research Council and UK Research and Innovation. It is now a BGS operated facility that provides an at-scale underground laboratory to facilitate collaborative research for investigation of shallow low-temperature mine-water geothermal energy and thermal energy storage resources. It is located within the Cuningar Loop Park in Rutherglen, South Lanarkshire, a site which is typical of towns and cities with post-industrial urban and coalfield legacies. Using the heat resources and storage offered by flooded disused mines is an efficient alternative method of heating and cooling that can contribute to decarbonisation efforts, but its take-up is limited by a number of technical, societal and economic challenges. The Observatory started operations in 2023, aiming to investigate and better understand some of these aspects. As such, it is equipped with geothermal infrastructure and state-of-the-art monitoring capabilities, including downhole and surface loggers and sensors, fibre-optic cables for distributed temperature sensing, and electrodes for inter-hole Electrical Resistivity Tomography (ERT) imaging. Three boreholes are screened at the level of the Glasgow Upper mine working (~50 m bgl) and two at the Glasgow Main mine working (~85 m bgl). The abstraction boreholes are equipped with variable speed submersible well pumps. The mine water abstraction is connected to a heat centre, which contains three types of heat exchanger, an output heat pump/chiller for active heating or cooling of mine water, and a sensor logging system. BGS PRIME ERT monitoring systems are deployed, one on each of three neighbouring borehole clusters, and connected to permanently installed downhole electrode arrays permanently installed on the outside of the borehole casing from ~30 m bgl to just below the depths of the screened intervals, with electrodes spaced at 0.75 m.

Here we present results of ERT monitoring of the mine-water system prior to, during, and following a 24-day heat abstraction experiment. Mine water was abstracted from the Glasgow Upper mine working via one borehole at a rate of 6 l/s, chilled by ~3.5°C, and reinjected into the same working using another borehole 135 m away. ERT measurements were made every half hour at the reinjection site and every 2 hours at the abstraction site. The data were inverted using an automated processing workflow to produce time-lapse images of the changes in resistivity induced by the injection of the colder water. Since groundwater electrical conductivity varies with temperature by ~2%/°C, and no other factors were expected to influence the resistivity significantly during the experiment, time-lapse resistivity changes could illuminate the thermal processes (see Figure). These included heat transport via conduction in the rock mass, the development of a thermal plume around the injection borehole, conduction and advection of the thermal influence of the reinjected minewater, and possible evidence of thermal breakthrough in the abstraction borehole. All of these effects are highly relevant to understanding and parameterising key factors controlling the geothermal setting of the Observatory.

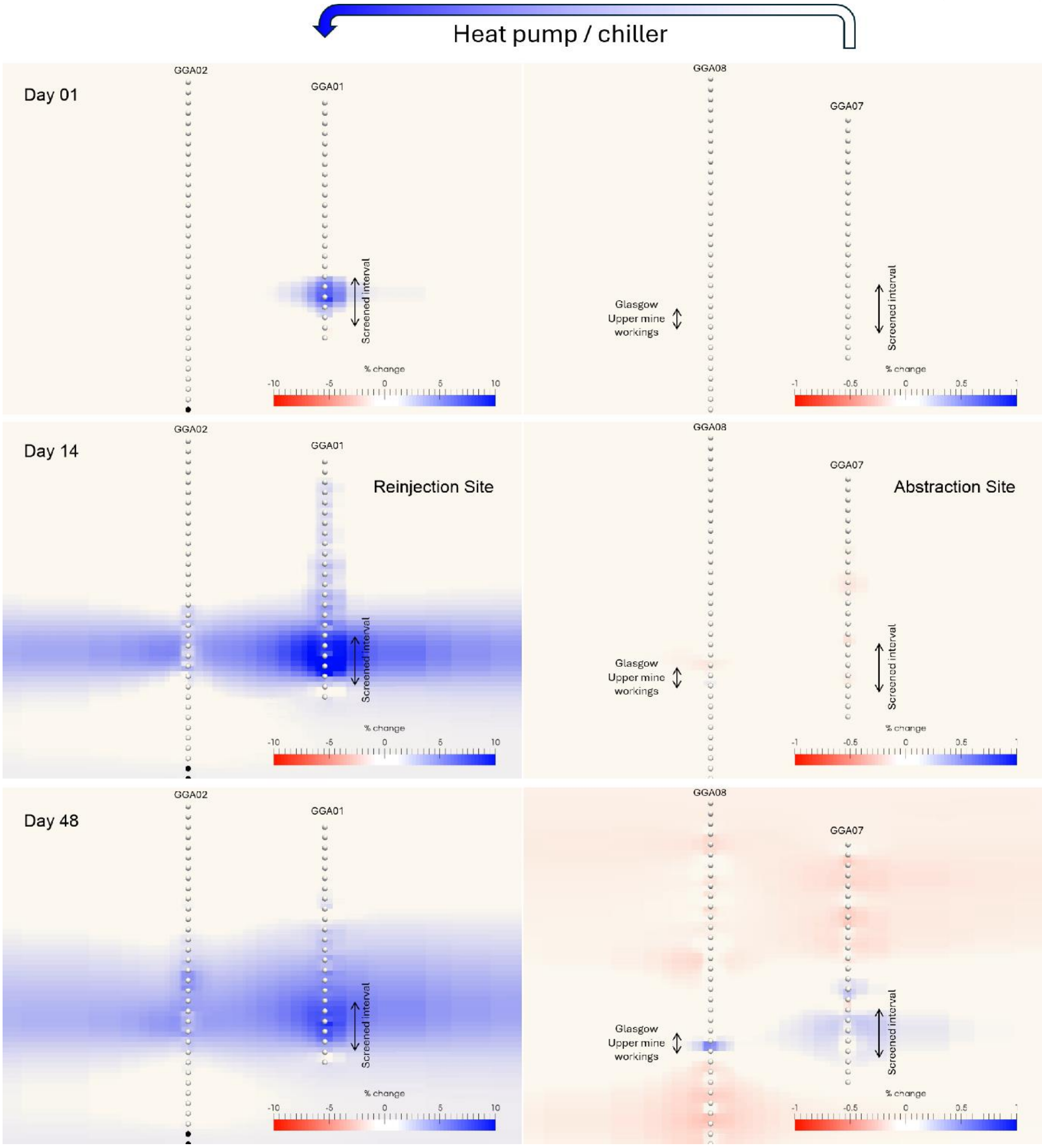

Figure: Monitoring results

Temperature II

4D ERT monitoring of Heating Process in the Coal Stock Pile

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Up to now, coal is the one of the main energy source for the generation of electricity. In the coal-fired power plant, we can easily observe many large coal stock pile waiting for the uploading to the power plant fascilities. Unfortunately, during the storage of coal, heat is accumulated inside the stock piles and eventually results in the self-combustion or coal fire, which is a very serious problem in terms of the safety, fuel management, and environmental aspect of the power plant facilities. To detect and forecast the coal fire, various methods had been suggested and tried but there are no proven early warning technology until today. Since it is well known that resistivity of subsurface material has a very good relationship with the temperature, ERT (Electrical Resistivity Tomography) monitoring technology was suggested to delineate the temperature changes in the coal stock pile. To examine the applicability of ERT monitoring for the temperature changes in the coal stock pile, a small scale coal stock pile was prepared, where electrodes were installed on the bottom of stock pile. Since heat accumulation inside the small-scale stock pile is not enough to induce the coal fire, we artificially applied heating in the center of the coal stock pile using heating system. The temperature was continuously increased until we can observe the real coal fire at the end of the experiments, while 3D ERT monitoring data were acquired with two hours intervals. The whole ERT monitoring data went through data processing including electrode filtering and time-series filtering. To obtain the resistivity change due to heating process, we tried the 4D inversion. In the 4D inversion results, we could identify the systematic change of resistivity values due to the heating process. Although resistivity is increased in the very early heating stage, increased resistivity is evident with the increase of coal temperature until self-combustion of coal. At the end of the experiments, direct measurement of the coal samples at the heating zone was tried and we could get extremely high resistivity values, which explains the heating of coals. Therefore, we could show and verify that 4D ERT monitoring technology can be a very promising method to detect and forecast the coal fire in the power plant facility.

Geoelectrical monitoring of temperature changes in the surrounding of a shallow geothermal heating system

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Utilising geothermal energy to generate electricity and heat is one of the key elements in the transition from conventional (fossil) to renewable energies. Depending on their area of application, geothermal systems cover a broad range from large and deep to small and shallow systems. Latter ones play an important role in the decentralised renewable energy and/or heat supply of residential buildings or small industrial areas. For planning and operation of geothermal systems, it is important to know the thermal properties of the underground (thermal conductivity and heat capacity). A monitoring of the soil temperature during the operation of the thermal system can be used as a proof that the underground installations are properly designed.

As previous studies have shown (e.g. Ko et al. 2023), the electrical resistivity of sandy and clayey soils changes by approx. 1-2 % per 1 K temperature change. Thus, temperature changes can theoretically be calculated from variations in electrical resistivity.

This study looks at how accurately it is possible to monitor the temperature variation of the subsurface caused by a geothermal heating/cooling system with geoelectrical methods under field conditions. For this purpose, repeated geoelectrical measurements are taken on an exemplary geothermal system in Schönhorst, Germany. It supplies a house with heat in winter and cold in summer. From January to October 2024, 7 data sets were recorded every 1-2 months. All data sets were inverted twice using the RES2DINV software (Loke & Barker 1996): Fully separated/uncoupled from each other and as time-lapse inversion. Both variants show a high degree of similarity.

The monitoring reveals relatively large resistivity variations of up to 50 % over the course of the year. Especially the first two meters below the surface are strongly affected by the natural seasonal variation in temperature as well as moisture differences. To isolate the resistivity changes caused by the geothermal plant, the mean effect of seasonal variations is removed from the inversion results. In the vicinity of the collectors, the remaining resistivity variations are negative in summer (higher temperatures) and positive in winter (lower temperatures), which matches the expectation.

These results show that it is possible to detect temperature changes in the subsoil caused by the operation of shallow geothermal systems using geoelectrical monitoring. However, it seems difficult to quantify the temperature changes due to overlaying effects like weather-related seasonal temperature variations and moisture differences. The objective of further investigations is to identify and quantify the environmental influences on the underground temperature as precise as possible. This will enable a more accurate assessment of the temperature field generated by the geothermal plant and facilitate the implementation of an effective programme to control its operation.

References:

Ko, H., Choo, H., & Ji, K. (2023). Effect of temperature on electrical conductivity of soils–Role of surface conduction. *Engineering Geology*, *321*, 107147.

Loke, M. H., & Barker, R. D. (1996). Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method1. *Geophysical prospecting*, *44*(1), 131-152.

Mapping heat plumes for shallow geothermal potential: a case study in Chalk aquifers using TL-CHERT and DTS

Yin Jeh Ngui, Mihai Cimpoiasu, Adrian White, Joseph Kelly, Katerina Kyrkou, James Boyd, Judith Porter, Harry Harrison, Phil Meldrum, Paul Wilkinson, Fleur Loveridge, Adam Booth, David Boon, Edward Hough, Matthew Jackson, Oliver Kuras, Jonathan Chambers

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Thermal response testing (TRT) is a critical method for assessing the thermal conductivity of subsurface materials and understanding heat transfer dynamics for geothermal applications. While conventional TRT provides bulk thermal properties, its capacity to resolve the heterogeneity of geological formations is limited. This study addresses this gap by integrating cross-hole electrical resistivity tomography (CHERT) and distributed thermal sensing (DTS) to enhance the characterisation of thermal transport processes in a Chalk aquifer with complex hydrogeological properties. The focus is on monitoring subsurface thermal dynamics and identifying preferential flow paths, with implications for improving geothermal system design and management.

The test site in Berkshire, England, features a 100 m closed-loop ground heat exchanger subjected to thermal response testing (TRT) with heat injection. While DTS provided high-resolution spatial and temporal temperature data along the borehole, CHERT enabled detailed 2D tracking of thermal plume development across subsurface. Time-lapse CHERT surveys were conducted using low-power BGS PRIME ERT system to monitor temperature-induced resistivity changes. In-hole dipole-dipole arrays captured early thermal snapshots, while cross-hole arrays between the injection borehole and a downstream monitoring borehole mapped resistivity changes in the subsurface. Given the short TRT timeframe and stable hydrogeological conditions below the groundwater table, resistivity variations were primarily attributed to temperature increases. A 2% resistivity reduction, corresponding to a temperature rise of approximately 1°C, was observed in a fractured Chalk Rock horizon at 25 mAOD, indicating a preferential groundwater flow path.

The DTS system measured temperature changes every 0.5 m along the heat exchanger at 4-minute intervals, complementing the ERT by identifying thermal responses in specific geological units. Notably, DTS delineated groundwater flow zones with high precision, revealing differential flow dynamics across thin geological layers. However, at shallow depths, minimal thermal transmission was observed between the boreholes, likely due to rapid groundwater movement in the dual-porosity Chalk matrix.

This study demonstrates the sensitivity and spatial resolution of CHERT in capturing subsurface thermal variations associated with heat injection. ERT data provided a clear visualisation of plume evolution and preferential flow paths that traditional TRT or DTS alone could not achieve. The findings highlight the potential of TL-CHERT as a diagnostic tool for understanding hydrogeological variability and thermal transport in complex aquifer systems.

While this combined approach is unlikely to be economically feasible for routine closed-loop geothermal systems, it offers significant insights for the design and monitoring of open-loop systems and aquifer thermal energy storage (ATES). In such systems, understanding site-specific flow dynamics and thermal interactions is critical for optimising performance and long-term sustainability. This case study underscores the utility of CHERT in providing high-resolution thermal and hydrogeological characterisation, setting the stage for improved subsurface energy solutions.

Permafrost

Time-lapse joint inversion of seismic refraction and electrical resistivity monitoring data – Part I: Theory and synthetic studies

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Permafrost degradation is a global phenomenon with significant implications, including the release of greenhouse gases from thawing soils and increased risks of rock falls or landslides in alpine regions. Geophysical monitoring methods provide a unique, non-invasive means to observe permafrost dynamics at high spatial and temporal resolutions. However, quantitatively estimating pore-filling constituents such as ice, water, and air content from a single geophysical method remains challenging due to the ambiguous relationships between these parameters and their geophysical signatures. This challenge is further aggravated by unknown porosity distributions and uncertainties in petrophysical equations, which involve additional parameters often assumed to be spatially and temporally constant.

In this contribution, we present a methodology for the inversion of geoelectrical and seismic refraction monitoring data using petrophysical and temporal coupling. The petrophysical coupling enables the direct estimation of pore-filling constituents honoring petrophysical relations and physical plausibility (i.e. volumetric constraints). The temporal coupling enables the differentiation between parameters that are assumed to be invariant within a monitoring window (e.g., porosity) and those parameters, which are expected to exhibit a dynamic behavior (e.g., ice and liquid water contents). We demonstrate the advantages and limitations of this time-lapse joint inversion framework based on synthetic experiments and several field data sets (the latter being presented by Hilbich et al. in Part II of the same contribution) and conclude on necessary advancements, such as the integration of other geophysical methods, to make geophysics-based ground ice estimation more reliable and robust.

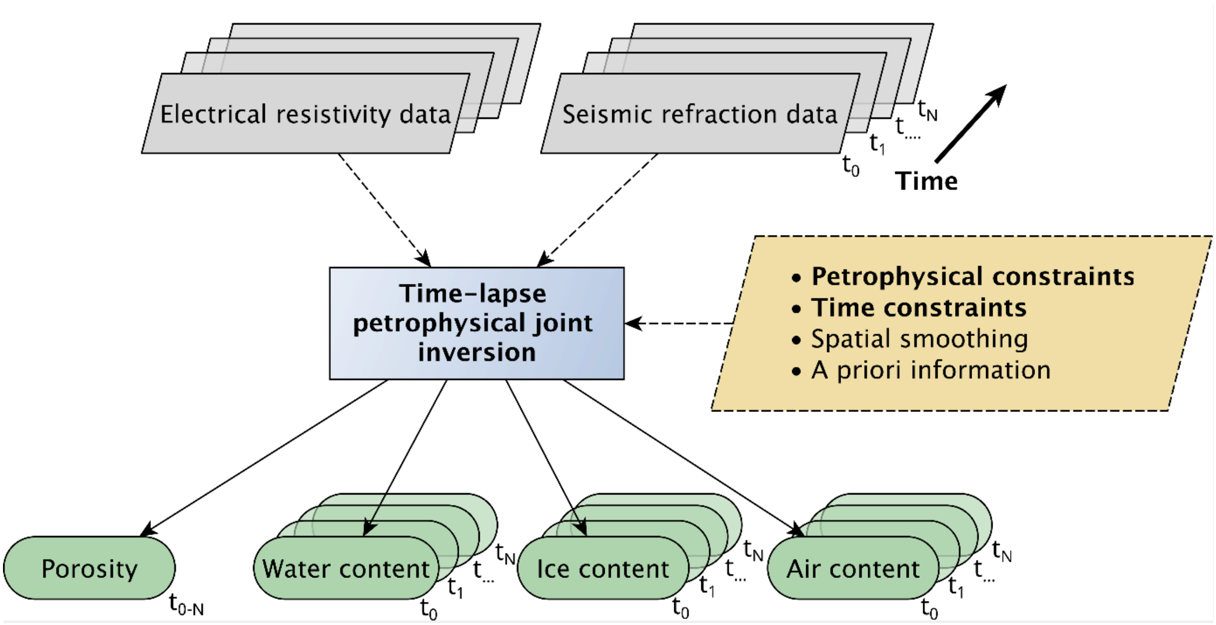

Figure: Inversion schema

Time-lapse joint inversion of seismic refraction and electrical resistivity monitoring data – Part II: Field applications

Christin Hilbich, Bernd Etzelmüller, Christian Hauck, Ketil Isaksen, Coline Mollaret, Cécile Pellet, Florian Wagner

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Geophysical monitoring has become more and more popular in permafrost environments due to its remarkable success to detect permafrost thawing and associated spatio-temporal changes in the ground ice content. However, the quantification of ground ice contents and especially of their temporal changes are still challenging tasks. Recent advancements in the petrophysical joint inversion of seismic refraction and electrical resistivity monitoring data (as presented by Wagner et al. in Part I of the same contribution) now allow for a time-lapse application of the petrophysical joint inversion approach (TL-PJI), which ensures a time-consistent porosity distribution and therefore improves the reliability of predicted ice content changes.

We here apply this time-lapse petrophysical joint inversion (TL-PJI) approach to four different mountain permafrost sites in Norway that have been subject to substantial change over the past decades.

The dataset consists of various profiles that have first been measured in 2008 (two sites in Northern Norway) and 2010 (two sites in Southern Norway) and were repeated in 2019 and again for some profiles in 2024. Initially, the permafrost conditions of the sites ranged from relatively cool permafrost (Juvvass_PACE), over warm permafrost (Guolasjavri) to advanced stages of degradation with isothermal conditions (Iskoras, Tron). This is evidenced by borehole temperatures down to 20 m depth at all sites. Until today, all borehole records have shown significant warming, in some cases leading to severe permafrost degradation down to depths of 15 m or more.

The repeated geoelectric and refraction seismic surveys at all four sites cover this period of strong permafrost warming and provide a unique opportunity to evaluate the performance of the TL-PJI approach regarding changes in the ground ice, water, and air content. A special focus will be placed on the data sets with multiple repetitions to analyse the influence of using different time instances on the predicted porosity distribution (assumed to be invariant in time) and the respective other pore-filling constituents, which may change with time.

Automated ERT processing to obtain the temporal change in electrical resistivity on 20 mountain permafrost profiles

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In permafrost research, geoelectrical surveys are increasingly used to detect the presence and extent of permafrost and to characterise the stratigraphy and material composition of permanently frozen terrain. When repeated, the resulting temporal changes in electrical resistivity can be related to changes in ground temperature and ice content, and therefore also to ground ice loss over time. However, for financial and logistical reasons, there are only a few continuous electrical resistivity tomography (ERT) permafrost monitoring profiles in the world. An alternative approach is manual but regularly repeated ERT measurements, such as, among others, in the context of the Swiss Permafrost Monitoring Network (PERMOS, 2024). The promotion of ERT repetitions on permafrost is one of the main objectives of the IPA (International Permafrost Association) Action Group entitled International Database of Geoelectrical Surveys on Permafrost (IDGSP) and launched in 2021. More than 200 ERT profiles have already been inventoried in Switzerland (but it is estimated that there are more than 500) and are part of the dedicated IDGSP database (publicly accessible via a searchable web map, which is available at https://resibase.unifr.ch). Recently, several field campaigns have aimed to repeat these individual ERT measurements, around 30 profiles in Central Europe.

These data are re-processed using filtering and inversion routines (based on the work of the IPA Action Group, Herring et al. 2023). For this, a dedicated script was developed to process all different profiles, whether they are single or repeated measurements. This is challenging due to the diversity of permafrost soils and landforms, which exhibit a wide range of resistivity values that can differ strongly from site to site, leading to the need to improve the automated processing. Comparison between sites is further complicated by the different individual dates of the available ERT repetitions. In this contribution, we discuss the robustness of the results and analyse the temporal changes in resistivity at all available profiles in the context of climate warming and permafrost degradation.

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Poster session temperature, permafrost and contaminants

Geophysical monitoring of temperature variation and rock moisture changes in a frost weathering cave

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The critical factor in determining the efficiency of frost weathering and their associated phenomena is the moisture content of the rock. However, the phenomenon and associated processes remain only partially quantified. While direct measurements with punctual sensors, e.g., temperature sensors, provide important discrete information, spatial variability in the parameters of interest is key. Electrical conductivity and induced polarisation (IP) measurements have already been employed on the field scale for groundwater detection and also in the observation of rocks during freezing and thawing processes (Coperey et al., 2019). Here we explore the use of IP imaging for the quantification of temperature changes and rock moisture along the ceiling of a frost-weathering cave in carbonate rocks.

The IP monitoring was conducted in the *Untere Traisenbacher Cave* (Lower Austria) over three days in February 2020, with measurements conducted every 48 minutes, encompassing a total of 77 individual measurements. Imaging data were collected using the DAS-1 instrument (from multi-phase technologies), comprising 64 electrodes in a distance of 10 cm using a multiple gradient configuration with potential dipoles of one to five times the electrode spacing. Rock temperature measurements were taken at the entrance with sensors directly installed in the rock wall at three depths (3 cm, 10 cm, and 40 cm) below the cave ceiling and at the surface.

Before the inversion, the following filtering steps were used: 1) We removed quadrupoles with negative apparent resistivity readings, 2) Additional outliers were defined based on a histogram analysis, and 3) we used only quadrupoles, which were found in all time steps. The data were inverted using the open-source libraries pyBERT and pyGIMLi. Three inversion approaches were employed: 1) Independent inversions, 2) difference inversions, 3) Simultaneous inversion of three consecutive time steps by using the z-axis as the time dimension.

Our results show only slight variations between the different inversion approaches (the smoothest solution was derived with approach 3) demonstrating that raw data quality and the data processing steps are key for consistent time-lapse imaging results in our site. The time-lapse analysis reveals a linear correlation between temperature and conductivity, which was used for the removal of temperature effects from the conductivity images to evaluate changes in water content. The conductivity values, which permit the determination of water content, fluctuate between -30% and +30% throughout the monitoring period. The alterations manifest with particular swiftness and clarity in the outer 10 cm, as this is the weathering layer, which is notably fissured and in direct exchange with the environment. Nevertheless, alterations in rock moisture can also be observed at greater depths, which can be attributed to differences in rock porosity and permeability. The results demonstrate that time-lapse IP imaging is a useful tool for the estimation of the susceptibility of the rock to frost weathering.

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Daily geo-electric monitoring of an active Volcanic Hydrothermal System

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Geo-electric methods have become increasingly important in characterizing volcanic and geothermal systems. As the methods depend on parameters such as temperature, saturation, and the presence of clays, they have applications in reservoir characterization, and edifice stability, but previous studies remain mainly static. With the ERupT project, we aim to assess the suitability of ERT and IP to visualize the dynamics in volcanic hydrothermal systems with the long-term aim of improving hazard assessment related to hydrothermal eruptions.

The Reykjanes Geothermal field was chosen for the experiment. In September 2022, the field was characterized using geo-electric methods (ERT/IP/SP) allowing us to identify zones of high and low activity and areas where new surface manifestations are likely to occur. The location of the monitoring profile was chosen where we expect the most changes to occur.

Monitoring includes a daily measurement of ERT and TDIP in normal and reciprocal settings using the multi-gradient protocol. The profile is 355 m long and has a DOI of 30-50m. Auxiliary data includes monitoring of the soil CO_2 concentration, temperature, and humidity and tremor monitoring.

The 2021 eruption at Fagradalsfjall marked a new age of volcanism in the Reykjanes peninsula, since the start of the ERT monitoring 5 eruptions occurred. The first eruption happened in the Fagradalsfjall system on July 10th 2023, after that activity moved towards the Svartsengi system, which has been periodically erupting since December 18th 2023. The eruptions are located at respectively 10 and 25 km from the field site.

Although the ERT system is located at a considerable distance from the eruption sites and the investigation depth is shallow, we observed signals possibly related to both eruptions and accompanying unrest, manifesting as a significant increase in resistance (figure1). When visualizing this with the earthquake magnitude on the peninsula, a pattern can be observed. An increase in resistance is followed by an earthquake swarm and later a volcanic eruption but with a different time-lag. In this context, an increase in resistance is likely caused by a drop in water saturation due to high gas levels, which can be caused by magma degassing during the uprise. This raises the question of the time difference, possible factors are the difference in morphological context and preferential flow paths relative to our monitoring site. It should be noted that this signal is not present in all data points and was thus not visible in the inversion result. By including some pre-inversion PCA and clustering we were able to isolate the signal and visualize this process.

To our knowledge, this is the first time that ERT has been used for daily monitoring of a volcanic system. With joint interpretation to deduce the signal origin, we believe that ERT can be a valuable addition to volcanic monitoring networks.

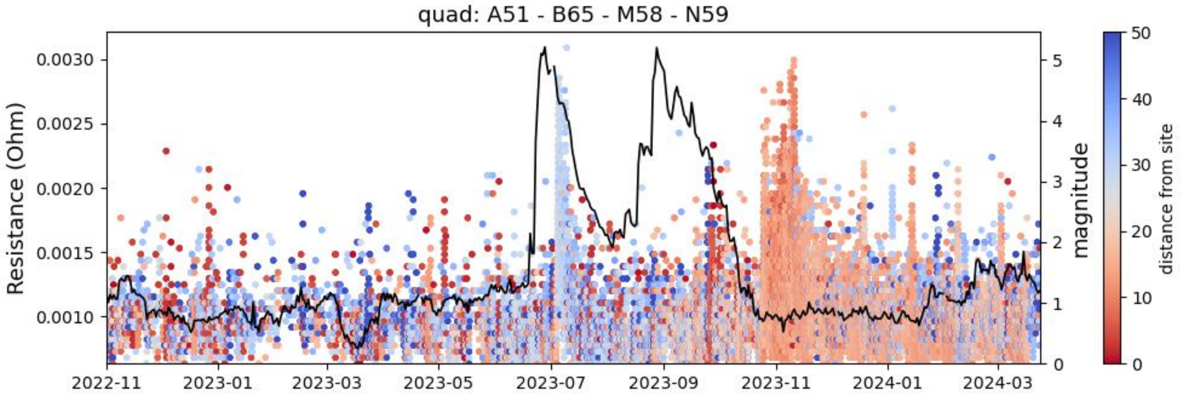

Figure: Temporal changes in transfer electrical resistances

Borehole electrical monitoring of a thermal response test

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Thermal response tests (TRT) are used to estimate the equivalent thermal conductivity and sometimes the volumetric capacity of the subsurface, which are required for the design of geothermal fields. TRTs involve circulating heated water through a ground heat exchanger while measuring temperature changes at the borehole inlet and outlet over time (Pasquier et al., 2016). This process traditionally relies on water temperature measurements rather than direct observations of the bedrock temperature. Geoelectrical measurements have been used to monitor temperature variations caused by heated water injected in the ground (Hermans et al. 2012). Hence, borehole geoelectrical measurements could provide indirect imaging of the temperature variations around the borehole during a TRT. In this study, we investigate the use of geoelectrical monitoring during TRTs to enhance the accuracy of subsurface thermal property estimation.

We carried out a proof-of-concept study in Varennes, Québec, Canada, to explore electrical monitoring during a TRT at a site with a 215 m deep standing column well (SCW). SCWs are open-loop ground heat exchangers that pump groundwater to the surface to exchange heat with heat pumps before being reinjected into the same well. While heat transfer with the geological environment during normal operation is mostly conductive, SCWs can be operated with a net pumping rate. This operation, called bleed, enables advective heat transfer and boosts the thermal performance of the SCW (Pasquier et al., 2016). For the electrical TRT, the SCW was subjected to a heating phase of 11 days, followed by two days of bleed. Geoelectrical measurements were conducted using a cable with 32 electrodes spaced 25 cm apart and deployed at a depth of 150 m. Time-lapse apparent resistivity measurements were collected using a pole-pole configuration, with electrode spacings ranging from 25 cm to 7.75 m. Additionally, borehole temperatures were monitored with fiber optics, and water conductivity was measured using an LTC probe. Measurements continued for an additional five days after the cessation of all operations to monitor the recovery to undisturbed ground conditions.

The experiment's expected electrical response was modeled using infinite line and cylindrical line source models to simulate temperature variations around the SCW. Electrical resistivity changes were predicted based on the temperature dependence of electrical resistivity (Hayley et al., 2007), accounting for temperature changes in both the rock and the SCW. Finally, preliminary field data analysis demonstrated that there is a strong correlation between apparent electrical resistivity and temperature variations during heating and recovery cycles. Specifically, a maximum variation of approximately 27% in apparent electrical resistivity was observed for a temperature variation of 20 °C at 25 cm electrode spacing. Minimal variation was observed for electrode spacings greater than 2 m, consistent with the modeled response. Therefore, these findings suggest that the thermal behaviour in the rock surrounding the borehole can be monitored by geoelectrical measurements. Further analysis of these results could potentially improve the accuracy of thermal parameter recovery.

Cross-borehole electrical resistivity tomography (ERT) measurements for the monitoring of ice-rich mountain permafrost

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Significant increases in rock glacier velocities have been observed in the European Alps. These movements are mainly influenced by external climatic factors, with patterns of acceleration alternating with periods of stagnation or deceleration. Recent studies highlighted air and ground temperatures, along with snow cover and ground water content, as key drivers of these movements. The integration of rock glacier displacement data, water input, and subsurface data, as thermal, hydrological or stratigraphic information, is crucial for understanding the complex relationship between external factors and rock glacier dynamics.

Due to logistical and financial constraints, direct subsurface data from rock glaciers are scarce. Borehole temperature measurements are commonly used to monitor temperature regimes, active layer thickness, and thermal anomalies. However, temperature data alone cannot be used to distinguish between ice and water, which can coexist at 0°C or below due to, e.g., electrolyte and clay content, making water content data essential for understanding rock glacier dynamics. To address this, surface ERT measurements are widely used to investigate and monitor permafrost, but its limited depth resolution poses a challenge. Cross-borehole ERT provides higher resolution data and can help to distinguish between ice and water in ice-rich permafrost and monitor changes over time.

At two sites in eastern Switzerland, we installed an innovative combination of borehole sensors to study rock glacier temperatures, water content and internal displacement. In summer 2020, we drilled three boreholes at the Schafberg Ursina III rock glacier and five boreholes in summer 2024 at the Muragl rock glacier, reaching depths of up to 26 m. These boreholes were equipped to monitor ground temperatures (*YSI 44031* thermistors and *C225* temperature string; http://www.ysi.com; https://www.campbellsci.com), pore water pressure (*Keller PAA-36XiW piezometers*; http://keller-druck.com), vertical displacement (*ShapeArray SAAV 500mm* https://measurand.com), and ground resistivity (ERT). For the cross-borehole ERT setup, we use a *Syscal Pro Switch 48* device in combination with a *Syscal Monitoring Unit*, which automatically collects, records and transmits the data on a daily basis (https://www.iris-instruments.com). We use two multi-core cables, which are installed in two boreholes 5 m apart. The 10 cm long stainless-steel electrodes are integrated into the cable with an electrode spacing of 0.5 m. The contact between the electrodes and the ground was improved by stainless-steel clamp collars and a sand-gravel mixture, which was filled between the electrodes and the borehole walls. We measure direct and reciprocal data points using a dipole-dipole array and analyse the data using the Python-based open-source software ResIPy.

In our contribution, we will present the two cross-borehole ERT setups and compare the results with our complementary measurements. Our multi-year monitoring at Ursina III captures a phase of deceleration followed by acceleration, associated with variations in ground water content. To assess the applicability of our initial setup at the Ursina III to other sites, we will compare these results with data from the Muragl site. Cross-borehole ERT might be a key for measuring relative water content and, along with other data, improves our understanding of the role of water in rock glacier dynamics.

Geoelectrical imaging of saline permafrost at Drew Point, Alaska

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Saline permafrost is primarily found in marine deposits beneath shallow shelf seas and can often extend several kilometres inland from present Arctic coastlines. On land, saline permafrost forms when previously submerged marine sediments are exposed to the atmosphere, either through a sea level regression or post-glacial rebound. Cryopegs are perennially cryotic layers or pockets within saline permafrost that remain unfrozen due to their high salt content. In a warming Arctic, the expansion of cryopegs poses a potential risk to coastal infrastructure, making it crucial to study their distribution and thickness. In July 2018, we conducted multiple electrical resistivity surveys and an amphibious onshore-to-offshore transect at Drew Point, Alaska. Preliminary results from many soundings showed a trend of decreasing apparent resistivity with increasing electrode spacing, suggesting the presence of conductive regions in the subsurface. Borehole data confirmed cryopegs at or near sea level, although these data did not provide precise depths for the bottom of these features. We present geoelectrical data on saline permafrost using 2D smooth inversions and 1D global inversion approaches at selected soundings. Our goal is to characterize cryopegs and demonstrate the effectiveness of geoelectrical surveying in mapping these structures.

Monitoring saltwater tracer injections with 3D time-lapse electrical resistivity tomography for the localization of fractures in alpine bedrock permafrost

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Time-lapse electrical resistivity tomography (ERT) has been established as a suitable tool to monitor tracers moving through the earth's subsurface (e.g., Singha and Gorelick, 2005; Cassiani et al., 2006). Here, we apply the method at the Cime Bianche plateau (Aosta valley, Italy), a permafrost monitoring site (highly weathered bedrock) at 3100 m a.s.l. undergoing permafrost degradation (Pogliotti et al., 2015), where borehole temperature measurements and geophysical imaging have shown a high spatial variability in temperature and subsurface electrical properties (Maierhofer et al., 2024), suggesting the presence of fractured areas. We injected saltwater into eight different locations to localize flow paths associated with fractured areas and conducted 3D time-lapse ERT measurements to record changes in the subsurface electrical conductivity associated with the movement of the tracer. For the 3D measurements, we used a Syscal Terra with 20 channels for potential readings, which permits us to collect data at a high temporal resolution (5-10 minutes per time step). Data were collected in a grid array with 8x9 electrodes and a separation of 3 m. For the inversion we used the R3t code in the ResIPy wrapper (Blanchy et al., 2020), and tested different time-lapse inversion approaches (independent, difference, background-constrained). In five of eight points the water infiltrated quickly (from several minutes up to hours) into the subsurface leading to only slight changes in the electrical conductivity close to the injection point. In the other three points the injection disappeared after a few seconds, resulting in large conductivity changes, not only in close vicinity to the injection point but also in a depth of >10 m. Our results reveal the presence of highly fractured materials, which act as preferential flow paths for groundwater, and which might represent a key path for advective heat exchange between the atmosphere and the subsurface in alpine bedrock permafrost. Knowing the geometry and location of such features is essential in thermal modelling and further understanding of the permafrost degradation processes at the site.

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The evolution of glacial and post-glacial areas in southern Spitsbergen on geophysical data - 9 years of observations from Hornsund Fjord area.

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Climate change has considerable impacts on our society, and hence, its effects and impacts are increasingly being studied using geophysics. The effects of climate change are especially evident in polar areas, where, due to the Arctic amplification, they are observable over relatively short periods. This gives a view of possible environmental changes not only on a local but also on a global scale.

One of the key issues is the evolution of post-glacial areas, which are subject to rapid shifts conditioned by surface temperature. Variations in air temperature both directly and indirectly condition thermal and hydrological alterations in the ground to considerable depths, significantly contributing to the rapid changes observed in the forelands of retreating glaciers and local aquifers even up to 40 m under the surface (Marciniak et al. 2022, Majdanski et al. 2021). This study investigated the internal structure and seasonal variations of cryo-hydrogeological and physical features in the areas near the Polish Polar Station Hornsund in Svalbard. Two representative sites, the Fuglebekken catchment and the forefield of the retreating Hans glacier, revealed the significant and rapid evolution of this southernmost area of the Arctic. This research used a multi-method approach to capture spatial and temporal variations in dynamic cryo-hydrogeological conditions, combining in-situ borehole and piezometer data with geophysical methods such as Ground Penetrating Radar (GPR), Electrical Resistivity Tomography (ERT), and Frequency Domain Electromagnetic Method (FDEM). Accelerated permafrost degradation and reduced seasonal soil freezing have led to a shift from permafrost to seasonally frozen conditions, with active groundwater flow paths persisting year-round. As a result of the conducted research, a detailed geoelectric profile was obtained for selected sections of the Fuglebekken catchment. Deep zones of seawater infiltration were identified as extremely low-resistive areas. A drastic reduction in the volume of permafrost over time, especially in the terminal part of the profile, was noticed. The obtained geoelectric profile enables a significantly better understanding of changes in the permafrost structure, especially when compared with previous data from boreholes and GPR measurements.

The results of FDEM measurements allow for determining the depths of freezing and thawing near the surface. Additionally, these measurements facilitate spatial visualization of resistivity distribution in the near-surface zone (up to approximately 2.5 meters), allowing the identification of local thawing zones. The boundary between the active layer and the permafrost is marked by a strong resistivity contrast.

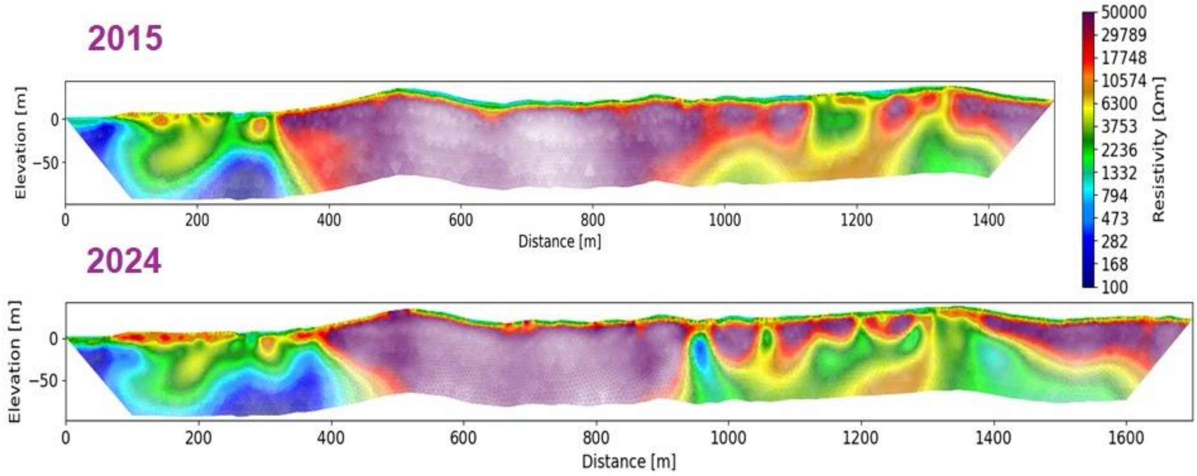

Figure: Inversion results for data collected at two different years

Spectral induced polarization imaging to monitor seasonal and annual dynamics of frozen ground at a mountain permafrost site in the Italian Alps

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High-mountain environments are facing a rapid increase in air temperatures, leading to increased permafrost temperatures, active layer thickening and decreasing ice contents. Thus, continuous temperature monitoring of the permafrost evolution in mountainous regions has become an essential task. Electrical resistivity tomography (ERT) is known to provide high-resolution spatial estimates of subsurface electrical properties sensitive to variations in temperature and water content, complementing spatially sparse borehole monitoring observations. Hence, in the last decades, electrical monitoring arrays were set up at several permafrost sites throughout different European mountain ranges to assess the temporal evolution of subsurface properties and processes relevant for permafrost investigations. Nonetheless, the interpretation of electrical signatures in terms of ice, air, and rock is still open to discussion, and uncertainties remain that are often reduced by combining ERT investigations with complementary geophysical methods. Recent studies have revealed that ice exhibits a characteristic spectral induced polarization (SIP) response. Expressed in terms of the complex resistivity, the real component relates to the resistivity measured through ERT, while the imaginary component relates to surface conductivity arising e.g., from the accumulation and polarization of charges at the electrical double layer formed in the ice–water or rock–water interface, as well as protonic defects in the ice surface.

We here present the application of SIP monitoring to understand seasonal and annual variations in the freeze–thaw processes in permafrost by examining the frequency dependence of subsurface electrical properties. We installed a permanent SIP monitoring profile at a high-mountain permafrost site in the Italian Alps in 2019 situated at an elevation of ~3100m, where long-term borehole temperature and meteorological data are available for validation. In particular, we collected SIP data in the frequency range between 0.1–75 Hz over 5 years. Shielded cables and an adequate measuring protocol were deployed to minimize the electromagnetic coupling in the SIP data. Data were collected as normal and reciprocal pairs for the quantification of data error, and we developed an analysis scheme for data quality that considers changes in time and in the frequency to remove spatial and temporal outliers and erroneous measurements.

The SIP imaging results were interpreted in conjunction with complementary seismic and borehole data sets. In particular, we investigated the phase frequency effect, i.e., the change in the resistivity phase with frequency. We observe that this parameter is strongly sensitive to temperature changes and might be used as a proxy to delineate spatial and temporal changes in the ice content in the subsurface, providing information not accessible through electrical resistivity tomography (ERT) or single-frequency IP measurements. Temporal changes in ϕFE are validated through laboratory SIP measurements on samples from the site in controlled freeze–thaw experiments. We demonstrate that SIP is capable of resolving temporal changes in the thermal state and the ice / water ratio associated with seasonal freeze–thaw processes. We investigate the consistency between the ϕFE observed in field data and groundwater and ice content estimates derived from petrophysical modelling of ERT and seismic data.

Understanding Permafrost Stability and Contaminant Pathways in Drilling Mud Sumps in the Mackenzie River Delta Using Electrical Resistivity Tomography (ERT)

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The Mackenzie River delta is home to over 200 drilling mud sumps, remnants of oil and gas exploration activities. These sumps were created by excavating the ground, filling it with drilling fluid wastes, and then backfilling with excavated material, under the assumption that permafrost would eventually freeze and prevent contaminants from escaping. However, with the accelerating warming of the Arctic due to climate change, the long-term stability of these sumps is increasingly uncertain. In this study, we use Electrical Resistivity Tomography (ERT) to monitor the apparent electrical resistivity of the shallow subsurface to observe changes in the temperature and ice content of permafrost beneath these sumps and the surrounding tundra. Data were collected at three time points: August 2023, June 2024, and August 2024. Our results offer valuable insights into the dynamics of permafrost thawing and potential contaminant pathways, contributing to a better understanding of the environmental risks associated with these legacy sites.

Resource or Environmental Liability? Development of Novel Ground Imaging Tools for Legacy Mine Wastes

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Legacy mine wastes present both opportunities and challenges in a circular economy context. These sites offer potential secondary sources of critical metals but also carry environmental risks that require comprehensive assessment. Traditional investigation methods, such as borehole drilling and geochemical sampling, can be costly, environmentally disruptive, and often insufficient for capturing the spatial variability of these tailings.

Geophysical techniques provide a non-invasive alternative, leveraging subsurface variation to map metal composition and distribution across mine waste deposits. By identifying metal-rich zones and assessing environmental hazards without physical intrusion, geophysics offers a practical approach to characterizing these complex sites.

This project focuses on advancing geophysical imaging tools to analyze legacy mine wastes in Southwest England and the Philippines. In the Philippines, petrophysical experiments on historic copper tailings investigate the relationships between metal content, moisture levels, and electrical resistivity. Results from these experiments will be correlated with field resistivity data collected using the PRIME geophysical monitoring system at the site. Parallel studies on legacy mine tailings in Southwest England involve petrophysical experiments, which will be similarly aligned with field resistivity data. Integrating resistivity measurements with geochemical, mineralogical, and hydrogeological data—enhanced by machine learning—this research aims to develop robust methods for characterizing legacy mine wastes. These approaches are expected to benefit sustainable resource recovery and environmental management initiatives beyond the target regions, contributing to global circular economy goals.

Geoelectrical monitoring of novel solvents and hydrodynamics in tailings deposits in the Philippines

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An increase in the worldwide production of metals is required to match the forecast of increasing demand, with a significant proportion of increasing demand needed to facilitate the green revolution. In order to produce sufficient materials, innovative solutions in the field of mineral extraction will be required as part of a multi-faceted solution. In addition to traditional mineral resources, waste mining material in the form of tailings can often contain valuable concentrations of metals, particularly in older tailings deposits that were originally processed using less efficient techniques than those in modern times. Many current processing techniques can be costly, and use solvents with considerable toxicity (e.g. High Pressure Acid Leaching [HPAL]). This has the potential to cause environmental issues, and facilities can be prohibitively expensive resulting in loss of value for countries and local communities when ore or concentrates have to be shipped elsewhere for further processing.

The authors investigate the use of novel, low-toxicity solvents for the extraction of copper in historic tailings at a copper/gold porphyry mine in Benguet Province, Philippines. Contained tank experiments were used to study solvent reaction, flow, and metal extraction using tailings material from a historic tailings facility which is higher grade than the currently mined ore deposit. In order to study the solvent dynamics within the ~1 m^3 containerised experiments, cross-borehole ERT measurements were used to image a 0.3 x 0.3 m column over the full height of the tank. By studying the ERT monitoring datasets in conjunction with associated point sensor and effluent monitoring data it has been possible to build a detailed picture on solvent movement and reaction, metal extraction, and the effectiveness of solvent clearance following flushing.

Additionally, surface electrodes were installed across the in-situ tailings within the historic facility. Daily ERT measurements across a monsoon season have allowed better understanding of hydrodynamics within the undisturbed tailings. These two ERT datasets combined evidence the usefulness of ERT for future upscaling of experiments on the route to commercialisation of this scalable, affordable technology, with potential economic and environmental benefits to the Philippines and other locations around the world.

Characterisation of the capabilities of OhmPi v2024 and review of possible improvements

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OhmPi is an open hardware and open-source resistivity meter designed for laboratory and small-scale field monitoring applications. The 2024 version introduced substantial improvements in hardware design, software architecture, and interfaces. It features a redesigned receiver circuit, new acquisition strategies, a more robust web interface and the system can also perform on-board simple 2d inversion. The documentation has been thoroughly updated to support the open-source character of OhmPi and favour reproducibility.

This contribution aims to characterise the latest version of the OhmPi system under different acquisition conditions, in both laboratory and field settings.

We first examine the dispersion of transfer resistances measured on sets of test resistors, evaluating performances on an OhmPi and comparing it across several OhmPis. Under the test conditions, results show a repeatability in the range of about 1% across the tested OhmPi systems.

We then investigate how instrument setup and measurement strategies affect the quality of the signals received at the receiver during a soil transfer resistance measurement. In monitoring experiments, changes in the medium are expected to impact both contact and ground resistances, which typically results in temporally variable data quality.

The resolution and dispersion of the transfer resistances is therefore assessed under various acquisition conditions and new software and/or hardware improvements. We explore ways to deal with extremely low or high contact resistances and the best strategies to effectively measure a wide range of transfer resistances during monitoring experiments. Improvements to the methods for determining gains and the waveform sampling method are also investigated. Enhanced acquisition strategies have the potential to mitigate data quality variations, while having more insights into acquisition parameters can improve how data quality is addressed during data processing.

Several of these improvements will likely find their way into future releases of OhmPi.

Inversion

Inverting 3D crosshole monitoring data of an aquifer heat storage experiment with a tailored pyGIMLi tool

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Storing heat in aquifers contributes to the energy transition. To improve understanding of the processes in high-temperature aquifer thermal energy storage (HT-ATES), a controlled experiment of different heat storage cycles was carried out in a shallow aquifer in the TestUM test site near Wittstock/Dosse. Electrical resistivity is suited well for monitoring heat distribution due to the dependency of the conductivity to temperature. We Therefore, eight boreholes were installed with 0.5m spaced ERT electrodes in depths between 6.5 and 14m. Daily measurements were acquired over a period of eleven months. Here we focus on the first cycle including injection, storage, extraction and standby. We use the pyGIMLi tool CrossholeERT based on the TimelapseERT class to process, invert and visualize the data. We use a 4D inversion approach where all data are inverted with spatial and temporal geostatistical constraints, both for selected 2D planes and the whole 3D data set. From the inverted resistivity we derive a temperature distribution that fits well with data from temperature sensors. The toolbox is of great help for the automated data processing and can also applied to other settings. It allows various ways of visualizing data or models, e.g. in time series, but also filtering quadrupoles and masking data that will not go into inversion, extracting sub-datasets like 2D planes from 3D setups, or temporal model changes. Eventually, a reproducible workflow from the raw data to the final resulting figures can be achieved.

An open-source suite for deployment of automated DCIP monitoring: towards real-time monitoring applications

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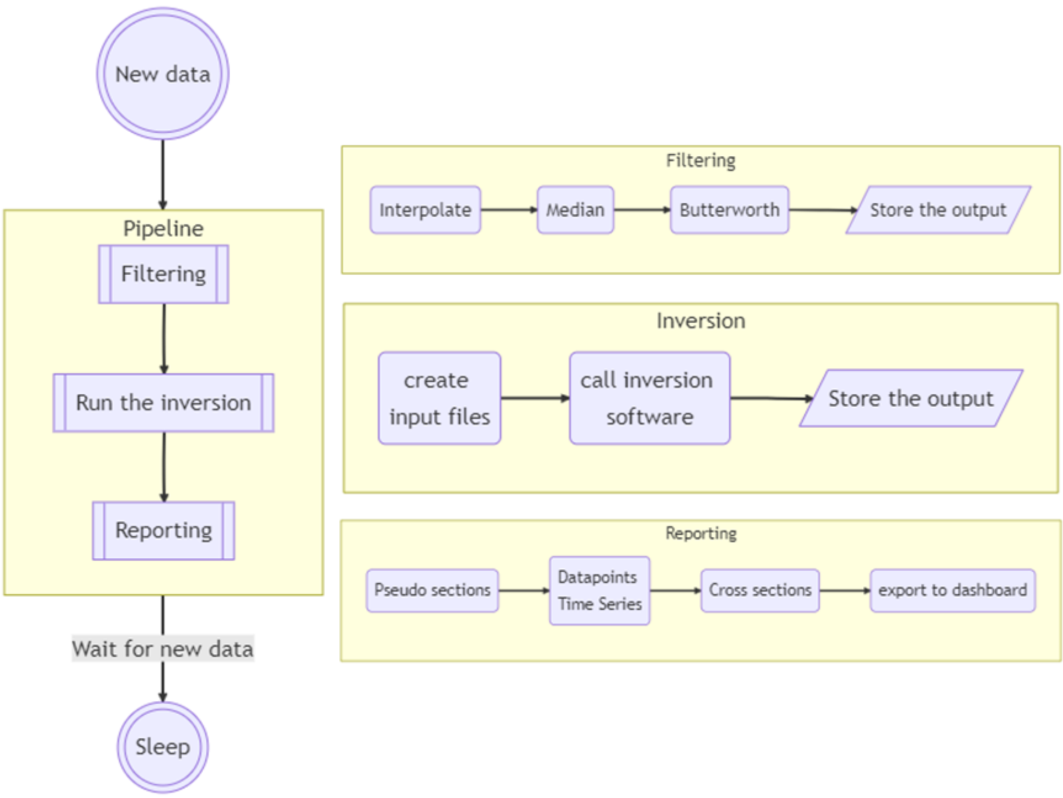
Geoelectrical monitoring is time-consuming, labor-intensive, and prone to human error if carried out manually. Therefore, the measurement process (from data collection to inversion) needs to be automated to reduce the time and effort required to conduct monitoring experiments (Dimech et al., 2022). Including Induced Polarization (IP) data, most commonly in the time-domain, adds another layer of complexity because the full waveform data (Olsson et al., 2016) and the chargeability decays (Flores Orozco et al., 2018) need to be meticulously evaluated.

We present an open-source Python suite that offers a complete solution for autonomous and automated monitoring experiments. The suite contains three major components i) data acquisition and handling ii) processing and inversion of DCIP data iii) a template for interactive visualization and reporting (Figure 1). Furthermore, the components can be used independently and customized to fit specific experiments and applications. Lastly, the use of cloud services can be leveraged to speed-up the execution of the data processing and inversion. An open-source interface that can be used to leverage cloud services is presented.

The proposed methodology has been evaluated across various scenarios and successfully implemented at four test sites, with results presented by e.g. Nivorlis et al. (2024) and Norooz et al. (2023). It provides a robust solution that requires minimal programming expertise, significantly streamlining the effort needed for geoelectrical surveys, especially in large-scale monitoring projects. By significantly reducing the time and effort required to conduct geoelectrical monitoring surveys we can enable close to real-time geoelectrical monitoring. Following the open-source example of other geoelectrical libraries (Cockett et al., 2015; Rücker et al., 2017), the aim is to create a central framework for geophysical monitoring tools and attract further contributions.



EEMverter, a new inversion tool for Electric and Electromagnetic data, designed with advanced features for Time-Lapse modeling.

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EEMverter is a modelling software specifically developed to model electric and electromagnetic data taking into account the IP phenomenon. Four distinctive features have been implemented in EEMverter: i) selectable IP parameterisations are allowed, ranging from Constant Phase Angle to Debye-Warburg decomposition, also making use of petrophysical relation for defining IP parameters in terms of hydraulic properties; ii) 1D, 2D and 3D forward modelling can be mixed sequentially or simultaneously in the iterative process within multiple inversion cycles, for diminishing the computational burden; iii) the joint inversion of Airborne IP (AIP), ground EM-IP and ground galvanic IP data is fully supported with a common IP parameterization; iv) time-lapse inversions of AIP, EM and galvanic IP data is possible with both sequential and simultaneous approaches.

In EEMverter the inversion parameters are defined on model meshes which do not coincide with the forward meshes used for data modelling: the link between model and forward meshes is obtained interpolating the model mesh parameters into the forward mesh discretization, as done for 1D AEM in Christensen et al. (2017), in 3D galvanic IP in Madsen et al. (2020) and in 3D EM in Zhang et al. (2021) and Xiao et al. (2022a,- 2022b). This spatial decoupling allows for defining the model parameters, e.g. the Cole-Cole ones, on several model meshes, for instance one for each inversion parameter. In this way, it is possible to define the spectral parameters, like the time constant and the frequency exponent in the Cole-Cole model, on meshes coarser than the resistivity and chargeability ones, vertically and/or horizontally, with a significant improvement in parameter resolution.
In this study, we present various electrical and electromagnetic Time-Lapse models produced using EEMverter, ranging from galvanic-ERT to Airborne-EM temporal studies. We detail the key features of EEMverter, including its flexible mesh definition for integrating different temporal datasets, the tunable Time-Lapse norms, and the comprehensive strategy used to define the Time-Lapse reference models and the strategy to minimize the objective function.
EEMverter also provides a protocol for modelling temperature variations occurring during the monitoring period without requiring direct thermal ground measurements. Instead, it can utilize the atmospheric temperature-data from the nearest weather station. This data is integrated into the inversion process through a thermal model applied obtained for the entire geophysical discretization employing the thermal diffusion equation and including the ground thermal diffusivity as inversion parameter.

EEMverter is distributed freeware in its LITE version, which allows to run modelling of galvanic data with induced polarization and of ground-based inductive data, together with EEMstudio, a QGIS plugin for data visualization processing in GIS environment.

We believe that EEMverter, with its highly flexible inversion capabilities—including customizable discretization and regularization, adaptable norms, seamless integration of ancillary information, and tailored inversion protocols—stands as a robust and comprehensive framework for achieving precise and reliable Time-Lapse modeling.

Evaluating data compression of ERT time-lapse measures in a DUNEA extraction well.

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Time-lapse electrical resistivity monitoring in geophysics involves the repeated measurement of subsurface resistivity over time to track changes in geological formations. This technique is particularly useful for monitoring processes such as groundwater movement, contamination, or the dynamics of natural hazards. By comparing resistivity data collected at different intervals, researchers can visualize variations in subsurface conditions and identify trends related to environmental changes.

Data are collected by deploying a series of electrodes in a specific arrangement, known as an array, on the surface of the study area. An electrical current is injected into the ground through selected electrodes, and the resulting voltage response is measured at other electrodes. This process is repeated for various electrode configurations, allowing for the collection of resistivity data at different depths. This process, especially when we want to monitor 3D volumes and the number of electrodes is large, can take lot of time and many environmental changes can occur while the ERT system is measuring. In some cases, the process we want to monitor can be too fast to me measured with traditional arrays.

One way to optimizing electrical resistivity (Stummer et al., 2004) measurements are based on sensitivity and involves adjusting measurement parameters to enhance the detection of subsurface features. Sensitivity analysis helps identify which electrode configurations and survey designs yield the most accurate and reliable data for specific geological conditions. Yet, this process treats all parameters of the inversion model as of equal importance and can still lead to many measures. It’s worthwhile noticing that reducing the number of measurements typically leads to different resolved models, when comparing with a “full” data set, making interpretation more difficult. Naturally, this approach is meaningful in sites where we expect rapid environment changes.

In this work we explore how machine learning techniques (ML) can help reducing the number of measures. The principle is based on collecting an extensive data set prior to the monitoring process and let ML learn how the data are related in such a way that only a small subset can reproduce the whole data set. Another way to describe this process is a near “lossless” compression of data. We apply this methodology on field data.

Spatio-temporal salinity dynamics of a coastal aquifer on Spiekeroog island

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Coastal aquifers at the transition zone between freshwater and saltwater show large salinity contrasts. Salinity is a key parameter to understand coastal groundwater flow dynamics and consequently geochemical and microbial processes in subterranean estuaries. Within the project DynaDeep, we apply geophysical and hydrogeological methods accessing either bulk or fluid conductivity to monitor the temporal and spatial salinity changes. Investigation area is a high-energy beach on the North Sea Island of Spiekeroog.

A unique dataset has been acquired since 2022, covering a 2D transect from the dune base to the low water line including strong topographic changes over the seasons. We use electrical resistivity tomography (ERT) to get access to 2D distributions in a six-week cycle. Additionally, continuous monitoring is carried out using a saltwater monitoring system (SAMOS) down to a depth of 20 meters located at the high-water line. Direct push (DP) data at various locations and EC values from fluid samples gathered via DP provide high-resolution 1D information. In three multi-level wells (6, 12, 18, and 24 meters depth) we log the fluid EC and temperature and take samples on a regular basis.

For a dense dataset between January and March 2023 we compare the applied EC methods in detail and found a general agreement after suitable calibration and temperature correction. We furthermore derive a formation factor model for the conversion to salinity. We use a combined inversion of the ERT data (salinity inversion) with the additional data aiming for fluid EC directly under the assumption of this temporally fixed formation factor model. In contrast to standard inversion techniques where often artefacts around formation changes are observed, this allows for a naturally occurring smooth transition of salinities over the different geological units. We found this to be critical when analyzing the spatial and temporal changes in comparison with the available non-ERT data. Furthermore, additional data are included in the inversion process in a joint inversion scheme.
As a result, we present the new algorithm and show salinity distributions based on the combined dataset along with the temporal dynamics of the dataset for the ERT campaigns and compare them to all available EC data.

Landslides

Real-Time ERT Monitoring for Analysis of Railway Infrastructure Slope Failure

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This project aimed to demonstrate the value of Electrical Resistivity Tomography (ERT) for remote condition monitoring of earthwork assets in live mainline railway settings. To this end, BGS PRIME ERT monitoring systems were installed on two rail embankments to provide near-real-time information on variations of subsurface moisture conditions over a continuous period of over two years. The outputs of PRIME can be delivered to end-users via a web dashboard to provide engineers with direct access to near-real-time subsurface images, alongside other geotechnical data streams, thereby enabling enhanced decision support.

The two test sites are known as Botley and Withy Beds, located in England near Southampton and London respectively. Both are mainline UK railway embankments constructed from London Clay which is known for being highly plastic and prone to deformation. Two types of installation were trialled, a grid of electrodes to monitor a local rotational failure in 3D at Botley, and a line of electrodes to monitor an extended region of embankment in 2D at Withy Beds. The Botley grid covered the full extent of the slip between the shoulder and toe of the embankment, an area of approximately 20 by 30 m. The Withy Beds installation comprised one line of electrodes covering a stretch of embankment approximately 325 m long. The line was not straight as it had to avoid obstacles and was installed in a zig-zag pattern to improve the resolution of local off-line structure.

To validate and complement the ERT monitoring outputs, traditional geotechnical monitoring, such as temperature, moisture and suction sensors, were manually installed in both sites. Both field and laboratory testing data can also be used to establish petrophysical relationships between geophysical parameters (e.g., resistivity), and geotechnical characteristics (e.g., moisture content and soil suction). Preliminary analyses revealed strong correlations between ERT-derived soil moisture estimates and traditional geotechnical measurements.

At Botley, a distinct low-resistivity layer was identified in the mid-embankment, indicating a high clay content and probable low hydraulic permeability. Time-lapse ERT data collected during periods of heavy rainfall revealed the slope's hydrological dynamics and the significant role of evapotranspiration, influenced by clusters of mature trees (Figure). Withy Beds revealed somewhat different behaviour. Previous slip failures had been remediated using sandy material. These sections of the embankment consistently remained drier, even after rainfall, allowing water infiltration into the underlying clay layers, which exhibited higher moisture content and seasonal surface drying.

This study offers unprecedented insights into the structure and moisture dynamics of mainline railway embankments through long-term, high-resolution ERT monitoring. The findings demonstrate the potential of ERT as a novel and operationally relevant tool for condition monitoring, providing critical data to support the management of vulnerable railway earthworks affected by complex ground conditions.

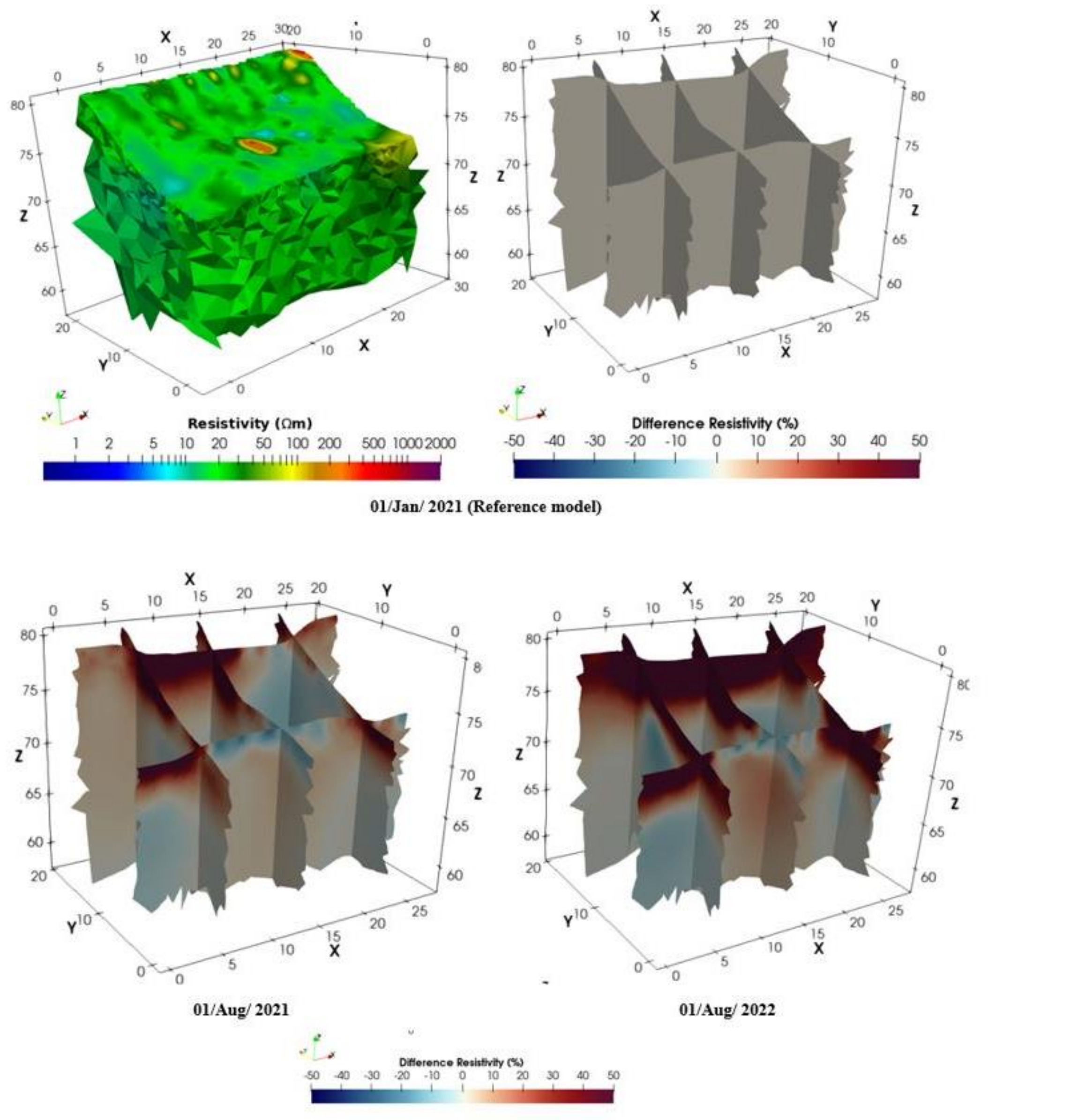

Figure: 3D inverted reference model for the Botley site (winter 2021), showing time-lapse resistivity variations for the summer seasons of 2021 and 2022. Red / blue regions have increased / decreased resistivity indicative of drier / wetter soils respectively.

Geophysical monitoring of a landslide under anthropogenic and climate pressure: the case study from Outhern Carpathians, Cisiec, Poland

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Landslides are complex geohazards that require a thorough understanding of the interchange between surface and groundwater flow. To properly characterize spatial and temporal changes, monitoring geophysical measurements plays a key role, as they allow us to characterize the sensitivity of landslide properties to external factors. This sensitivity includes both natural influences, such as shifts in precipitation patterns driven by climate change, and human-induced impacts related to land use changes and development. As urbanization increasingly spreads into mountainous regions for housing and recreational activities, there is an urgent need to understand both short- and long-term transformations in landslide-prone zones.

Understanding the parameters and development of a landslide's internal structure poses a major challenge in geophysical imaging. In this study, we adopted an integrated approach that combines seismic (Tomography, Multichannel Analysis of Surface Waves, Reflection Imaging, Seismological Monitoring) and electrical/electromagnetic techniques, in particular spectral induced polarization (SIP) and e.g. Electrical Resistivity Tomography (ERT), Frequency Domain Electromagnetic Method (FDEM), Audiomagnetotellurics (AMT), Transient Electromagnetic (TEM) and Spectral Ground Penetrating Radar (SGPR) to monitor the landslide under strong anthropogenic pressure. Located in the Outer Carpathians, this region experiences notable climate-driven changes, including temperature extremes, shifts in precipitation patterns, and strong warm winds. Additionally, the area is used as a ski slope, requiring artificial snow, which introduces human-induced factors affecting the landslide dynamics. Our integrated approach merging seismic and electrical techniques allowed us to visualize annual and seasonal feedback of the colluvium to environmental influences by assessing variations in the physical properties of the rock mass. The changes in physical parameters like electrical resistivity and seismic waves velocity, reaching up to 100% in the most prone areas, highlight the strong impacts of external factors on the subsurface properties. Furthermore, additional analyses using data clustering, combined with remote sensing data, enabled us to correlate surface discontinuities with our geophysical model. This led to identifying three distinct zones within the landslide, each with varying degrees of vulnerability to natural and human-induced slope instability.

The findings presented here provide a large-scale example of time-dependent geophysical monitoring of physical changes related to moisture-driven landslides. They address a research gap and offer valuable insights for similar geohazard studies globally.

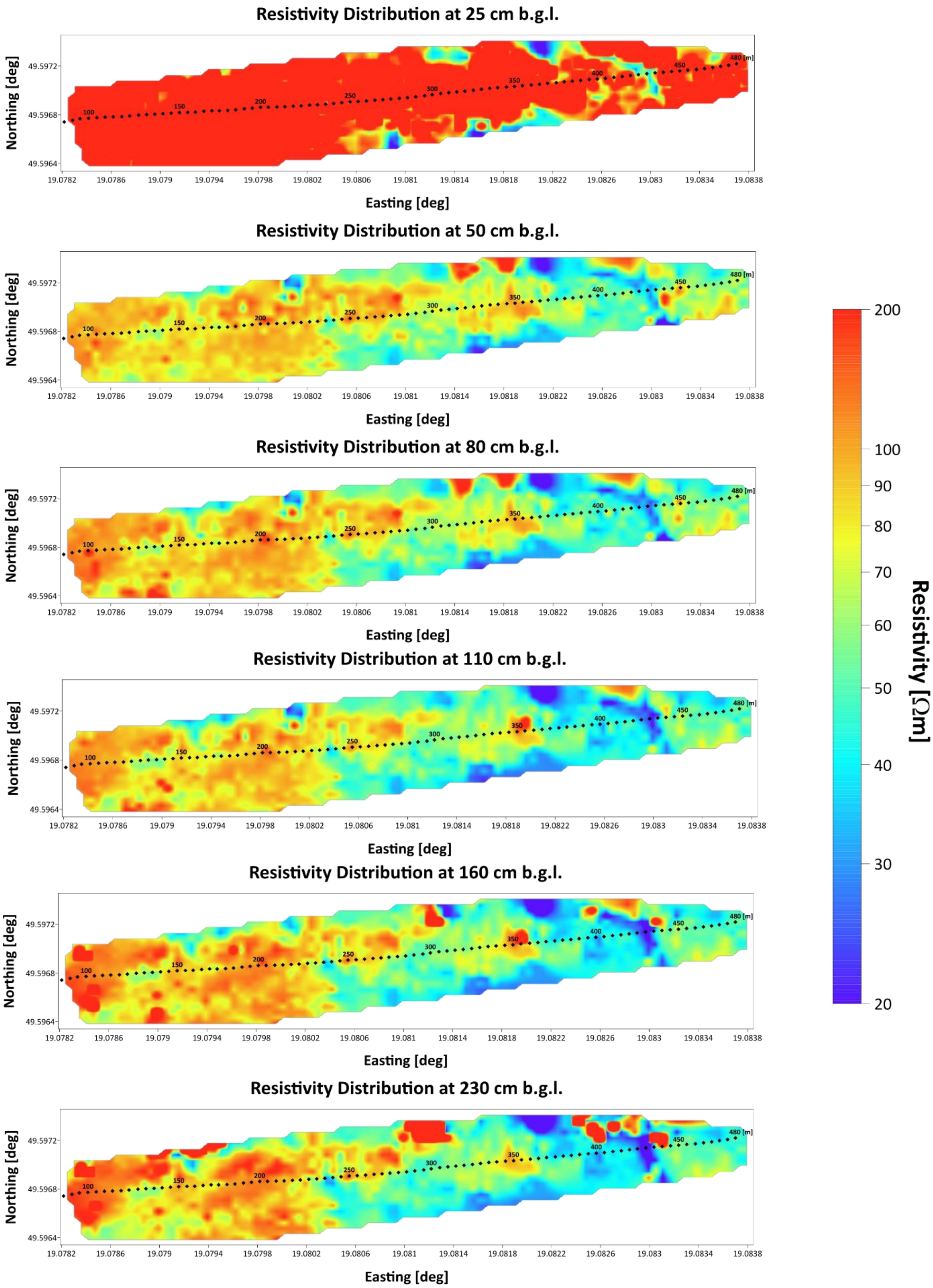

Figure: Inversion results at different depth

Monitoring electrical potential for Insights into landslide dynamics

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This study presents an integrated landslide monitoring program conducted in the landslide-prone Tizzano Val Parma region (Italy), employing both traditional and advanced geoelectrical techniques, including Deep Electrical Resistivity Tomography (DERT), Induced Polarization (IP), and Self-Potential (SP) methodologies. The investigation utilized both conventional Fixed-Base and unconventional Sparse Gradient array configurations. Application of the Analytic Signal Amplitude (ASA) technique facilitated enhanced identification of primary SP anomaly sources in the Sparse Gradient configuration, offering valuable insights for delineating areas of interest.

These region experiences recurrent landslides driven by complex geological and geomorphological factors, resulting in significant hydrogeological instability and environmental hazards. Borehole stratigraphy indicates a heterogeneous lithology, comprising sandstones, clayey marls, and coarse materials. The DERT-IP surveys provided a detailed characterization of various landslide types, identifying distinct domains such as complex quiescent, active, and undefined landslides. Evidence of active fault dynamics highlights zones of elevated risk.

Sparse Gradient SP monitoring captured short-term electrokinetic anomalies as well as stable long-term trends between 2022 and 2023. Both Fixed-Base and Sparse Gradient SP configurations revealed displacement anomalies oriented toward the valley, indicative of potential landslide movement. Interpretation of SP maps highlighted preferential water flow paths, suggesting heightened risks under intense rainfall conditions.

This study underscores the importance of integrated geoelectrical monitoring systems for early landslide detection and risk mitigation. The use of non-conventional and conventional SP arrays provided critical insights into anomaly persistence and repeatability. The integration of DERT-IP results with borehole data enabled the extrapolation of subsurface geological characteristics, offering a comprehensive understanding of the subsurface structure and identifying potential risk zones. Overall, this multidisciplinary approach contributes to more effective landslide management and emphasizes the dynamic nature of landslide-prone regions, underscoring the critical need for continuous monitoring and assessment.

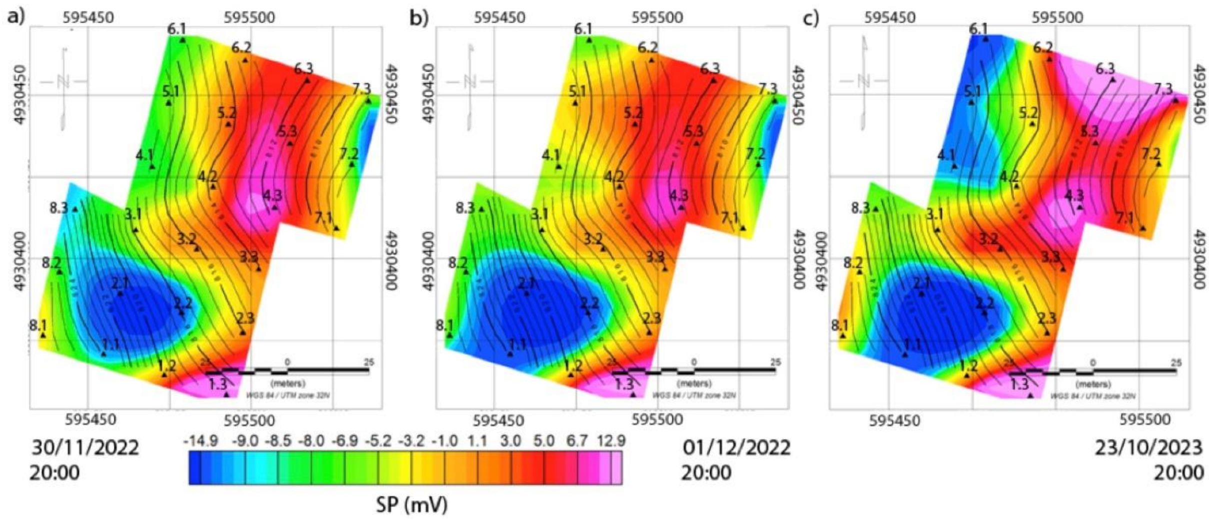

Figure: time-apse inversion results

Soil moisture

Subsurface Characterization of Water Table and Soil Moisture Using ERT Data Inverted by pyGIMLi: A Case Study in a Well-Documented Agricultural Field

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Geophysical prospection is a reliable, non-destructive technique for subsurface investigation, making it particularly useful for studies on agricultural sites. This work focuses on an agricultural field managed by INRAE, under mediterranean climate (Avignon, FR). The site is well-documented, featuring detailed lithological profiles and physico-chemical analyses, along with continuous monitoring of key parameters, including groundwater table depth and soil water content at a few depths. In this work, we used Electrical Resistivity Tomography (ERT) to attempt to identify the depth of the water table and estimate the water content in the unsaturated zone along a 2D (and 1D) subsurface profile, conducting regular fieldwork to track its evolution over time. The apparent resistivity data obtained from the ERT measurements were inverted using pyGIMLi to derive a 2D distribution of soil resistivity. From this resistivity model, we could estimate the possible location of the water table. Subsequently, petrophysical relationships were applied to the resistivity data to estimate water content along the profile. The results offer valuable insights into the hydrogeological properties of the site, enhancing our understanding of water distribution in agricultural environments. However, as resistivity data are influenced, in addition to water content, by soil texture or lithology the estimation of water content and water table depth may be influenced by the presence of various conductive lithological layers, which can obscure the signal. This limitation motivates us to couple ERT with additional geophysical techniques for a more comprehensive interpretation.

Application of 3D Geoelectrical Monitoring for Moisture Tracking on Standing Monuments in Thessaloniki, Greece.

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The presence of moisture in historic buildings can lead to various structural problems and remedial action must be taken. Since moisture affects the resistivity, possible variations in moisture content can be tracked using time-lapse ERTs. This method can be extended to 3D space to investigate possible areas of water infiltration.

In this work, we have applied a long-term 3D ERT monitoring on a major pillar of the world heritage monument of the Rotunda of Thessaloniki (N.Greece). The 3D measuring scheme involved the careful installation of 48 stainless steel nails inserted into the mortar, arranged in 4 rows of 12 electrodes each.

A full 3D ERT protocol with 48 electrodes may involve a large number of measurements, but acquisition is challenging even with modern instruments, especially when it comes to monitoring dynamic events. Since this work focuses on monitoring daily humidity variations with 3D ERTs and certain measurement setups can negatively influence the inversion results, the ERTs are obtained with a protocol specifically optimized for our needs, consisting of arbitrary 3D measurement setups which were also tested with synthetic data.

The collected data were filtered and inverted with a difference inversion algorithm (pyGIMLi). The inverted results in combination with meteorological records show that the resistivity changes occur throughout the year after extensive rainfall. Overall, ERT monitoring seems to be a promising and effective tool, especially for heritage conservation studies, where minimizing interaction with the structure is important but a permanent monitoring station is essential.

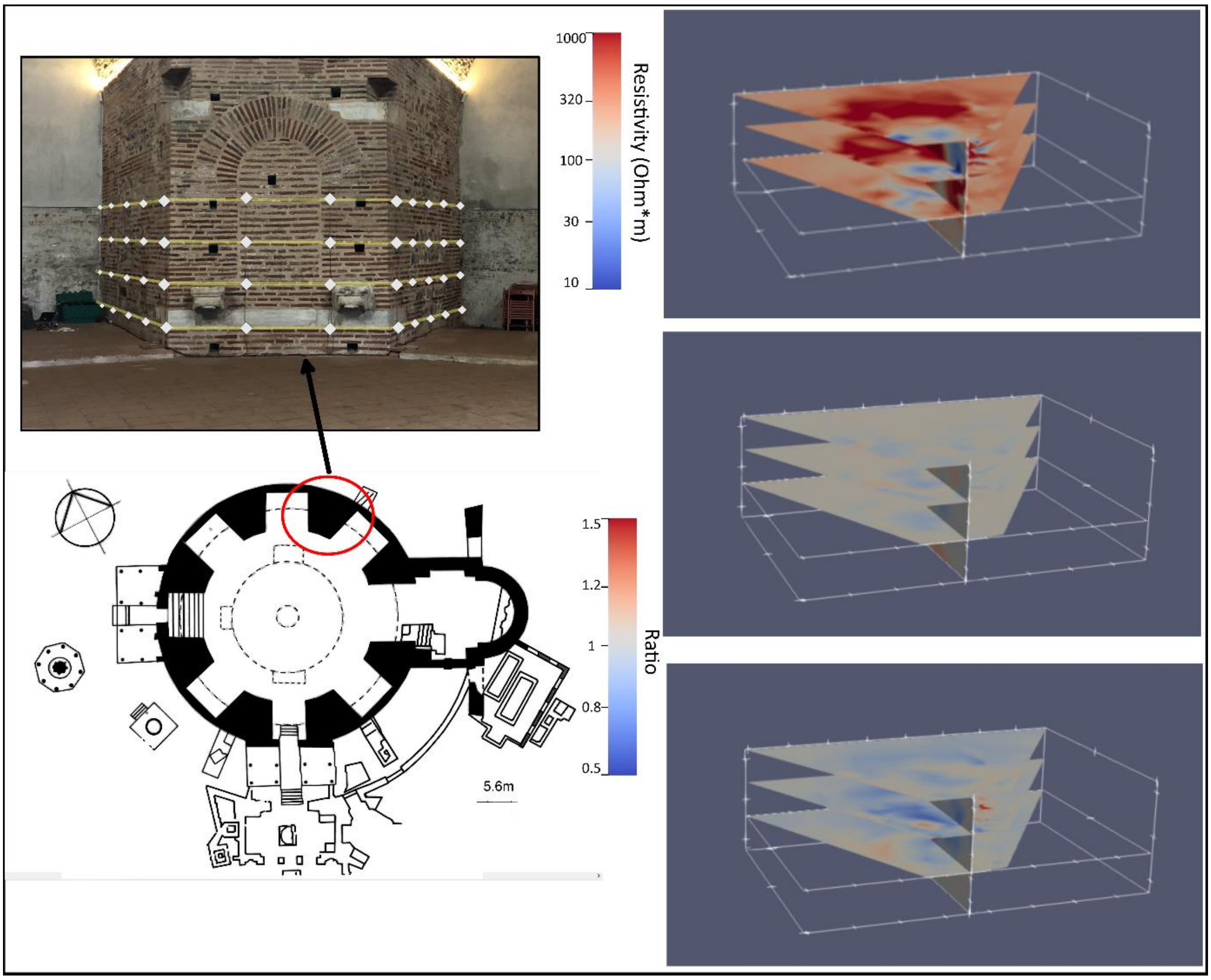

Figure: A schematic diagram and an actual photo showing the electrodes surrounding the pillar (left). The results of the 3D ERT inversion (right).

Poster session inversion and landfill/dam

Increasing the ratio between value and cost of 4D ERT through automation of data acquisition, processing and reporting using integrated autonomous hardware and cloud based software: example applications for cryosphere research in Utqiagvik, Alaska and coastal dynamics from Lauwertsoog, the Netherlands

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Time-lapse electrical resistivity (4D ERT) has proven to be a unique tool for providing insights and understanding for a broad range of key subsurface processes. However, its adaptation outside of academia is still limited due to the ratio between value and cost. Subsurface Insights' objective is to increase this ratio. Increasing the value can be done by reducing the complexity of data and simplifying and streamlining result use. While due to the different processes, which can change subsurface electrical properties 4D ERT will always intrinsically be more complex than e.g. water level or temperature measurements, numerous enhancements (e.g. in data presentation, automated change detection, semi-automated inversions, the use of machine learning and the direct integration of ERT data in reactive transport models) are making 4D ERT data of increasingly higher value. Similarly, we can decrease the denominator in the ratio of value/cost substantially. This denominator (4D ERT costs) is spread across three categories. These are upfront costs, system maintenance costs and costs associated with data acquisition, processing and analysis. Upfront costs include the cost of field hardware (multi electrode resistivity system and multi electrode cables), the associated field-based infrastructure (for instance in many cases a field trailer, power and some kind of communication equipment), as well as system deployment and installation costs. These upfront costs typically are in the 10-100s of thousands of dollars. The other two costs (maintenance and processing and analysis) are generally labor related costs which (based on experience and discussions with numerous colleagues) are generally around 1 day/week (0.2 Full Time Equivalent) for the project duration. However, as shown both by Subsurface Insights and several other groups (the main one among them the British Geological Survey with their PRIME and ALERT systems) the use of novel autonomous instrumentation and automated data processing and reporting will substantially reduce initial and operational costs.

While there are common themes in how all groups approach this cost reduction there are multiple technical approaches possible. We will discuss the motivation and design considerations behind the approach chosen by Subsurface Insights in developing an autonomous 4D ERT monitoring capability. This approach was to develop a system which fully integrates hardware and (cloud based) software in an end to end system. The hardware consists of fully autonomous, self contained single channel, multi electrode dual time/frequency domain systems which can support thousands of electrodes per system. The cloud based software allows for system control and automated data analysis and processing. Associated with this and a core part of our approach is an easy to use capability for contextual data integration (through the open source package odmx, see odmx.org) and rich visualization capabilities, making functionality and data accessible through an API and implementation of data processing through the use of containerized open source codes. We will discuss our implementation using several case studies of currently deployed systems, including a system deployed for permafrost monitoring in Utqiagvik, Alaska, and a system deployed for coastal dynamics monitoring in Lauwertsoog, the Netherlands.

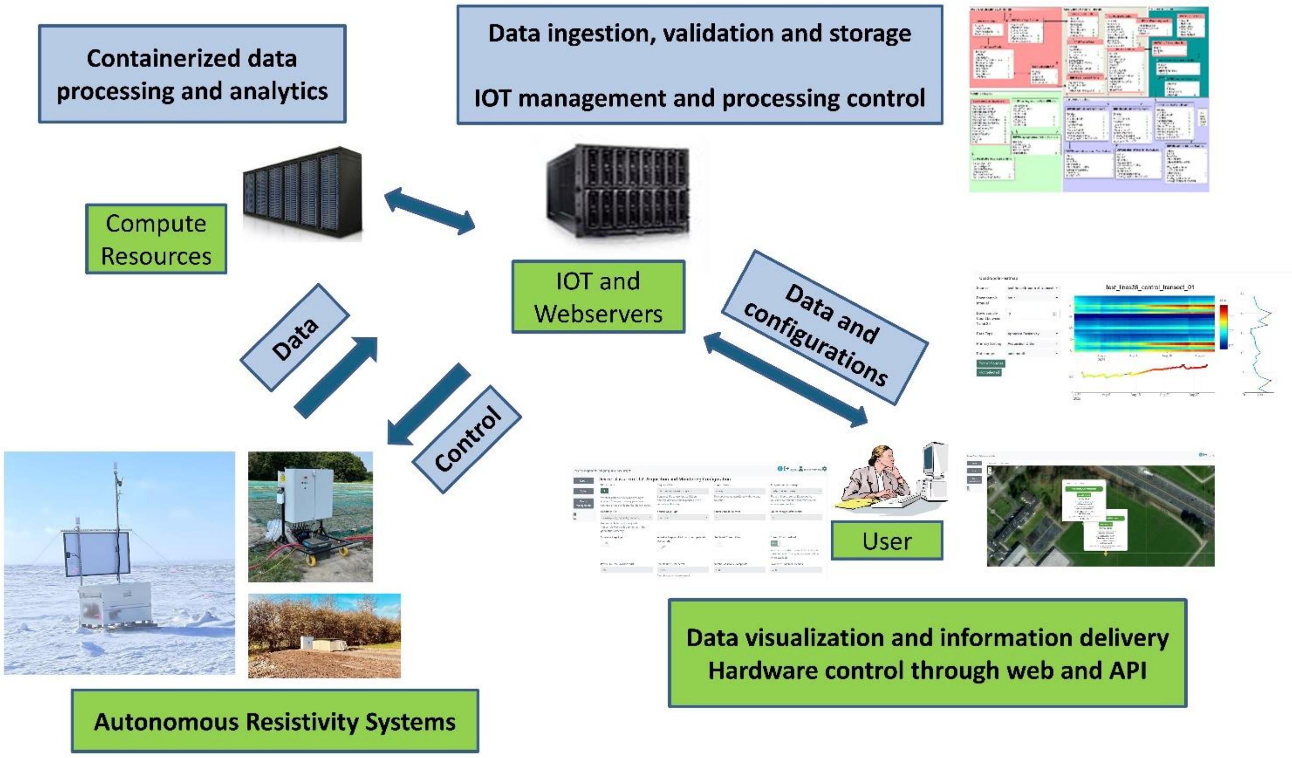

Figure: schematic diagram on the data manegement

Optimized experimental design strategies for geoelectrical monitoring of transient processes

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The non-invasive monitoring of subsurface fluid transport processes through geophysical methods has gained increasing attention in recent decades. Electrical resistivity tomography (ERT) is particularly well-suited for this purpose due to its sensitivity to variations in fluid content and temperature. ERT has been widely used to capture dynamic processes over time, such as the flow and transport of groundwater pollutants, reservoir fluids and radionuclides. Since monitoring of potentially fast transient processes requires efficient data acquisition, meaning high temporal and spatial resolution, maximizing the information content of planned (geo)physical measurements while minimizing acquisition time is of special interest.

Previous studies have introduced approaches for optimizing sensor positions and measurement configurations in ERT surveys for both static and dynamic subsurface targets. This study advances the concept of Optimal Experimental Design (OED) for transient flow process monitoring using geoelectrical measurements. We present three optimization strategies based on the Compare-R algorithm (Wilkinson et al., 2006). All strategies focus on targeting the survey to the relevant model region impacted by the transport process at every time step during the monitoring process. The first approach, a data-driven strategy, builds on Wilkinson et al. (2012) by using data from prior time steps to generate predictive focusing masks for the next time steps. The second, a model-driven approach, incorporates an underlying transport model describing the assumed fluid flow, which is used to predict affected model areas. The third, a model-based and data-supported (hybrid) approach, combines data- and model-driven methods, allowing for iterative adjustments of the underlying transport model based on acquired data. These three approaches are applied to simulated diffusive-advective transport processes on synthetic models of varying complexity to assess and compare their performance. Additionally, we examine the hybrid OED's capability to account for errors or inaccuracies in the assumed fluid flow model parameterizations.

The synthetic study results demonstrate the advantages of model-driven strategies in identifying transport-affected model areas, particularly for rapid subsurface flow processes or monitoring scenarios with longer intervals between monitoring time steps. The data-driven strategy's effectiveness correlates with the overlap between the masked and process-affected areas; significant discrepancies between these areas tend to produce less detailed representations of the process-affected area. Testing the hybrid OED approach across synthetic models of different complexity reveals its potential to combine the strengths of both data- and model-driven methods. The hybrid OED method can detect discrepancies between the modeled and observed subsurface fluid flow and adjust the underlying simulation for subsequent monitoring steps. Thus, it can contribute to reliable geoelectrical monitoring by providing spatially and temporally optimized acquisition protocols while giving additional insights on the monitored processes.

Cascade Inversion of time-domain IP data for Cole-Cole Parameters

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Recently, Induced Polarization method is gaining its importance since it can provide crucial subsurface geoelectrical information that is closely related with constituent material, shape and distribution of elements so on. In the interpretation of IP data, chargeability can be obtained based on the resistivity inversion software. Since recent induced polarization equipment measures full-time series or averaged apparent chargeability for the pre-defined time slots, we can easily identify decaying pattern of apparent chargeability. Since these time slots can be regarded as a new dimension or axis, which is analogous to the time-axis in the 4D Inversion concept, we can apply 4D inversion concept to the inversion of multi- time-slot IP data. In this approach, the entire multi-time-slot data set is simultaneously inverted, where the apparent chargeability and model chargeability at entire time-slots are composed into a single data and model vectors in the space and channel domains. Regularizations not only in the space domain but also in the time-slot domain is applied to reflect the characteristic of chargeability curves. Furthermore, we introduce the concept of structural similarity between resistivity and chargeability models by using minimal cross-gradient constraints. Developed inversion algorithm was applied to several simple subsurface models and we could show that reasonable chargeability can be derived. As a further step, to develop a new systematic approach toward a quantitative interpretation of time-domain IP data, an inversion algorithm to obtain images of Cole-Cole parameters is proposed that can be used for the inversion results obtained by 4D inversion of IP data. In this approach, inverted chargeability sections are used as input data set for the inversion, while distributions of Cole-Cole parameters (intrinsic chargeability, time constant, frequency dependence) are calculated by iterative inversion process. By adopting inequality constraints and smoothness constraints on the inverse model parameters, we could calculate reasonable images of Cole-Cole parameters from the SIP inversion results suppressing inversion noises. When IP inversion results from 4D inversion is used as input to the inversion, we could obtain accurate Cole-Cole parameter distributions in the model experiments, while strong artefacts are observed when inversion results from conventional separate inversion is used. The inversion algorithm was applied to the real field data obtained for the mineral exploration and we could get reasonable values of Cole-Cole parameters, which provides a way to evaluate the constituent material and their distributions. Therefore, we could show that a very stable cascade inversion approach consisting of 4D inversion of IP data followed by Cole-Cole parameter inversion is a promising tool in the quantitative interpretation of IP data.

Monitoring of the leachate levels in a municipal solid waste landfill through full-waveform electrical tomographic data

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One of the most critical issues of waste management is the possible negative impact of leachate on the surrounding environment. The leachate is a potentially highly polluting liquid arising from the infiltration of rainwater, which comes into contact with buried wastes. The leachate leakage outside the landfill is the main cause of contamination of groundwater and soil, but it can also trigger geotechnical instability for slope landfills.

The objective of this work is to use full-waveform electrical tomographic data to detect and monitor the leachate accumulation zones at a municipal solid waste (MSW) landfill located in Central Italy on a steep slope. Geophysical electrical methods, such as electrical resistivity tomography (ERT) and time-domain induced polarization (TDIP), represent a cost-effective high-resolution tool to achieve this target since the main physical parameters being investigated (electrical resistivity and chargeability) are good proxies for leachate detection. In this work, we present the results of the 2024 campaign in comparison with previous data (2019), to assess the effectiveness of the drainage network built in 2021. We acquired full-waveform ERT/TDIP data on three profiles within the landfill (G9, G6 and G4) using the ABEM Terrameter LS 2 (GuidelineGeo), with a multiple gradient array (4 stacks) and a 100% duty cycle. Raw data were then processed with a newly developed Matlab code, to compensate for the main sources of noise that compromise the correct extraction of TDIP data (drift, spikes and outliers), following Olsson et al. (2016). For the inversion process, we used the VEMI software (De Donno and Cardarelli, 2017), which uses a Gauss-Newton inversion algorithm and the finite element method to solve the forward problem.

The 3D reconstruction of the geophysical inverted models allows the detection of leachate accumulation zones in the eastern part of the landfill, characterised by high conductivity ($\rho<$ 5 Ωm) and a decreasing chargeability with respect to the surrounding environment (dry waste). The geophysical results are also validated by the Casagrande piezometers installed along the terraces. When compared with the results of a previous campaign (2019), a similar layering can be recognized, but with an overall slight increase of resistivity which proves the success of the drainage network. Therefore, the results of this work pave the way for implementing a continuous monitoring system of the landfill site.

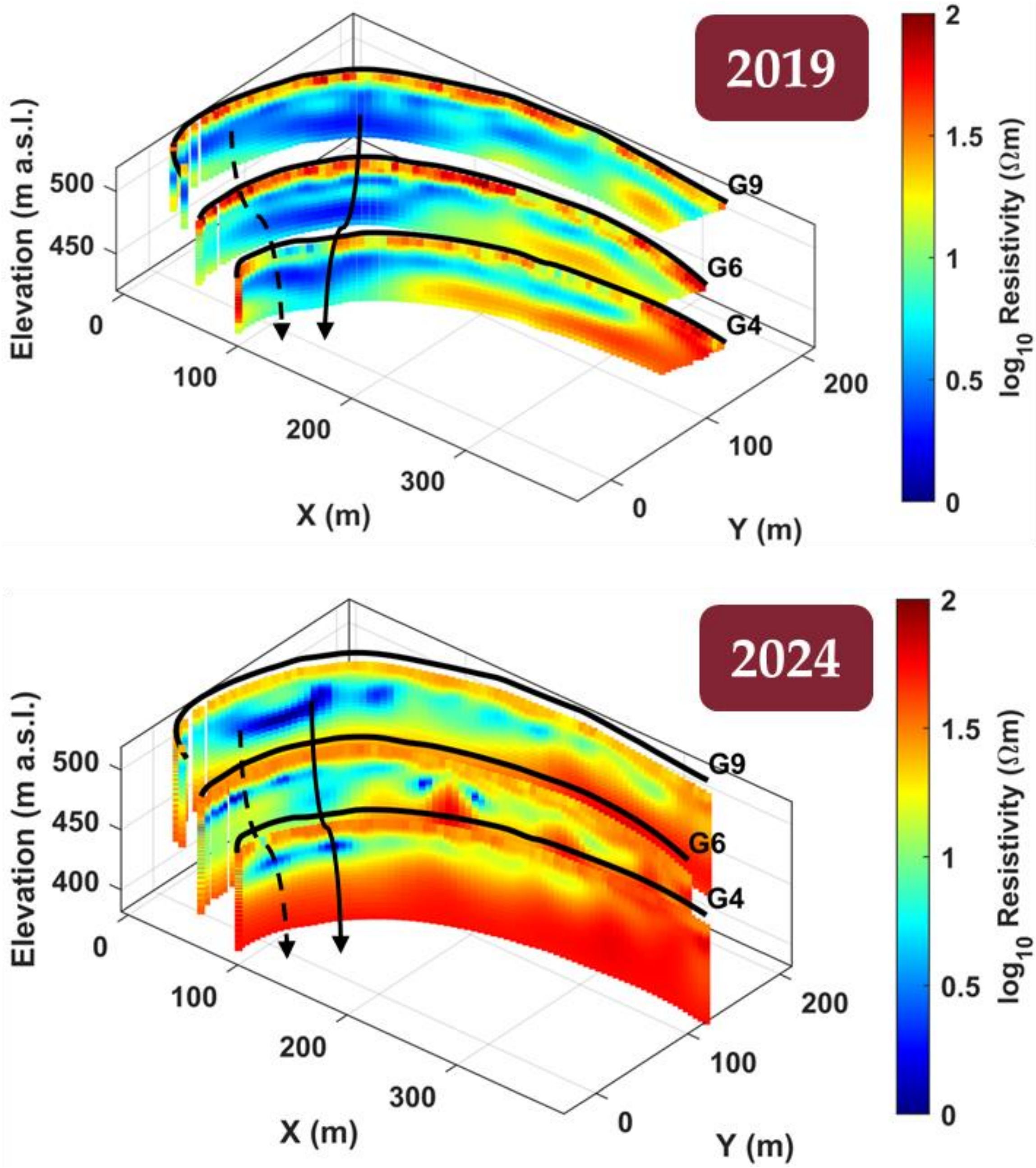

Figure: Inversion results at different years

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Condition assessment of an industrial reservoir dam through joint-inversion of ERT and seismic refraction data

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2024 was the fifth time the Supervisory Authority for Regulatory Affairs (successor of the Hungarian Mining and Geological Service) conducted geophysical measurements on behalf of WESSLING Hungary Ltd. in order to inspect the state of the Gyöngyösoroszi Industrial Reservoir's dam. The purpose of these measurements was to assess the stability of the dam and to identify elements that could cause a stability risk (e.g., areas of moisture infiltration, hollowing, etc.), and also attempt to record any changes that may have occurred over time.

The dam is composed primarily of clay-cored mining waste. A water drainage system with a 78 meter long precipitation collector tunnel was built to prevent the erosion of the dam body.

Due to the complexity of the probable risk elements, a single geophysical method does not yield reliable results, therefore methods that differ in both spatial resolution and methodology were necessary in order to thoroughly investigate the problem. Hence, electrical resistivity tomography and seismic (P-wave and S-wave refraction tomography) measurements were carried out to complete the research task. These methods produce independent datasets based on different physical parameters and therefore they are suitable to inspect the dam's structure from different aspects.

One of the ERT lines and a seismic line were measured on the crest, close to the crest edge of the protected side. For the ERT section 2.5 meter electrode spacing and a mixed electrode array was used. The total length of the profile was 147.5 meter. The seismic line was 145 meter long with 1 meter geophone spacing and source distance. For generating signals, a 5 kg hammer and a special 80 kg S-wave hammer was used.

The penetration depth of the applied direct current resistivity measurement reaches up to 30 meters, although spatial resolution is lower. This method can detect high (e.g., clay) and low conductivity materials in the dam, saturated zones (probable infiltration zones), and can locate potential large cavities. The P-wave and S-wave tomography were applied to detect the mechanical compactness of the dam, therefore find loosened zones – if any – with good penetration and fine resolution.

By performing independent inversions of these measurements, one can obtain information on the physical properties of the medium, within the limitations of the given measurement geometry. Furthermore, by selecting a common geometry and gridding, joint inversion of the two different measurements is possible, which combines the inversions of the two methods with different measurement parameters, improving resolution and aiding interpretation.

First, initially performed independent inversions were carried out on both the electrical and seismic data, and then a joint inversion were tested on a well-chosen common grid, using identical initial conditions. According to our results, main structural elements seem to be marked more precisely and anomalies on the individual inversion results are better explained after the joint inversion.

Structural analysis of an industrial water reservoir dam using time-lapse inversion of ERT data in Gyöngyösoroszi, Hungary

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The periodic inspection of the internal structural condition of man-made infrastructure is crucial for both environmental protection and disaster management, especially when it comes to dams and barrages. The failure of these objects can cause harm in many ways from flooding to the contamination of water resources. The wide range of geophysical measurement and data processing methods available today provides favourable conditions for the non-destructive investigation of these structures.

Since 2016, the Geological Survey of Supervisory Authority for Regulatory Affairs and its predecessor institutions have been regularly carrying out condition assessments using seismic, ERT and GPR methods on the valley closure dam of a former industrial reservoir in Gyöngyösoroszi, Hungary. The investigated object was built in 1964, therefore requires regular monitoring of stability and internal structural changes that could potentially lead to a failure.

ERT measurements were carried out biennially to identify possible anomalous seepage and hollowing areas that can lead to internal structural changes in the dam body and can pose a risk to the stability of the object. 9 profiles were measured along 7 lines, keeping the geometry and measurement settings the same since 2016 to enable the application of time-lapse inversion. An additional section was measured perpendicular to the dam to examine the distorting effect of the dam’s topography on the electric current field.

Our poster presents the results of the measurements carried out in the period 2016-2024 through time-lapse inversion. We identify anomalies indicative of possible structural changes, isolating differences between sections measured in different years due to errors in the measurement method and varying field conditions.

Poster session infiltration/recharge

Influence of different vegetation types on resistivity changes during precipitation events

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This study was conducted at the geophysical outdoor test site near the village of Pöverding (Lower Austria), which was established by the GeoSphere Austria in 2020. The general subsurface structure of this site is quite homogenous and is characterized by a topmost soil layer with a thickness in the range of 50-80 cm succeeded by a mostly solidified quartz sand layer of the so called "Melker Sande". The focus of this study was to specify the influence of different vegetation types (grassland – artificially planted energy forest) on resistivity changes during precipitation events (infiltration processes). Since the topmost soil layer at the monitoring profile showed unexpected heterogeneities in the initial resistivity distribution, it was essential to take into account the differences in grain size distribution of this soil layer. Therefore, soil samples were taken at four different locations along the monitoring profile, which have to be considered for interpretation.

The ERT monitoring profile consisted of 93 electrodes at a spacing of 0.5 m and was set up in a way that the two vegetation types were evenly covered by the profile. During the first monitoring period between March 15th and July 11th 2023, data was collected by the Geomon4D system. During the second monitoring period between July 26th and August 13th, data was collected with the new Geomon4D-IP system (for details about the ERT systems see Ottowitz et al. 2022).

One full resistivity measurement was conducted every day, consisting of about 4500 measuring points in a gradient electrode configuration. Complementary subsurface monitoring data (soil temperature, water content, soil conductivity) were acquired at two locations (grassland and forest). Additionally, the monitoring data set was completed by a weather station as well as by a photo monitoring station to record the start of the main vegetation phase. Within the monitoring period several distinct precipitation events could be recorded. Corresponding resistivity changes show clear differences between the two vegetation types, which can also be explained by the complementary subsurface data. In addition, differences in the general behavior of the resistivity changes (distribution and amplitude) depending on the characteristics of the particular precipitation event as well as on seasonal variations could be observed. For interpretation of the observed resistivity changes (infiltration processes) also the general resistivity distribution of the topmost layer (controlled by the grainsize distribution) was taken into account. The main conclusion of this study is, that the vegetation type has a clear influence on the characteristics of resistivity changes due to precipitation events and that this has to be considered especially for small-scale applications of ERT monitoring focusing on infiltration processes.

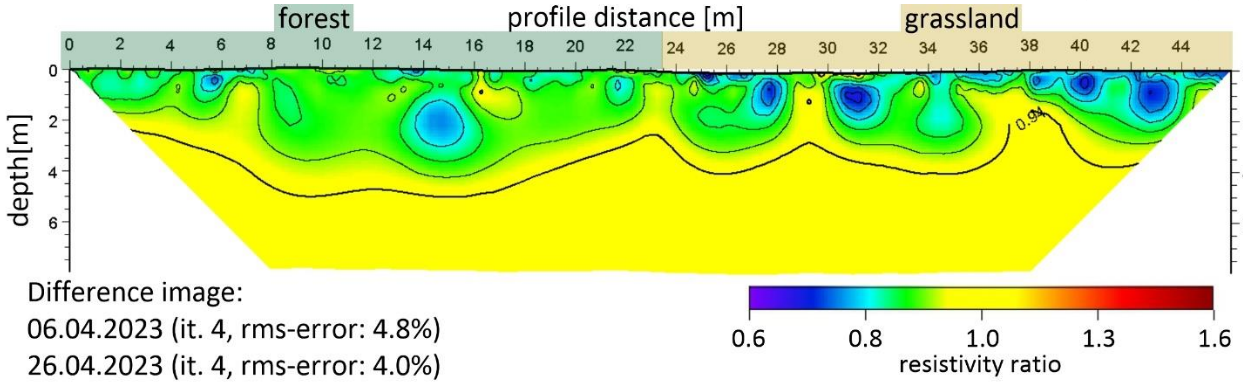

Figure: Difference image showing the resistivity ratio between datasets from 6th and 26th of April 2023. In this period several precipitation events appeared. Therefore, a clear decrease of resistivity within the first 3 meters of the subsurface can be observed (green to blue colours). Furthermore, a distinct difference in the characteristic of the resistivity decrease between the forest area and the grassland is visible (lower amplitude, deeper infiltration in the forest area).

The result is based on the 4D-inversion algorithm (part of DC2DPro) developed by KIGAM (Korea Institute of Geoscience and Mineral Resources)

References:

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Monitoring the extraction of brackish water with crosshole tomography

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In the Dunea region of the Netherlands, an innovative approach to sustainable drinking water production was investigated through the extraction and desalination of brackish groundwater. The study focused on characterizing the layered hydrogeological system, consisting of freshwater at the top, brackish water in the middle, and saline water at the bottom, with the aim of optimizing the extraction process. A key objective was to maintain a consistent salinity level in the extracted water by dynamically adjusting pumping rates across multiple depths.

The experimental setup included an extraction well equipped with filters at three discrete depths, supported by three independently controlled pumps. Surrounding the well, four boreholes were drilled, and 48 electrodes spaced 1.33 meters apart were installed in each, forming roughly a square of approximately 20 × 20 meters. Autonomous electrical resistivity monitoring measurements are being conducted every 8 hours since February 2022. The data underwent preprocessing, including filtering to remove erratic values, and then they are being inverted using the pyGimli open-source library.

The results demonstrate that the saline–freshwater interface can be effectively mapped with this methodology. This high-resolution spatial and temporal characterization of the interface provides critical insights for optimizing groundwater extraction strategies, ensuring sustainable and efficient use of subsurface resources for drinking water production.

Integrating Geophysical Methods for Monitoring and Evaluating Infiltration Processes in an Artificial Recharge Pond

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The Vombverket water supply facility utilises 54 infiltration ponds as part of its Managed Aquifer Recharge (MAR) system, a key part of the water supply system in southwestern Scania, Sweden. Due to population growth, increasing industrial and agricultural demands, and the impacts of climate change, the production of the MAR plant needs to increase. In this study, one pilot pond is studied in detail using geophysical methods to provide a basis for optimising the use of the infiltration ponds.

To monitor the infiltration, a Direct Current Induced Polarization (DCIP) system, along with sensors measuring water conductivity, soil moisture, and temperature, was installed to gather data on water saturation and groundwater flow paths (see Dahlin et al., this workshop). The sandy sediments above the groundwater table exhibit high resistivity values (above 1 kΩm), while in the saturated zone, resistivity decreases to just a few hundred Ωm (Figure 1a). In the southern area near another infiltration pond filled with water, we observe a significant decrease in resistivity. This drop indicates higher groundwater levels and a transition to lower resistivity (refer to the pond location in Dahlin et al., this workshop). After 49 days of data collection, the pond begins to receive water, which is evident from the changes in water content.

The reduced resistivity, coupled with the induced polarisation (IP) response, helps identify the direction and depth of water infiltration (Figure 1e and 1f). The low chargeability of the area is attributed to the well-sorted glacial sediments (Figures 1b and 1d). Furthermore, the data show a correlation between changes in the inflow to the pond and variations in resistivity and groundwater levels observed in nearby wells. The sediment layers, the water table, and the 1-meter-deep washed sand filter media are also discernible (1g). Both the DCIP and Ground Penetrating Radar (GPR) results indicate a similar groundwater level in the pond, around 5 meters deep. High-resolution (with 170 MHz antenna) GPR measurements are conducted before and after water infiltrates the pond to capture shallow depth changes with precision.

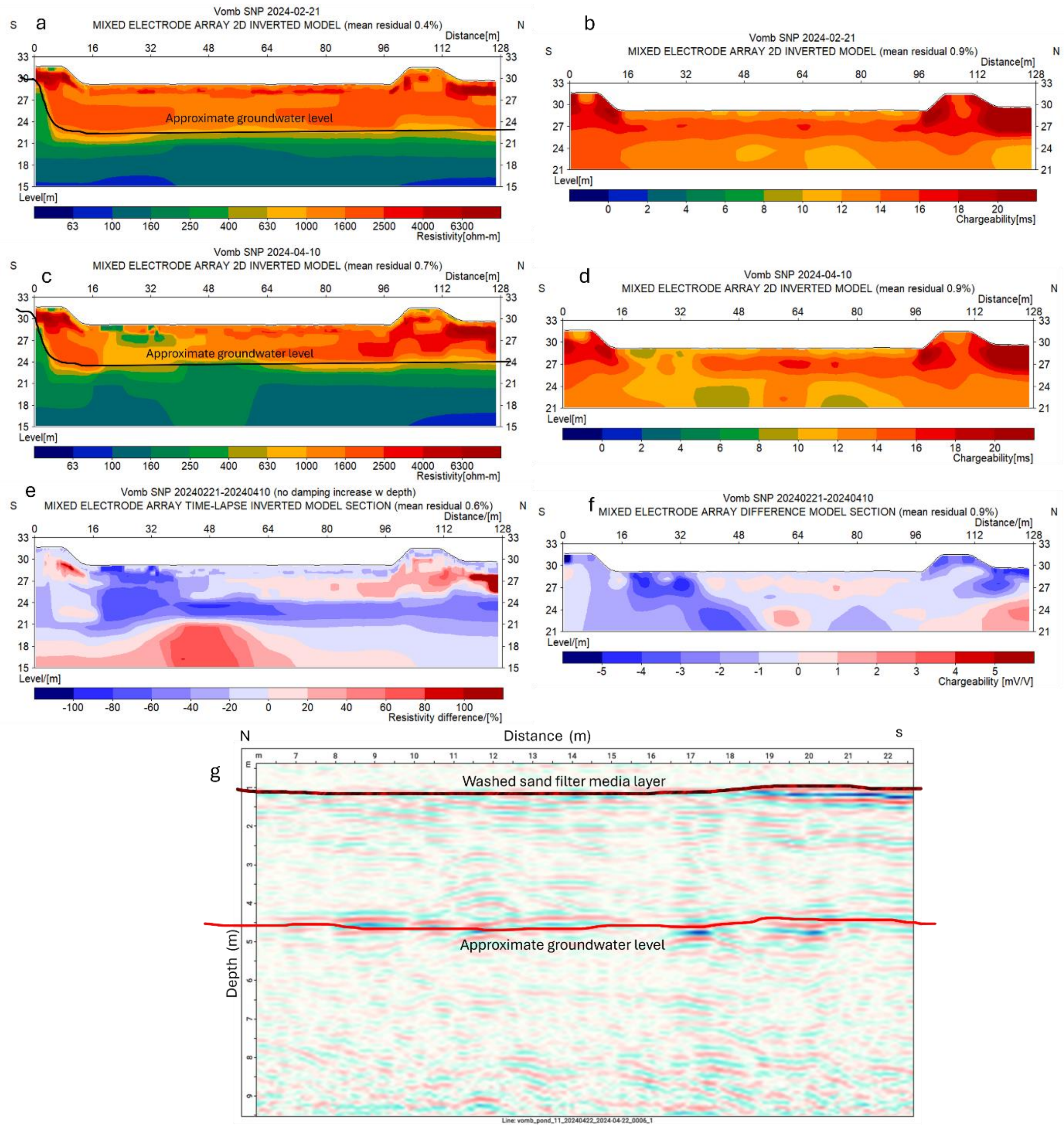

Figure: DCIP results a) Baseline resistivity of line SNP b) Baseline chargeability c) resistivity after water flowing into the pond and raised groundwater level d) chargeability after water flows into the pond e) Time-lapse resistivity indicating changed values f) Time-lapse chargeability g) GPR profile before water flows into the pond

The next steps involve estimating the soil's hydrological properties and integrating these findings into a hydrogeological model. This model will optimise water management and simulate future scenarios involving increased water demand and climate change impacts. Additionally, it will explore the potential for monitoring biofilm growth in sand filters.

Acknowledgements: This research is funded by the EU Interreg North Sea region via the "*Blue Transition – how to make my region climate resilient"* project, Sydvatten AB and Sweden Water Research (SWR).

DCIP monitoring installation at Vomb MAR

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A DCIP system has been installed in and around an infiltration pond within the Vomb managed aquifer recharge (MAR) plant in southern Sweden. The objective is to monitor the water saturation and transport under the infiltration pond to create a better understanding of the infiltration process, to form a base for optimised operation of the water works. Another objective is to assess the possibility to monitor the growth of biofilm in the sand filter.

The installation includes in total 416 electrodes divided between 3 lines with 128 to 160 electrodes each (Figure a). The electrodes consist of 10 cm x 10 cm stainless steel plates that were buried in trenches at 0.4 m depth and connected alternatingly to two parallel cables that are separated by around 0.7 m (Figure b). The instrumentation is based on an ABEM Terrameter LS2, a 16x32 relay switch with built-in lightning protection, and PC control via network. Furthermore, sensors for water conductivity, water level and temperature were installed. Instrumentation and computers are installed in an 8’ shipping container.

Measurements are taken using 100% duty cycle IP (Olsson et al. 2015) with 4 s pulses, and data are saved as full waveform with a sampling rate of 3750 Hz to allow advanced signal processing (Olsson et al. 2016). A roll-along approach has been implemented, in which selected subsets of the electrode spreads are connected to the instrument in a sequence. A multiple gradient array configuration adapted for separated spreads is used for the measurements, plus a pseudo pole-dipole array using the farthest electrode in the other end of the spread as “remote” electrode. Reciprocal measurements are made for 10 % of the data to allow quantification of observation errors. In total around 16 000 data points are measured daily. Data, including auxiliary measurements of water level, conductivity, and temperature, are transferred via SFTP to an off-site server for processing, archiving, etc.

A background series measured before water filling of the pond started shows electrode contact resistances mostly in the range 5-10 kW. Preliminary inversion of the apparent resistivity and integral chargeability data, without accounting for the burial depth of the electrodes, results in excellent data fit with mean residuals below 1 %. Sandy sediments above the groundwater level stand out with resistivities above 1 kWm, which drops to a few hundred Wm in the saturated zone, (Figure c). The gradually decreasing resistivity with depth may reflect changes in grain size of the sediments. In the southern end the measurement line is close to a neighbouring water filled infiltration pond which is reflected by a steep increase in the level of the interface to lower resistivity associated with higher groundwater level. The chargeability is rather low (Figure d).

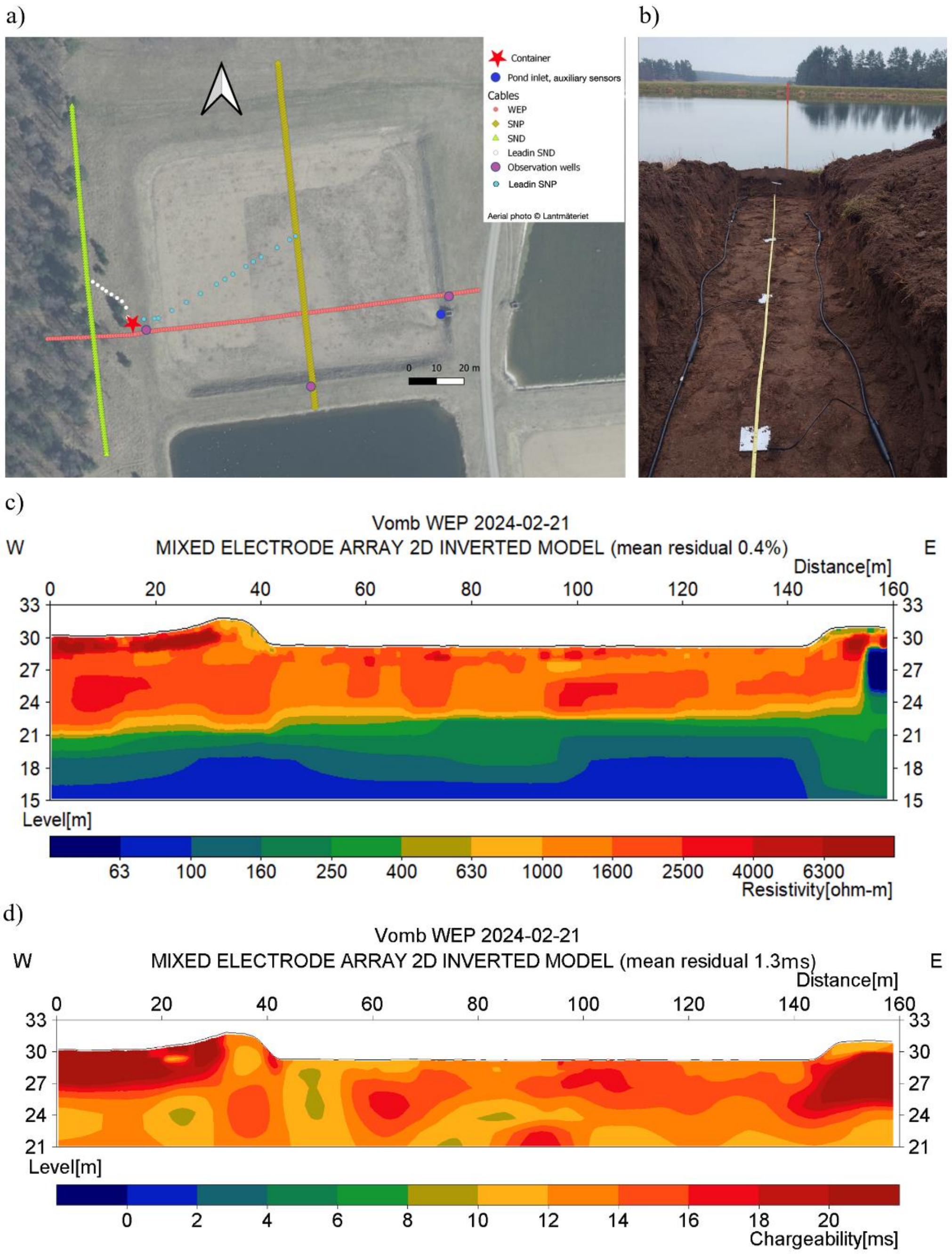

Figure: a) Positions of electrode spreads. b) Temporary trench for electrode installation in southern end of line SNP with neighbouring infiltration pond in the background. c) Background resistivity result. d) Background chargeability result.

Acknowledgements

The work is funded by the EU Interreg North Sea region via the "*Blue Transition – how to make my region climate resilient"* project, Sydvatten AB and Sweden Water Research (SWR). We thank Mike Torstensson and Stefan Svensson for excellent work and nice collaboration during the electrode installations.

Analysis of Vertical and Lateral Flow Components of Interflow

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Interflow (subsurface storm flow SSF) plays a crucial role in the formation of runoff at the watershed level and significantly influences the development of flood events. Due to its temporary occurrence and spatial variability, the subsurface process is difficult to research and measure. As part of the SSF Forcing research project (funded by DFG German Research Foundation and the FWF Austrian science fund), this study examines various techniques for capturing subsurface flows and pathways and its vertical and lateral flow components at the plot level. The goal is to develop a deeper understanding of these dynamic processes and to establish methods that enable quantification of SSF and their realistic representation in hydrological models.

To analyse the vertical and lateral flow components at the plot level, a combination of different methods is used, including Electrical Resistivity Tomography (ERT) and Time-Domain Reflectometry (TDR) in conjunction with artificial rain simulations (ARS). This combination of methods allows for a detailed investigation of hydrological processes under controlled conditions. Vertical water flows are captured using TDR and serve as reference points for the ERT profiles. Through two parallel ERT profiles within the irrigation plot, lateral flow paths are also observed during continuous measurements. The combination of ERT and ARS is an established method for detecting infiltrating water. However, due to the applied irrigation water and the resulting extreme reduction of resistivity at the surface, it remains challenging to differentiate between the effects of vertical flow and lateral flow. To observe the components of lateral flow without the influence of directly applied rainfall and the consecutively vertical infiltrating water, an ERT reference line below the main investigation plot is used. This reference line serves to verify the vertical and lateral spread of interflow and to confirm the detection of flows in deeper soil layers without the influence of directly applied rainfall.

In this study, we evaluate the feasibility of using 2D-ERT data to detect subsurface stormflow by means of ARS. A key challenge in this approach is determining whether vertical and lateral flow can be effectively distinguished, while minimizing inversion artefacts generated on or adjacent to the survey lines by the irrigation area. Addressing these challenges is essential to improve the clarity and reliability of subsurface flow detection using ERT.

Time-Lapse ERT Analysis to Monitor Subsurface Resistivity Changes in a tidally influenced estuarine aquifer system.

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This study applies time-series analysis to investigate the temporal relationship between tidal fluctuations and subsurface resistivity changes in a tidally influenced estuarine aquifer system. Time-lapse Electrical Resistivity Tomography (ERT) profiles were collected at 30-minute intervals near a tidal channel, along with concurrent tidal flow measurements, including stream height, velocity, and volume. The goal of this research is to explore how tidal forces influence the ground water salinity distribution over a tidal cycle, with a focus on identifying patterns and lags in the hydrological response of the estuarine aquifer.

To enhance data quality, noise reduction techniques were applied to the resistivity data. We will investigate the change in resistivity as a function of position and depth within the aquifer. This will tell us which part of the aquifer is being impacted by the salinity pulse associated with high tide. For position, we use the average location of the two potential electrode as a proxy. For depth, we use distance between current electrode as a proxy. Overall, we find that the resistivity of the estuarine aquifer generally increases at flood tide, because the increased water height in the channel pushes relatively fresh surface water into the relatively saline aquifer. The rise in resistivity with the flood tide is much sharper than the fall resistivity during the ebb tide.

Geophysical and hydrological monitoring of snowmelt at the Hirschgruben cave (Hochschwab, Austria)

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Snowmelt is a key parameter for groundwater recharge in alpine aquifer, yet the pathways controlling water flow from snowmelt into the epikarst and the vados zone are not well understood. To address this issue, we present here electrical resistivity tomography (ERT) monitoring measurements conducted at the Hochschwab karst massif (Styria, Austria), one of the most important catchments for Vienna's water supply. In particular, we present here results obtained from monitoring data collected at the Hirschgruben cave, which opens at 1896 m a.s.l. in limestone of the Dachstein Formation below a paleo surface with up to 40 cm soil cover. The cave passages near the entrance run horizontally into the mountain, while the surface topography increases with it, resulting in a rock overburden of up to 25 m. We aim at understanding the infiltration of snowmelt water into the uppermost vadose zone by combining ERT monitoring and hydrological measurements, namely drip water in the cave and soil moisture.

Imaging result presented here were obtained at two different monitoring periods, associated to different conditions. The first data set considers continuous monitoring of snowmelt events along three weeks between March and April (2024), representing dry and wet winter/spring conditions. The second monitoring period was between June and August (2024), representing dry as well as wet summer conditions. ERT monitoring data sets were collected using 96 electrodes (1 m spacing) along a profile extending from the surface through the cave entrance and ceiling to the drip water chimney. During the snowmelt period, ERT measurements were taken every 7 h, supplemented by three measurements during the summer months. Hydrological data are available at 10-minute intervals covering the entire observation period; Two surface stations measure precipitation, temperature and soil volumetric water content and in the cave a logger measures drip water from a chimney for discharge, fluid electrical conductivity, and temperature.

Temporal changes in the hydrogeological and geophysical data reveal good agreement for all occurred hydrologic events. Our analysis demonstrate that the combination of both direct and indirect methods provides information on the flow rates, saturation of the rock, and resident times in relation to the infiltration rate. While snowmelt leads to an increase in saturation also in the rock body, rain events show a quick recharge. These results show the importance of snowmelt as a diffuse recharge source as well as the importance of using different sensors to investigate recharge processes in Alpine karst systems.

Geoelectric response associated with heavy rainfall in an alpine catchment

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The Val d'Ursé sub-catchment is located above the town of Poschiavo in the Canton of Graubünden, Switzerland. It is being studied in terms of cryo-hydrological processes as part of the Poschiavo Critical Zone Observatory. With a projected increased stress on water resources due to climate change, an enhanced understanding and quantification of groundwater recharge, storage, and flow patterns in mountain environments becomes important because groundwater will play an increasing role in maintaining hydrological flows in the summer months. The Val d'Ursé, featuring many springs, streams and a rock glacier, is instrumented with a variety of sensors. There is a river monitoring station, and several springs are regularly surveyed. A few passive seismic stations are also installed in the area. Finally, a 200-meter-deep borehole located at approximately 2300 meters elevation is used to monitor pressure (yearly variations of 40 m) and temperature (decreasing long-term trend) at two depth intervals since 2010.

We report the first results of a recently acquired Electrical Resistivity Tomography (ERT) survey along a 470-meter NE-SW oriented line centred on the borehole. The profile is located in-between a geological interface between orthogneiss (within which the borehole is located) and schist, and the rock glacier. Both Wenner-Schlumberger and Dipole-Dipole configurations including Induced Polarisation measurements were recorded using a Syscal Pro Switch resistivity meter and a 10-meter electrode spacing. Data were acquired before (7th October 2024) and after (9th October 2024) a major rainfall event with 50 mm of precipitation falling on the 8th October 2024. There is a clear signature of the rainfall event in the Wenner-Schlumberger data with 30 % of the apparent resistivity data showing decreases exceeding 15 %, whereas only 4 % of the data show corresponding increases (Figure 1). The changes in apparent resistivity on the order of 10% seem to be mainly concentrated in the upper few meters, as expected. The positive apparent resistivity change values for longer electrode offsets are attributed to measurement noise.

We implement difference inversion of the apparent resistivity data using the PyGIMLi framework and apply geostatistical regularisation, with results indicating well-resolved decreases in resistivity in the upper meters of the unsaturated rock formation. These initial experiments in a difficult-to-access environment and corresponding results form the basis for more targeted and comprehensive geophysical measurements and monitoring campaigns over the coming years.

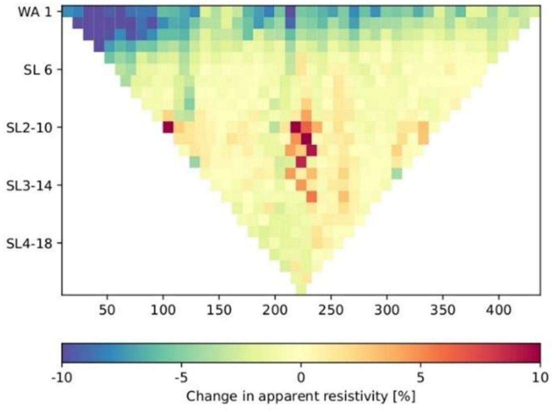

Figure: visualization of the raw data

Embankment

Geoelectrical monitoring of a Napoleonic-era estuarine flood embankment in the UK during a period of Spring tides and storm surge

Jim Whiteley, Paul Wilkinson, Adrian White, Samuel Oakley, Kate Aston, Jimmy Boyd, Georgina Wood, Oliver Kuras, Jonathan Chambers, Rob Newton

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The estuarine flood defence at Powderham Banks in the Exe Estuary, UK, is a 1.4 km long flood defence protecting a mainline railway, Exminster Marshes nature reserve and ~100 residential properties. Constructed over 200 years ago, relatively little is known about the internal structure or condition of the embankment. The last major upgrade to the defence took place in the 1960s, which comprised the addition of blockwork and stone pitching to the estuarine face (revetment) of the embankment. However, the revetment is currently in a deteriorating state, and requires frequent patch repairs that cost the UK Environment Agency (the asset operator) in the region of ~£100,000 GBP per annum. These repairs are typically undertaken in response to storm damage of the revetment, or are based on visual inspection of the revetment condition.

In early 2023 a significant breach occurred at the embankment after the ingress of water from the estuarine side and connection with an animal burrow in the landward side. Following this event, a non-intrusive characterisation survey of the embankment was undertaken using geophysics (3D resistivity, 2D ground penetrating radar and electromagnetic surveys) and UAVs (imagery, multispectral and thermal surveys). This survey identified 20 locations along the embankment, where multiple sources of evidence from the surveys indicated there may be deterioration and / or seepage within the internal structure of the embankment. Of these 20 locations, four have gone on to experience damage, comprising one area of revetment damage (April 2024), and three piping failures (one in August 2024 and two in October 2024, with an additional two areas experiencing piping failures that were not flagged in the initial geophysical survey).

In September 2024, two PRIME geoelectrical monitoring systems were deployed at the site. The electrode arrays were deployed toward the base of the embankment to avoid potential interference from the reinforced wave return located at the crest of the embankment. In the days following the system deployment, a period of Spring tides and storm surge occurred in the estuary, during which the PRIME systems recorded full datasets approximately every two hours. In this study, we present the PRIME monitoring results from this period, focusing on four piping failures that occurred, as well as the general condition of the embankment in response to the extreme estuary tide levels. We show how our monitoring setup is sensitive to piping failures toward the base of the embankment, but has reduced sensitivity to piping failures located higher up the embankment structure. We also show how the resistivity monitoring data indicates that recent repairs to the estuarine revetment have been successful at preventing further seepage through the embankment structure. The results of geoelectrical monitoring from this short but significant time period of extreme tidal levels underscore the capacity for resistivity monitoring to both detect immediate issues with the embankment, as well as monitor the efficacy of repairs, and therefore the longer-term resilience of the embankment to future extreme tidal events.

3D Electrical Resistivity Tomography for Detecting Internal Defects in the Älvkarleby Test Embankment Dam

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The purpose of this study is to investigate the application of Electrical Resistivity Tomography (ERT) for monitoring and characterizing material properties in embankment dams, and to integrate ERT data into seepage modelling to enhance the accuracy of leakage detection and internal erosion assessment. A test embankment dam with intentional defects was constructed in Älvkarleby, Sweden, to evaluate the effectiveness of different monitoring methods in detecting anomalies and potential leakage zones (Norooz et al. 2024).

The test dam included five well-defined intentional defects: a wooden block simulating a cavity, two horizontal permeable zones, a vertical loose zone, and a concrete block simulating a stone. The locations of these defects were kept secret to assess the capability of different monitoring methods including ERT in identifying them. A total of 224 electrodes were installed, and up to 14,000 ERT data points collected daily, providing a comprehensive resistivity coverage of the dam core.

The resistivity models revealed a layered structure within the dam core, likely caused by differential wetting, material grading variations, or compaction inconsistencies during construction. High-resistivity zones corresponding to intentional defects, one of the horizontal permeable zones and the vertical loose zone, were successfully identified. However, the smaller defects, one of the horizontal permeable zones and the wooden box, were not detected due to size and low resistivity contrast. Additionally, high-resistivity areas were observed around the concrete block, potentially indicating the presence of coarse-grained material in its vicinity.

Additional and more conspicuous anomalous resistivity zones were discovered, indicating potential preferential flow paths caused by unintentional defects. The resistivity data over time showed significant changes in the lower parts of the core and fine filter, suggesting variations in material properties and potential fine particle transport due to hydraulic gradients (Norooz et al. 2024).

The results of the seepage models showed that integrating ERT data significantly improved the seepage models, resulting in better alignment between predicted and observed pore pressures and leakage rates. By incorporating the spatial and temporal variations in material properties provided by ERT, the models were able to more precisely identify leakage paths and internal erosion processes that can explain the temporal changes. This suggests that ERT data allowed for a refined definition of the dam core properties and demonstrates its potential as a valuable tool for monitoring embankment dams, aiding early detection of leakage and internal erosion. The integration of ERT data into seepage modelling thus represents a significant advancement in offering a more comprehensive approach to dam safety and management.

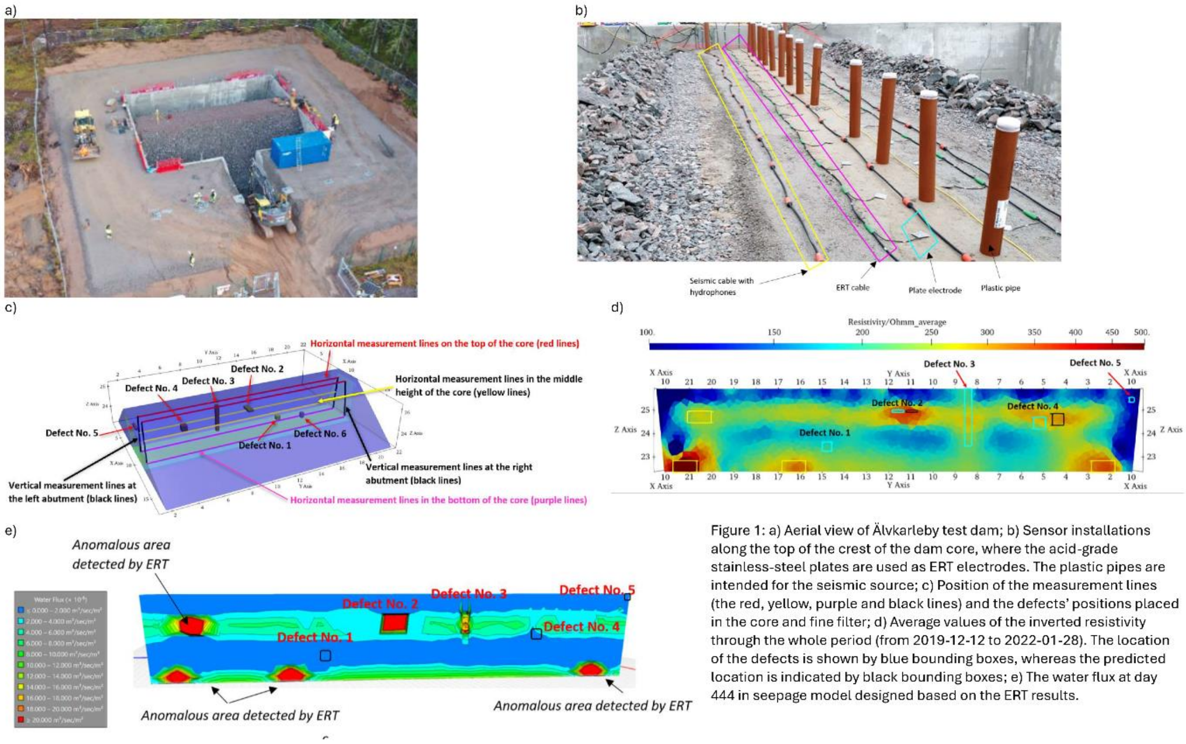

Figure: Field installation and inversion results

Acknowledgements
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Long-term ERT monitoring data analysis to evaluate the internal conditions of river levees: Colorno case study

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Electrical resistivity tomography (ERT) is becoming a widely used technique for monitoring the hydrogeological conditions of embankments, given the strong dependence of resistivity on soil water content. Recent developments in cost-effective systems allow to perform autonomous monitoring and help to support risk mitigation strategies. To successfully apply the ERT monitoring method in hydrogeological risk mitigation, it is necessary to take into account the effects of site-dependant factors such as the embankment geometry, the boundary conditions (mainly the water level in the river), and soil temperature variations. This study presents ERT monitoring data measured during the period December 2020-December 2022 on a river levee in Colorno, Italy. The study site had suffered a partial collapse in 2017 and the damaged part (about 30 m long) was reconstructed using clay-rich materials that differ from the original composition. A customized ERT monitoring system was later installed in November 2018 to monitor the repaired structure and the contacts between the reconstructed and the untouched sectors. The system supports 48 electrodes that are deployed at 0.5 m depth with unit spacing of 2 m and is accompanied with a rain gauge, an air temperature sensor and a soil temperature sensor at 1.5 m depth. The objective was to evaluate resistivity changes in response to rainfalls and water level changes in the river. Raw data were mainly corrected for 3D effects related to the specific geometry of the embankment and seasonal changes in the levee body and its boundary conditions (Hojat, 2024). A model was then calibrated for soil temperature variations with depth and the inverted data were corrected for temperature changes at each depth. An example of the results is shown in Figure below, where resistivity drops in response to main rainfalls can be observed together with a general seasonal trend characterized by higher resistivity values during summer and autumn months, due to drier conditions of the embankment. Seasonal trends are similar for the reconstructed and original levee sections, but a remarkable difference in absolute values is observed due to the higher clay content of the reconstructed structure. By analysing the tomographic sections generated daily no local anomalies were observed during the two years period, indicating that the structure is safe and no problems were reported for the contacts between the original levee and the reconstructed section.

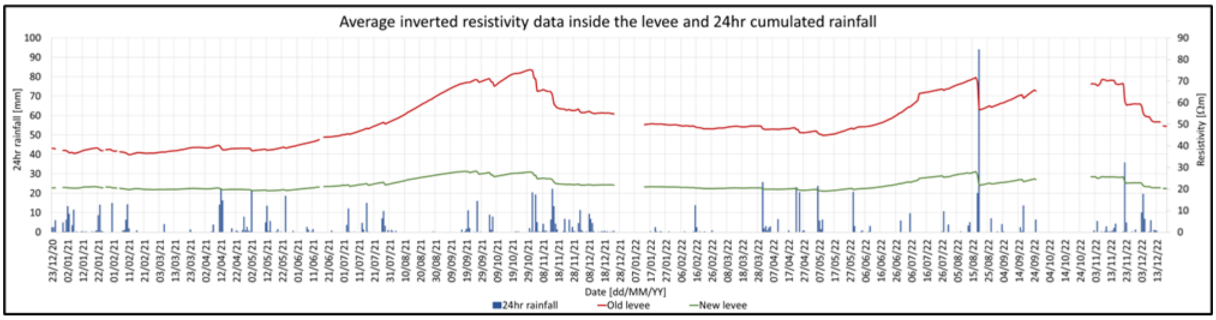

Figure: Average values of the inverted resistivity data separately calculated for the reconstructed section (new levee) and for the original segments of the levee (old levee)

References:

Hojat, A. (2024): An iterative 3D correction plus 2D inversion procedure to remove 3D effects from 2D ERT data along embankments. Sensors, 24(12):3759. DOI:10.3390/s24123759.

TL-ERT and FDEM acquisitions for the monitoring of leeves: test site Tatarena river (Trevi, Italy)

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In recent years, there has been a significant increase in the frequency and intensity of extreme flooding, particularly in Italy, attributed to factors such as climate change and insufficient maintenance of hydraulic infrastructure. River levees play a critical role in protecting human lives and economic activities, serving as essential barriers against extreme events; thus, their analysis and maintenance are crucial for mitigating hydrological risk. The main drivers of embankment failure include erosion, both external and internal, and instability mostly caused by strong water pressure exerted during river floods. In addition, other meteorological phenomena, human activities, as well as the presence of animals and certain types of vegetation can weaken embankments and act as drivers of instability, subsidence or breakage. Therefore, levees are systems that can have several internal heterogeneities that can destabilise the hydraulic balance during a stream filling phase. Without proper identification of heterogeneities within the system, there is a risk of underestimating hydrological risk, as levee resilience depends on the presence or absence of weak points. To address these limitations, non-invasive geophysical techniques have been introduced, offering a more comprehensive view of the study area and supplementing data from direct investigations. This study focused on monitoring a stretch of the Tatarena River levee, located in Umbria, near the village of Cannaiola (PG). The study aimed to analyze the heterogeneities of the levee and to monitor the hydraulic behaviour of them over time in relation to river levels, in order to assess levee stability and prevent failures during floods. The first phase involved characterizing the levee using frequency-domain electromagnetic (FDEM) surveys and electrical resistivity tomography (ERT). Integrating these techniques enabled the identification and delineation of the area where a semi-continuous geoelectric acquisition system was installed to monitor changes in resistivity parameters over time. Longitudinal time-lapse ERT (tl-ERT) surveys provided detailed profiles of the levee, revealing seasonal resistivity variations, while the electromagnetic technique, applied over a broader stretch of the levee, facilitated the verification of ERT results by identifying areas of high and low conductivity and observing their changes over time. Currently, the geoelectric acquisition system operates in a semi-continuous mode, still requiring technical personnel to initiate acquisitions, as there are no low-cost systems for continuous monitoring. To address this, a low-cost georesistivitymeter inspired by the OhmPi project was developed to continuously and remotely acquire data. The OhmPi system automates the acquisition process, allowing for remote control and regular interval data collection to monitor resistivity evolution over time. The final goal is to develop a low-cost instrument that can be permanently installed at the levee monitoring site, enabling constant remote monitoring. This work was supported by the European Union NextGenerationEU/NRRP, Mission 4 Component 2 Investment 1.3, Call DD 2356 (02/23/2024), under the project PE00000005 "Multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate (RETURN)," Spoke VS1 "Water," subproject "Riduzione del Rischio di Collasso Arginale (R2CA)," CUP D43C22003030002.

Time-Lapse Airborne EM for monitoring the evolution of a saltwater aquifer

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In this study, a multitemporal Airborne EM survey (2015, 2022, 2024) is conducted to monitor the groundwater changes in the shallow aquifer of the Bookpurnong floodplain, South Australia. Over 200 km of AEM lines were acquired during each survey in this naturally high-salinity aquifer region, with the aim of tracking the freshwater recharge induced by the River Murray's discharge. A comprehensive comparison between the benefits achieved by applying Time-Lapse modelling to Airborne EM data is provided, showcasing also a synthetic experiment before the real case study. In both instances, enforcing temporal constraints, characterised by the Asymmetric Minimum Support Norm (AGSM, Fiandaca et al., 2015, doi: 10.1093/gji/ggv350), proves crucial in reducing noise-induced and equivalence-induced model differences that could mislead interpretations. Specifically, a Spatial Constrained Inversion approach (Viezzoli et al., 2008, doi: 10.1190/1.2895521), which enables quasi-3D solutions by spatially linking neighbouring EM soundings, is integrated into the unified Time-Lapse framework, where all the dataset are inverted simultaneously using a cascade-style approach. In the latter, the multitemporal models are connected to a reference model, obtained from an initial dataset. Moreover, specific processing procedures are implemented to suppress noise induced anomaly propagation. The Time-Lapse results reveal a clear evolution of the floodplain within the geophysical models, unveiling a different hydrogeological behaviour from the shallow parts of the models, of primary interest for the groundwater management in the area, to the deep portions (~-120m). A full validation of the results is carried out first employing the available log-EM data for the floodplain and then performing an Independent Hydrogeological Validation (IHV), where hydrogeological indices, calculated following Vonk (2024, doi: https://doi.org/10.5281/zenodo.10816741), are compared to the geophysical outcomes.

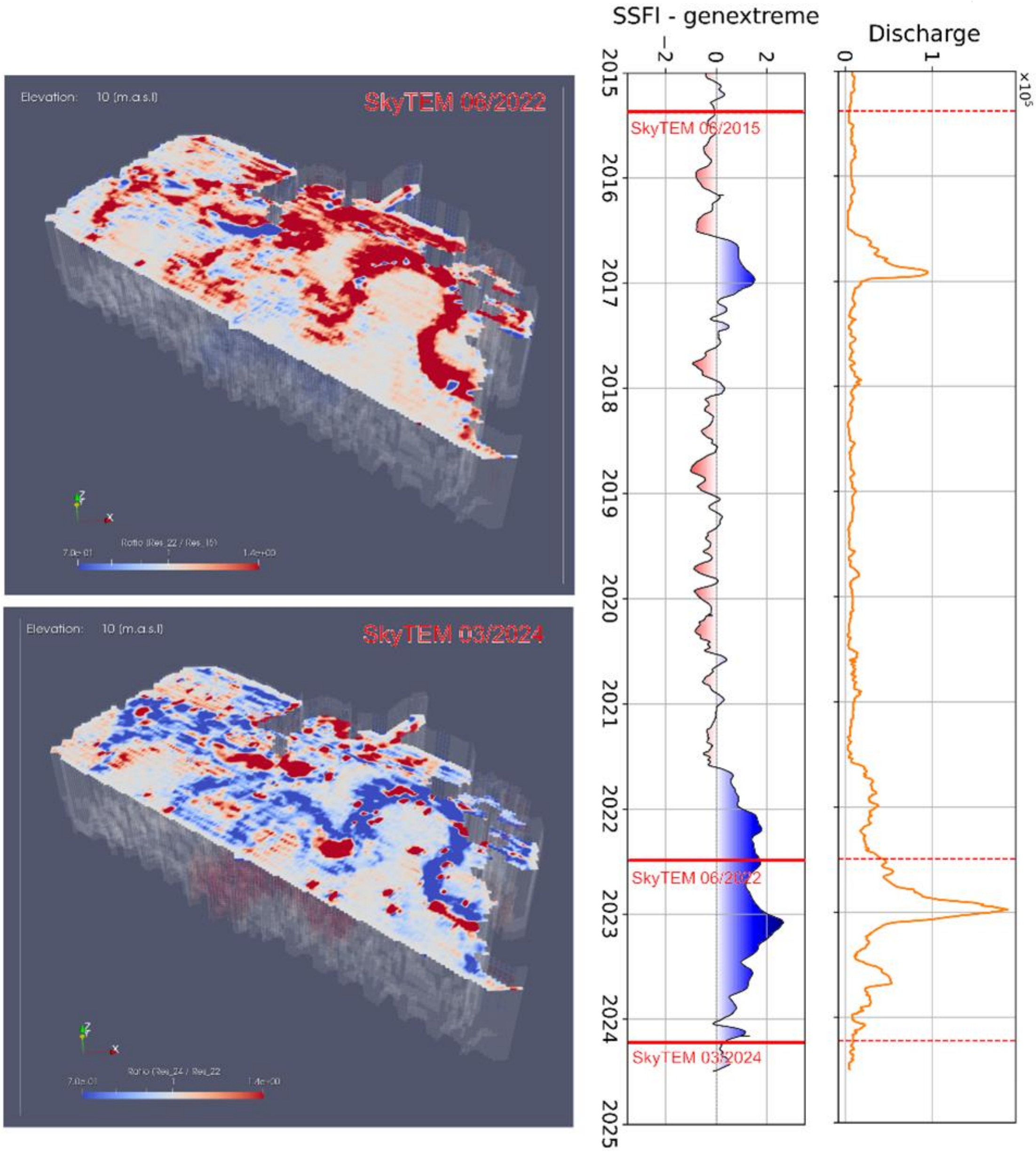

Figure: Inversion results

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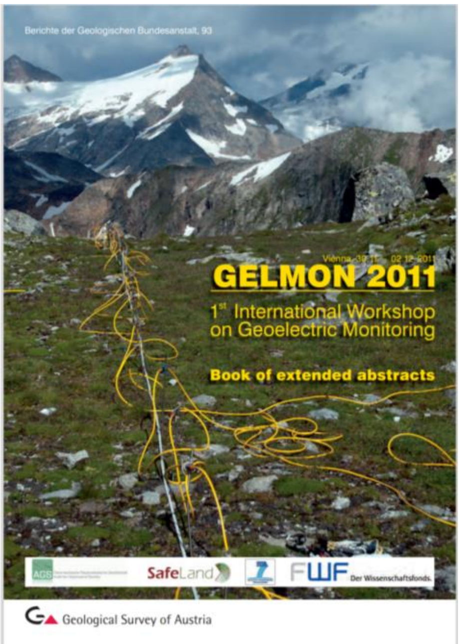

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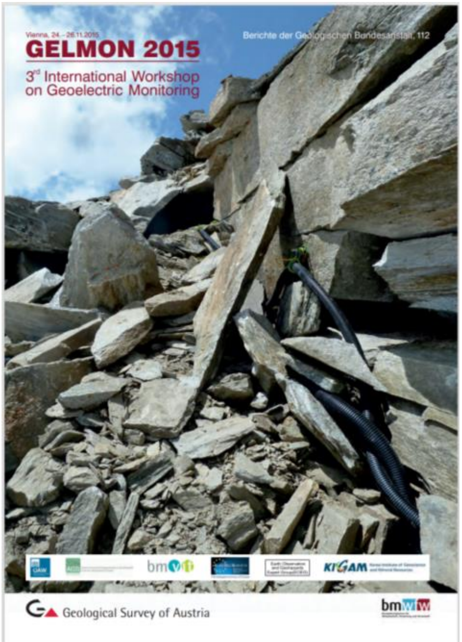

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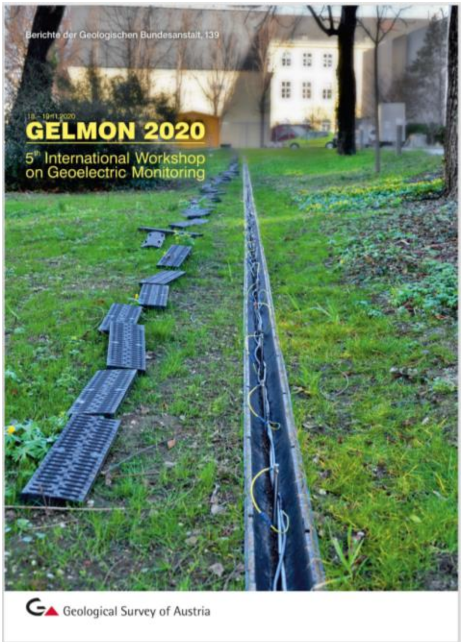

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